

Київський національний університет технологій та дизайну

ТЕХНОЛОГІЇ ТА ІНЖИНІРИНГ

Науковий журнал

Том 25, № 6, 2024

Київ
2024

ISSN 2786-5371
e-ISSN 2786-538X

Засновник журналу:
Київський національний університет технологій та дизайну

Рік заснування: 1999 р.

Періодичність випуску: 6 разів на рік

*Рекомендовано до друку та поширення
через мережу Інтернет Вченою Радою
Київського національного університету технологій та дизайну
(протокол № 4 від 18 грудня 2024 р.)*

Державна реєстрація:
Ідентифікатор медіа: R30-05423
Рішення Національної ради України з питань телебачення і радіомовлення № 2520,
протокол № 22 від 8 серпня 2024 року

Журнал внесено до категорії «Б» Переліку наукових фахових видань України,
відповідно до якого можуть публікуватися результати дисертаційних робіт на здобуття наукових
ступенів доктора та кандидата наук зі спеціальностей:
технічні (наказ Міністерства освіти і науки України №735 від 29 червня 2021 р.):
122 – Комп’ютерні науки, 131 – Прикладна механіка, 133 – Галузеве машинобудування,
151 – Автоматизація та комп’ютерно-інтегровані технології, 161 – Хімічні технології та інженерія,
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електротехніка та електромеханіка, 144 – Теплоенергетика, 171 – Електроніка.

**Журнал представлено у міжнародних наукометричних базах даних,
репозитаріях та пошукових системах:** Національна бібліотека України імені В. І. Вернадського,
Crossref, Google Scholar, OUCI, Фахові видання України, EBSCO, Dimensions, UCSB Library, University of
Oslo Library, University of Hull Library, BASE, Ulrichsweb Global Serials Directory

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01011, вул. Мала Шияновська, 2, м. Київ, Україна
тел/факс: +38 (044) 256-84-27
E-mail: info@technologies-engineering.com.ua
<https://technologies-engineering.com.ua/uk>

Kyiv National University of Technologies and Design

**TECHNOLOGIES
AND ENGINEERING**

Scientific Journal

Vol. 25, No. 6, 2024

Kyiv
2024

ISSN 2786-5371
e-ISSN 2786-538X

Founder:

Kyiv National University of Technologies and Design

Year of foundation: 1999

Frequency: 6 issues per year

*Recommended for printing and distribution
via the Internet by the Academic Council
of Kyiv National University of Technologies and Design
(Minutes No.4 of December 18, 2024)*

State registration:

Media identifier: R30-05423

Decision of the National Council of Television and Radio Broadcasting of Ukraine No. 2520,
Minutes No. 22 dated 08.08.2024

The journal is included in category “B” of the List of scientific professional publications of Ukraine, in which the results of dissertations for the degree of doctor and candidate of sciences can be published in the following specialties: technical (Order of the Ministry of Education and Science of Ukraine No. 735 dated 29.06.2021): 0612 – Database and network design and administration, 0715 – Mechanics and metal trades, 0714 – Electronics and automation, 0711 – Chemical engineering and processes, 0588 – Inter-disciplinary programmes and qualifications involving engineering, manufacturing and construction, 0723 – Textiles (clothes, footwear and leather), 0713 – Electricity and energy, 0714 – Electronics and automation. Beginning with issue 4 of 2024, the editorial board narrowed the thematic scope of the journal

The journal is presented in the international scientometric databases, repositories and scientific systems: Vernadsky National Library of Ukraine, Crossref, Google Scholar, OUCI, Professional Publications of Ukraine, EBSCO, Dimensions, UCSB Library, University of Oslo Library, University of Hull Library, BASE, Ulrichsweb Global Serials Directory

Editors office address:

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Terraform vs Ansible: When and how to use infrastructure tools as code

Ivan Byzov^{*}

Postgraduate Student

V.N. Karazin Kharkiv National University

61022, 4 Svobody Sq., Kharkiv, Ukraine

<https://orcid.org/0009-0004-2950-7814>

Abstract. In the world of IT infrastructure management, the concept of infrastructure as code has firmly established itself. Two popular tools for implementing this approach – Terraform and Ansible – are widely used by DevOps professionals to automate and manage cloud and on-premises resources. Although both tools perform analogous tasks, they have distinct principles of operation, architecture, and application scenarios. The purpose of this study was to provide the key differences between Terraform and Ansible, their strengths and weaknesses, and use cases for each of these tools. Recommendations for choosing a tool depending on specific tasks were offered. Terraform, as a declarative style tool, enables users to describe the end state of the infrastructure, after which it automatically brings it to that state. Ansible, on the other hand, supports both declarative and imperative approaches, making it flexible for managing server configurations and performing orchestration. The study presented practical examples of using both tools. The first example demonstrated how Terraform can be used to automatically deploy cloud infrastructure in Hetzner Cloud. In this example, actions with a cloud service took place using declarative configuration files. The second example described how Ansible can be used to configure servers and how to automate server tasks. The study included scientific aspects related to the evaluation of IaC effectiveness, specifically formulas for calculating the time of application of changes in the infrastructure. The use of formulas helped to quantify the time and overall efficiency of work in the infrastructure to increase overall transparency and control over management processes. Thus, understanding the scenarios in which each tool is most effective will help engineers properly organise infrastructure management processes

Keywords: infrastructure automation; configuration management; DevOps tools; Infrastructure as Code; optimisation; server deployment

Introduction

The automation of infrastructure management has become an integral part of the effective work of modern DevOps teams. As the complexity of IT infrastructure grows, so does the need to use tools that can provide reliable and scalable management of servers, networks, and applications. Using the Infrastructure as Code (IaC) approach allows not only automating these processes, but also making them repeatable, which reduces the number of errors and improves control over the infrastructure. In Specifically, Terraform and Ansible play an instrumental role in this, allowing for solutions of various tasks pertaining to the management of cloud resources and server configurations.

According to the examples provided by S. Bhatia & C. Gabhane (2024), Terraform demonstrates high efficiency in the infrastructure deployment process thanks to a

declarative approach that allows centralised management of resources in distinct cloud environments. R. Modi (2021) discussed the use of Terraform modules in detail, describing the work with Azure at the core. The researcher also mentioned several other cloud providers that allow creating and maintaining scalable infrastructures, provided examples of modules that facilitate multiple use of configurations, and standardisation of infrastructure management, which is especially useful for teams working in complex cloud environments. Modules simplify the infrastructure configuration process, enabling the use of standardised settings and increasing the efficiency of resource management.

A.M. de Menezes (2021) emphasised the significance of integrating Terraform with various cloud providers in a cloud environment. The researcher focused on the tool's

Suggested Citation:

Byzov, I. (2024). Terraform vs Ansible: When and how to use infrastructure tools as code. *Technologies and Engineering*, 25(6), 11-17. doi: 10.30857/2786-5371.2024.6.1.

^{*}Corresponding author



ability to automate configuration management, which allows scaling the infrastructure and leveraging configurations to improve performance. Swedish students A. Witt & S. Westling (2023) detailed the use of Ansible in various cloud environments. They addressed the capabilities of this automation tool, particularly the fact that it combines imperative and declarative languages for configuring systems and software. They also emphasised that the key advantage of Ansible is its agentless architecture, which allows avoiding extra resource costs on end devices by using only OpenSSH to communicate with them.

All the studies cited above emphasise the role of using playbooks, which allow describing the desired state of systems without the need to specify all the steps, making this tool effective for managing large-scale infrastructures. Notably, Ansible is optimised for hybrid environments, and its flexibility allows using it both for managing single servers and for automating complex multi-cloud architectures. Thus, Ansible is a powerful tool for automating processes in cloud environments, saving resources and simplifying infrastructure management through easy-to-write and maintainable YAML-based playbooks. However, the choice between Terraform and Ansible is often uncertain. Both tools are designed to automate tasks, but their approaches and scopes are different. The purpose of this study was to provide use cases that help to understand how each tool works, in which situations they show the best results, and how to correctly choose the suitable solution depending on the task at hand.

Materials and Methods

The efficiency coefficient Formula (1) helped to determine in which cases each of the tools is the most effective and how their joint use can increase the overall automation of IT systems deployment and configuration processes.

$$E_{IaC} = \frac{A_{total}}{T_{total}} \cdot (1 - P_{error}), \quad (1)$$

where A_{total} is the total number of automated operations, i.e., how many tasks or stages of infrastructure management were successfully automated using IaC; T_{total} is the total time required to perform all automated operations (this may include time to deploy resources, apply changes, and adjust configurations); P_{error} is the probability of an error during the execution of automated operations (the lower the probability of errors, the higher the efficiency of automation).

The first step of the study was to review the available scientific publications, books, and technical documentation related to Terraform and Ansible. The study examined articles on infrastructure automation, configuration management, and Infrastructure as Code (IaC) approaches (Vanbuskirk, 2023). Attention was paid to the research describing the successful use cases for these tools, as well as the analysis of their performance and effectiveness in different conditions.

The stage of comparative analysis of architectural features explored the key architectural principles of Terraform

and Ansible. Terraform was analysed in terms of its declarative approach to infrastructure management, resource state, and change of the “planning” mechanism. Ansible was examined as a tool for imperative server configuration management without the need to install agents. Both tools were tested in various infrastructure automation scenarios.

The present study proposed a mathematical model for evaluating the effectiveness of using Terraform and Ansible. For this, an efficiency factor was introduced (E_{IaC}), which factors in the time of operations, the probability of errors, and the degree of process automation. Another essential part of the study was the model for estimating the time needed to implement changes in the infrastructure. For this, Formula (2) was introduced:

$$T_{apply} = \sum_{i=1}^n (t_{create}(R_i) + t_{modify}(R_i) + t_{destroy}(R_i)), \quad (2)$$

where $t_{create}(R_i) + t_{modify}(R_i) + t_{destroy}(R_i)$ is the time for creation, modification, and deletion of the resource. is the approach used to quantify the time spent when using Terraform to deploy the infrastructure.

Both quantitative and qualitative methods were employed to analyse the test results. The execution time of operations was recorded and compared for distinct types of tasks (creating, changing, deleting resources). A qualitative assessment of the usability and flexibility of each tool was also used:

- ◆ For infrastructure deployment: Terraform (v1.9.0) with providers for Hetzner Cloud.
- ◆ For server configuration: Ansible (v2.15.12).
- ◆ Standard tools such as Terraform plan and Ansible playbook logging were used to monitor performance and estimate operation times.

Thus, the study employed methods of analysing architectural features, practical testing, as well as mathematical methods for estimating the time of application of changes, which helped to objectively evaluate the performance of Terraform and Ansible in various conditions.

Results and Discussion

A typical infrastructure deployed in the Hetzner Cloud consisting of a virtual machine and network resources was chosen for practical testing. Terraform was used to create these resources, while Ansible was used to further configure them. Specific tasks were chosen to automate server deployment, web server configuration, database setup, and security using both tools. The testing itself was performed using plan files.

Example 1: Cloud infrastructure deployment with Terraform. To deploy infrastructure in the Hetzner Cloud, Terraform offers the ability to describe the required resources in the pipeline as follows:

```
provider "hcloud" {
  token = var.hcloud_token
}
resource "hcloud_firewall" "fw" {
  name = "fw"
```

```

rules = [
  {
    direction = "in"
    protocol = "tcp"
    port = "22"
    source_ips = ["0.0.0.0/0", "::/0"]
  },
  {
    direction = "in"
    protocol = "tcp"
    port = "80"
    source_ips = ["0.0.0.0/0", "::/0"]
  },
  {
    direction = "in"
    protocol = "tcp"
    port = "443"
    source_ips = ["0.0.0.0/0", "::/0"]
  },
  {
    direction = "out"
    protocol = "tcp"
    port = "all"
    destination_ips = ["0.0.0.0/0", "::/0"]
  }
]
}
resource "hcloud_ssh_key" "solokey" {
  name = "solokey"
  public_key = file(var.ssh_public_key)
}
resource "hcloud_server" "my_server" {
  name = "Nginx_server"
  image = "ubuntu-20.04"
  server_type = "cx21"
  ssh_keys = [hcloud_ssh_key.solokey]
  firewall_ids = [hcloud_firewall.fw.id]
}
output "server_ip" {
  value = hcloud_server.my_server.ipv4_address
}

```

This example creates a virtual machine in the cloud using Hetzner. This process is fully automated and described declaratively. Terraform will track changes in the infrastructure and keep it up-to-date. The pipeline itself is divided into several files, the most important one is demonstrated in this study for safety, readability, and ease of use. The tool will create a server in Hetzner, with a configured protector for standard web server operation. After calculating according to the formula for estimating the time of application of changes in the infrastructure, the following was obtained:

- Resources:
1. Server (R1)
 2. Firewall (R2)
 3. SSH key (R3)

Time was spent on the performance of these tasks (t_{create}), which was taken from the real-time execution of the plan of the file. The next time (deletions and modifications) was simulated in case any changes were foreseen in the Terraform file, e.g., Package cx21 was changed to cx22. Accordingly, if the server was edited, Terraform checked with a cloud provider and since it did not have a cx21 server, the tool deleted the existing server and created a new one

according to the tariff plan, then according to the formula, $t_{create}(R_i) + t_{destroy}(R_i)$ need to be calculated.

1. Server (R1):

$t_{create}(R_1) - 5$ minutes
 $t_{modify}(R_1) - 5$ minutes
 $t_{destroy}(R_1) - 1$ minute

2. Firewall (R2):

$t_{create}(R_2) - 30$ seconds
 $t_{modify}(R_2) - 10$ seconds
 $t_{destroy}(R_2) - 15$ seconds

3. SSH key (R3):

$t_{create}(R_3) - 20$ seconds
 $t_{modify}(R_3) - 15$ seconds
 $t_{destroy}(R_3) - 10$ seconds

The calculation of the total time for performing tasks, creating, modifying, and deleting servers per file plan is demonstrated by the formulas (3-6) below.

$$R1T_{apply} = 5 + 5 + 1 = 11 \text{ min.} \quad (3)$$

$$R2 T_{apply} = 0.5 + \frac{1}{6} + \frac{1}{4} \sim 0.9 \text{ min} \sim 55 \text{ sec.} \quad (4)$$

$$R3 T_{apply} = \frac{1}{3} + \frac{1}{4} + \frac{1}{5} \sim 0.7 \text{ min} \sim 45 \text{ sec.} \quad (5)$$

$$SumT_{apply} = 11 + 0.9 + 0.75 \sim 12.7 \text{ min.} \quad (6)$$

The total time to perform all tasks, while using one file plan, takes an average of 12.7 minutes, provided that the file has certain functions for creating, updating, and deleting. On a real project, this time is much shorter. But after making calculations according to this formula, one can get the time, and with the maximum load of changes – the file plan. To calculate the file plan from the example, there is only one need to calculate $t_{create}(R_i)$ since there are no changes or deletions in the example, and the amount was calculated according to formula (7) taking only the values of R1, R2, R3 for $t_{create}(R_i)$:

$$SumT_{apply} = 5 + 0.5 + 0.3 \sim 5.5 \text{ min.} \quad (7)$$

Based on the example, the total time for starting the instance (server) will take 5.5 minutes.

Example 2: Configuring servers with Ansible. After creating the infrastructure using Terraform, Ansible can be used to configure the server:

```

---
- name: Configure server with Ansible
  hosts: all
  become: yes
  vars_prompt:
    - name: python_version
      prompt: "Enter the Python version to install (e.g., 3.10.5)"
      private: no
      default: "3.10.5"
    - name: mysql_root_password
      prompt: "Enter the MySQL root password"
      private: yes

```

```

tasks:
- name: Update and upgrade apt packages
  apt:
    update_cache: yes
    upgrade: dist

- name: Install required packages and dependencies
  apt:
    name:
      - mysql-server
      - python3-pip
      - mc
      - nginx
      - git
      - curl
      - ncd
      - fail2ban
      - make
      - python3-dev
      - default-libmysqlclient-dev
      - build-essential
      - libssl-dev
      - zlib1g-dev
      - libbz2-dev
      - libreadline-dev
      - libsqlite3-dev
      - llvm
      - libncurses5-dev
      - libncursesw5-dev
      - xz-utils
      - tk-dev
      - libffi-dev
      - liblzma-dev
    state: present

      - name: Create socket file for project
  copy:
    dest: "/etc/systemd/system/{{project_name}}.socket"
    content: |
      [Unit]
      Description=unicorn socket

      [Socket]
      ListenStream=/run/{{project_name}}.sock

      [Install]
      WantedBy=sockets.target

    owner: root
    group: root
    mode: '0644'

- name: Create directory project
  file:
    path: /projects
    state: directory
    owner: root
    group: root
    mode: '0755'

- name: Reload systemd and enable services
  systemd:
    daemon_reload: yes
    name: site.service
    enabled: yes
    state: started

- name: Change SSH port
  lineinfile:
    path: /etc/ssh/sshd_config
    regexp: '^#?Port\s+'
    line: 'Port 222'
    state: present

- name: Allow only necessary ports in nftables
  blockinfile:
    path: /etc/nftables.conf
    block: |
      table inet filter {
        chain input {
          type filter hook input priority 0; policy drop;
          iif lo accept
          ip protocol icmp accept
          ip6 nexthdr ipv6-icmp accept
          ct state established,related accept
          tcp dport { 222, 80, 443, 8000 } accept
        }
      }

- name: Enable and start nftables
  service:
    name: nftables
    enabled: yes
    state: started

- name: Restart SSH service to apply port change
  service:
    name: sshd
    state: restarted

- name: Ensure users are present with home directories
  ansible.builtin.user:
    name: "{{ item.name }}"
    state: present
    home: "/home/{{ item.name }}"
    shell: /bin/bash
    create_home: true
    groups: root
    loop: "{{ users }}"
    when: item.name != 'root'

- name: Set up authorized keys for users
  ansible.builtin.authorized_key:
    user: "{{ item.0.name }}"
    key: "{{ item.1 }}"
    state: present
    loop: "{{ users | subelements('ssh_keys') }}"

- name: Ensure user is added to sudoers with NO PASSWD
  privileges
  ansible.builtin.lineinfile:
    path: /etc/sudoers.d/{{ item.name }}
    create: yes
    line: "{{ item.name }} ALL=(ALL) NOPASSWD:ALL"
    validate: 'visudo -cf %s'
    loop: "{{ users }}"
    when: item.name != 'root'

- name: Ensure Nginx is enabled and running
  systemd:
    name: nginx
    enabled: yes
    state: started

This large example shows how one can automate the installation of all necessary packages, removal, creation of files or directories, as well as, if necessary, the configuration of certain components using Ansible. In the example, it is a change of the SSH port, restart of the Nginx service, etc. Ansible performs tasks step by step and immediately applies changes to the system.

```

Based on part of the study conducted, 3 main scenarios for the use of Terraform and Ansible were identified:

Scenario 1: Deploying the basic infrastructure with Terraform. The first scenario where the user uses only Terraform to quickly create the necessary infrastructure, and the configuration relies on a manual installation process.

Scenario 2: Configuration of servers with Ansible. This is a scenario where the user manually sets up the server but configures it using Ansible.

Scenario 3: Optimised combination of Terraform and Ansible. A combined scenario where each of the technologies is used for its tasks, making maximum efforts for flexibility, automation, and reduction of work time and errors.

It is the best combination that allows achieving maximum automation. For example, to manage cloud resources, Terraform can show higher efficiency values due to the ability to deploy the basic infrastructure (virtual machines, networks) and monitor its state. Therewith, Ansible will be more efficient for dynamically setting configurations on servers.

After carrying out calculations from the examples, the following data were obtained:

Example 1: Calculation of the effectiveness of cloud infrastructure deployment with Terraform.

Calculation data:

- ◆ A_{total} : 10 automated operations (creating a provider, firewall, SSH key, server, network, etc.);
- ◆ T_{total} : 0.25 hours (15 minutes) for all operations;
- ◆ P_{error} : 0.02 (2% probability of error).

Calculation:

$$E_{IaC} = \frac{10}{0.25} \cdot (1 - 0.02) = 40 \cdot 0.98 = 39.2. \quad (8)$$

Interpretation: The efficiency factor for Terraform in this case is 39.2. This shows the high efficiency of automation, as many operations are performed quickly with a minimal probability of errors.

Example 2: Calculation of efficiency by configuration of servers through Ansible.

Calculation data:

- ◆ A_{total} : 15 automated operations (updating packages, installing programs, configuring system files, creating users, etc.);

◆ T_{total} : 0.5 hours (30 minutes) to complete all tasks;

◆ P_{error} : 0.05 (5% error probability).

Calculation:

$$E_{IaC} = \frac{15}{0.5} \cdot (1 - 0.05) = 30 \cdot 0.95 = 28.5. \quad (9)$$

Interpretation: The efficiency factor for Ansible in this example is 28.5. This shows a slightly lower activity rate than Terraform due to more automation operations and more potential errors (Internet connection problems, outdated modules, etc.)

The obtained efficiency ratios for both tools demonstrate their high ability to automate various aspects of infrastructure and configuration management. The values E_{IaC} show considerable time savings and a reduction in the

risk of errors in automation processes. Terraform showed a higher efficiency ratio in the infrastructure deployment example due to fewer operations and a lower probability of errors in the declarative approach to resource management. Ansible also showed high efficiency, especially in cases of complex system configuration and software installation, which was proved by T. Noviana (2024). Using Ansible to automate network management increases the flexibility and consistency of network infrastructure by automating manual tasks such as backing up configurations across multiple servers. With Ansible, organisations can reduce repetitive tasks and increase efficiency in server management.

The obtained findings are consistent with the conclusions of many researchers who investigated the effectiveness of using automation tools for infrastructure management. S.H.V. Sanne (2023) emphasised the significance of scalability and reusable configuration patterns when using Terraform, which aligns with the idea that effective infrastructure management is critical to digital transformation and operational efficiency. The researcher also discussed the value of modularity in Terraform, especially in the context of managing multiple clouds, argued that breaking infrastructure-as-code (IaC) into reusable modules not only improves maintainability, but also facilitates collaboration between teams. Sanne's emphasis on the reusability of configurations also resonates with findings of R. Modi (2021). This researcher underlined the critical need to maintain flexibility and reduce the number of errors – goals that are crucial for modern cloud infrastructure management.

Z. Yap (2024) noted that Ansible also provides a prominent level of automation in configuration management, although the E_{IaC} score of 28.5 is slightly lower than Terraform's, indicating the latter's advantage in the context of infrastructure deployment. The findings presented by S. Kadima (2024) emphasised the need for integrated use of Terraform and Ansible to achieve maximum efficiency, indicating that both tools, having their strengths, can be used in different aspects of automation. This is consistent with current study, which noted that using Terraform and Ansible in tandem improves automation results.

Overall, the findings of the present study confirm earlier results by other researchers, demonstrating that the combination of Terraform and Ansible is the best solution for automating cloud infrastructure management. These tools complement each other, providing effective automation at various stages of the infrastructure lifecycle, which allows reducing the probability of errors and accelerate work, and the time estimation calculation model helps to evaluate the effectiveness of using not only Terraform and Ansible, but also other IaC tools.

Conclusions

The conducted study confirmed the high efficiency of using Terraform and Ansible tools for managing infrastructure and configurations within the Infrastructure as Code (IaC) approach. The principal advantage is that Terraform offers powerful capabilities for automated creation and manage-

ment of infrastructure, including virtual machines, networks, and firewalls, while Ansible provides flexible and granular configuration of server software. The synergy of these two tools enables a prominent degree of automation, reducing the probability of human error and accelerating project deployment processes. The study showed that using Ansible enables swift and efficient systems setup and upgrades, while Terraform reduces the time required to deploy the underlying infrastructure by 50-70%. Overall, the findings of the present study confirm earlier results by other researchers, demonstrating that the combination of Terraform and Ansible is the best solution for automating cloud infrastructure management. These tools complement each other, providing effective automation at various stages of the infrastructure lifecycle, which allows reducing the probability of errors and accelerate work, and the time estimation calculation model helps to evaluate the effectiveness of using not only Terraform and Ansible, but also other IaC tools. Compared to conventional manual server setup methods. A mathematical model for calculating the deployment time showed that the total time for operations such as creating, modifying, and deleting

resources allows quantifying the performance of these tools in various scenarios.

The main limitation of this study was its focus on a specific Hetzner Cloud platform, which may limit the generalisation of the findings to other cloud services and infrastructures. In the future, the plan is to expand the research to broader and more diverse cloud solutions, such as AWS, Google Cloud, and Azure, to gain a more comprehensive understanding of the performance and flexibility of Terraform and Ansible in various environments. Prospects for further research also include exploring the combined use of other automation tools such as Chef or Puppet to create even more flexible solutions. Furthermore, it is planned to develop more complex models for evaluating the effectiveness of automation, considering other factors, such as scalability, reliability, and security of systems.

Acknowledgements

None.

Conflict of Interest

None.

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Terraform та Ansible: коли і як використовувати інструменти інфраструктури як код

Іван Бизов

Аспірант

Харківський національний університет імені В. Н. Каразіна

61022, майд. Свободи, 4, м. Харків, Україна

<https://orcid.org/0009-0004-2950-7814>

Анотація. У світі управління IT-інфраструктурою міцно зарекомендувала себе концепція інфраструктури як коду. Два популярні інструменти для реалізації цього підходу – Terraform та Ansible – широко використовуються фахівцями DevOps для автоматизації та управління хмарними та локальними ресурсами. Хоча обидва інструменти виконують аналогічні завдання, вони мають різні принципи роботи, архітектуру та сценарії застосування. Метою цього дослідження було надати ключові відмінності між Terraform та Ansible, їхні сильні та слабкі сторони, а також сценарії використання для кожного з цих інструментів. Були запропоновані рекомендації щодо вибору інструменту в залежності від конкретних завдань. Terraform, як інструмент декларативного стилю, дозволяє користувачам описати кінцевий стан інфраструктури, після чого він автоматично приводить її до цього стану. Ansible, з іншого боку, підтримує як декларативний, так і імперативний підходи, що робить його гнучким для управління конфігураціями серверів та виконання оркестрування. У дослідженні були представлені практичні приклади використання обох інструментів. Перший приклад продемонстрував, як Terraform можна використовувати для автоматичного розгортання хмарної інфраструктури в Hetzner Cloud. У цьому прикладі дії з хмарним сервісом відбувалися за допомогою декларативних конфігураційних файлів. Другий приклад описував, як можна використовувати Ansible для конфігурації серверів та автоматизації серверних завдань. Дослідження включало наукові аспекти, пов'язані з оцінкою ефективності IaC, а саме формули для розрахунку часу застосування змін в інфраструктурі. Використання формул допомогло кількісно оцінити час та загальну ефективність робіт в інфраструктурі для підвищення загальної прозорості та контролю над процесами управління. Таким чином, розуміння сценаріїв, в яких кожен інструмент є найбільш ефективним, допоможе інженерам правильно організувати процеси управління інфраструктурою.

Ключові слова: автоматизація інфраструктури; управління конфігурацією; інструменти DevOps; Infrastructure as Code; оптимізація; розгортання серверів



Coagulation and flocculation effects in the purification of tannery waste solutions

Anatoliy Danylkovych

Doctor of Technical Sciences, Professor
Kyiv National University of Technologies and Design
01011, 2 Mala Shyianovska Str., Kyiv, Ukraine
<https://orcid.org/0000-0002-5707-0419>

Olga Sanginova*

PhD in Technical Sciences, Associate Professor
National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"
01056, 37 Beresteiskyi Ave., Kyiv, Ukraine
<https://orcid.org/0000-0001-6378-7718>

Nataliia Tolstopalova

PhD in Technical Sciences, Associate Professor
National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"
01056, 37 Beresteiskyi Ave., Kyiv, Ukraine
<https://orcid.org/0000-0002-7240-5344>

Tetiana Obushenko

Senior Lecturer
National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"
01056, 37 Beresteiskyi Ave., Kyiv, Ukraine
<https://orcid.org/0000-0003-0731-0370>

Dmytro Yavorskiy

Postgraduate Student
National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"
01056, 37 Beresteiskyi Ave., Kyiv, Ukraine
<https://orcid.org/0009-0003-3216-9740>

Abstract. Available methods of wastewater treatment of tanneries require improvement to ensure the desired efficiency of purification and regeneration of valuable components contained in the waste process solutions. The purpose of this study was to provide a comprehensive coagulation-flocculation treatment of liquid waste from tanneries using mathematical modelling methods. The study conducted experimental investigation of the effectiveness of coagulants – aluminium sulphate and iron (III) chloride – and flocculants: polyhexamethylene guanidine hydroxychloride and its acetate, as well as reagent P228. The effect of pH on the coagulation process was examined. The efficiency of the coagulation process was evaluated by an integral indicator - the degree of purification, which was determined considering the turbidity and optical density of the purified water samples. The study presented the findings on coagulation and flocculation effects that occur during the purification of samples of tannery waste process solutions after the filling-fattening and dyeing processes. The studied samples are characterised by high concentrations of sulphates (over 9,000 mg/dm³) and chlorides (over 1,500 mg/dm³), an increased content of suspended solids (over 845 mg/dm³) and metal ions: chromium (III), iron, and aluminium. According to the findings of the study, the aluminium-based coagulant is more efficient than the iron-based coagulant. Among the flocculants,

Suggested Citation:

Danylkovych, A., Sanginova, O., Tolstopalova, N., Obushenko, T., & Yavorskiy, D. (2024). Coagulation and flocculation effects in the purification of tannery waste solutions. *Technologies and Engineering*, 25(6), 18-28. doi: 10.30857/2786-5371.2024.6.2.

*Corresponding author



polyhexamethylene guanidine hydroxychloride is the most effective, while the pH value should be 10. The results of experimental studies were used to obtain a mathematical model that described the coagulation process with a sufficient degree of accuracy. The results of mathematical modelling can be used to calculate the optimum parameters of the coagulation process

Keywords: tannery wastewater; chemical precipitation; degree of purification; optimisation of the coagulation process

Introduction

Leather production is characterised by multiple stages, using a considerable number of chemical reagents of various compositions, their high concentration in spent solutions, and a high degree of echogenicity. Notably, the content of pollutants in wastewater significantly depends on the specific features of technological processes at each stage of leather production. If, at the stage of preparatory processes, the spent solutions have a high content of insoluble organic and mineral substances, water-soluble proteins, and degraded keratin residues, then the following stages are characterised by a significant content of unreacted organic and mineral reagents. In this regard, the primary task of modern innovative production lies in minimising the environmental hazards of spent technological solutions, which is achieved by using a complex of mechanical, physicochemical, biological, and other treatment methods. For this, a wide range of chemical reagents is used – coagulants, flocculants, and other reagents of various chemical compositions. At the same time, developing effective methods of complex cleaning of spent solutions involves the study of the mechanism of their action, considering the features of the specific production technology.

According to F. Chiampo *et al.* (2023), tannery wastewater may contain pathogenic microorganisms and toxic substances that cause disease and pose a health hazard to humans when ingested. B. Jiang *et al.* (2020) noted that liquid and solid wastes from the leather industry and tanneries, if not treated before being released into water bodies, create an increasing burden on the environment. According to N.M. Sivaram & D. Barik (2019), raw tannery wastewater can contain high levels of numerous pollutants, namely up to (mg/dm³): suspended substances – 10,000, sulphides – 300, surfactants – 250, chromium (III) ions – 150, wool – 50, fats – 600, chemical oxygen demand (COD) – up to 6000, biological oxygen demand-5 (BOD₅) – 1500, the pH of the total effluent reaches 11.5.

A. Bhardwaj *et al.* (2023) studied various treatment methods such as membrane separation processes, advanced oxidation process (AOP), adsorption, biological treatment, and hybrid treatment technologies, which were found to be effective for treating tannery wastewater. It was noted that although these cleaning methods proved to be effective, they require further development and improvement to meet stricter regulatory standards. L. Sabliy *et al.* (2019) developed a technology for complex wastewater treatment from leather production, which involves biochemical treatment after mechanical cleaning and flotation in an anaerobic environment and a membrane

bioreactor. At the same time, wastewater enters the membrane bioreactor with reduced indicators of chemical and biological oxygen consumption by 8.8 and 17.0 times as a result of biological treatment.

M. Nigam *et al.* (2023) highlighted several conventional physicochemical (equalisation, coagulation, and adsorption) technologies, advanced approaches (Fenton oxidation, ozonation, cavitation), thermocatalytic, and biological wastewater treatment methods, and their integrative approaches. The researchers considered the conventional and oxidation methods suitable for pollutant degradation (70-99%). Due to membrane cost and contamination, membrane filtration processes are adequate but not used on an industrial scale.

S. Mim *et al.* (2023) proposed a coagulation-adsorption method for the pre-treatment of tannery effluents with a high content of sulphides, which provides 90-98% removal of suspended solids. The researchers provided a technological scheme of wastewater treatment of a tannery, which includes non-pressure filtration units, electrocoagulation-flotation devices, and dehydration of flotation sludge. S. Mim *et al.* (2024) offered the sorption method of cleaning spent solutions of leather and fur production. For this, natural aluminosilicate glauconite was used, containing (%): 44-56 SiO₂, 3-22 Al₂O₃, 0-27 Fe₂O₃, 0-8 FeO, 0-10 MgO, up to 10 K₂O, 4-10 H₂O. The efficiency of treatment of spent solutions from chromium (III) compounds reached 80-95%, depending on the chemical composition of glauconite.

M.A. Aboulhassan *et al.* (2021) conducted Jar-Test experiments to evaluate the effectiveness of tannin-based polymer (TBP) in treating these tannery wastewaters. The findings showed that TBP is more effective than the classical ferric chloride coagulant, enabling it to remove over 60% and 96% of COD and colour from industrial wastewater, respectively. Compared to ferric chloride, TBP produces less sludge, has the highest dewatering efficiency, generates well-settable sludge, and allows for higher water recovery rates than FeCl₃. Coagulation flocculation proved to be an effective method, while TBP can be used as a replacement for conventional coagulants in treating industrial wastewater.

B. Othmani *et al.* (2020) extensively investigated plant-based coagulants/flocculants for their effectiveness in removing various pollutants from water. Apart from safety and efficacy, the biodegradability of the substances under study is one of the exciting features that can promote the application of green products for water treatment as an alternative to persistent chemicals. To increase the

widespread use of the biocoagulant, the researchers recommended scaling up the laboratory research on pilot plants. According to A. Nath *et al.* (2021), the disadvantage of natural plant-based coagulants is the price, and therefore their use on an industrial scale is still ineffective compared to synthetic coagulants.

Therefore, the industrial effluents of leather production contain a wide range of pollutants of different chemical compositions, which depends on the specific features of the manufacturing technology of a particular type of leather material and the chemical reagents used at various stages. This necessitates the development of complex technologies for cleaning wastewater from leather production, which includes mechanical, physicochemical, and biological methods. The purpose of this study was to perform complex coagulation-flocculation cleaning of spent technological solutions after the filling, greasing, and dyeing processes of semi-finished chrome tanning for shoe uppers.

To fulfil the purpose, the following tasks were set:

- ◆ to identify the factors affecting the process of coagulation cleaning of spent solutions of leather production after the stages of filling, greasing, and dyeing;
- ◆ to conduct experimental studies to determine the most effective coagulants and flocculants;
- ◆ to obtain an adequate mathematical model that describes the coagulation process and to investigate the coagulation-flocculation effects of the cleaning process of spent leather production solutions.

Materials and Methods

For the study, a leather production solution was used after the filling-greasing and dyeing of semi-finished chrome tanning for shoe uppers. The characteristics of the solution under study are presented in Table 1. Wastewater samples were investigated in the Central Biochemical Laboratory “CBL” (n.d.), Kyiv.

Table 1. The Contribution of agroforestry practice to pesanggem household income

Water Quality Index	Value	Norm*	Regulatory document
pH	3.79	6.5-9.0	DSTU No. 4077-2001 (2003)
Suspended solids, mg/l	843	300	KND No. 211.1.4.039-95 (1995)
TS, mg/l	16,130	1,000	MVV No. 081/12-0109-03 (2004)
Sulphates, mg/l	9,513	380	MVV No. 081/12-0007-01 (2002)
Chlorides, mg/l	1,587	240	MVV No. 081/12-0004-01 (2002)
Ammonium, mg/l	39	20	DSTU ISO No. 7150-1:2003 (2004)
Fe total, mg/l	10	0.5	DSTU EN ISO No. 11885:2019 (2020)
Mn, mg/l	2.28	0.68	DSTU EN ISO No. 11885:2019 (2020)
Cu, mg/l	0.52	0.3	DSTU EN ISO No. 11885:2019 (2020)
Al, mg/l	10.79	2.72	DSTU EN ISO No. 11885:2019 (2020)
Cr total, mg/l	36.88	2.3	DSTU EN ISO No. 11885:2019 (2020)
COD, mgO/l	12,000	500	DSTU ISO No. 6060:2003 (2004)

Note: *based on the Order of the Executive Body of the Kyiv City Council... (2011)

Source: developed by the authors of this study

As Table 1 shows, all the indicators of the sample of the used technological solution significantly exceed the normative values, especially for sulphates and COD, which are 25.0 and 24.0 times higher, respectively.

The research used:

- ◆ coagulants – 25% solutions of $\text{Al}_2(\text{SO}_4)_3$ concentration and FeCl_3 ;
- ◆ flocculants – 5% solutions of crystalline poly hexamethylene guanidine hydrochloride (PGMG-HC), its acetate (PGMG-A) and reagent F-PET, obtained in the laboratory of the Department of Organic Chemistry and Technology of Organic Production, National Technical University of

Ukraine “Igor Sikorsky Kyiv Polytechnic Institute” through sequential waste destruction polyethylene terephthalate under the action of monoethanolamine and glycerine at 180-200°C as a mixture of terephthalic acid oligomers and polyols with terminal ammonium groups;

- ◆ pH regulator – 60% solution of crystalline KOH.

Figure 1 schematically represents the experiment procedure. To determine the optimum consumption of coagulant and flocculant, the test coagulation method was used using a modified laboratory setup with 6 beakers, each containing 1,000 ml. Figure 2 schematically represents the setup.

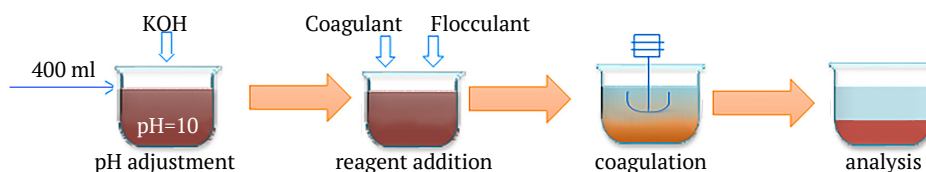


Figure 1. Scheme of experimental research

Source: developed by the authors of this study

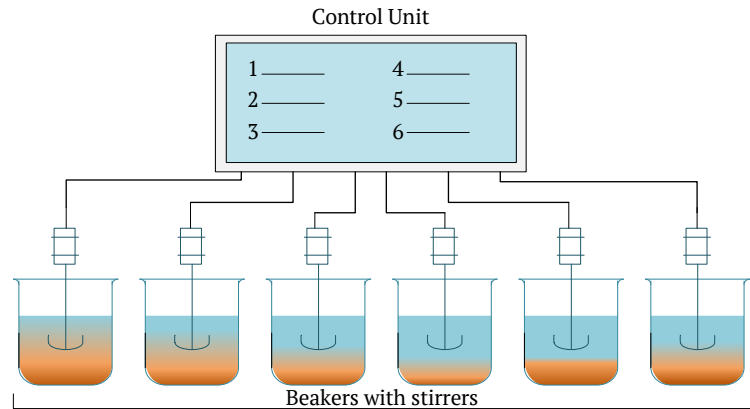


Figure 2. Laboratory setup

Source: developed by the authors of this study

To prepare the studied samples, 400 ml of each spent technological solution was diluted in a ratio of 1:10, the pH was adjusted within 9-10, while coagulants and flocculants were combined with the selected sample. Subsequently, the resulting solution was stirred for one minute, stirred slowly for 20 minutes, and settled for 10 minutes. A stationary CyberScan WL Turbidimeter TB1000 (USA) turbidimeter was

used to investigate the turbidity of solutions. The optical density of the samples of the treated solution was analysed on a spectrophotometer ULAB 101 (China). The treatment index was the selected indicator of the quality of the coagulation process. It was calculated based on the optical density measured by a spectrophotometer and is determined by the graph presented in Figure 3.

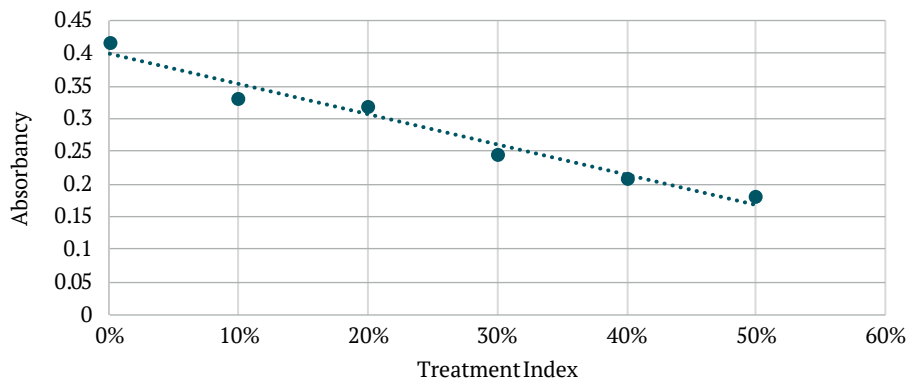


Figure 3. Graph of dependence of the optical density of water samples on the treatment index

Source: developed by the authors of this study based on the findings of experimental research

Experimental studies were performed according to the plan of a full factorial experiment (Volokyta & Selivanov, 2022). Statistical processing of the obtained findings was performed as follows:

- ◆ the effectiveness of coagulants and flocculants was assessed by the closeness of the correlation between the dose of flocculant/coagulant and the treatment index; the value of the correlation coefficient was calculated according to known formulas (Bondarenko et al., 2024);

- ◆ the adequacy of the mathematical model was evaluated using the built-in tools of the STAR system (Mathematical and computer..., n.d.) by the following indicators: standard deviation, correlation ratio, F-ratio.

The STAR system was used to model the coagulation process and assess the adequacy of the obtained models.

Results and Discussion

The study of the effect of coagulants and flocculants was divided into 4 stages. At each of the stages, the influence of individual parameters on the treatment index was investigated.

Stage 1: Study of the effect of coagulant $Al_2(SO_4)_3$ and flocculant PGMG-HC.

Stage 2: Study of the effect of coagulant $Al_2(SO_4)_3$ and PGMG-HC flocculant.

Stage 3: Study of the effect of coagulant $Al_2(SO_4)_3$ and flocculant PGMG-A.

Stage 4: Study of the effect of coagulant $Al_2(SO_4)_3$ and flocculant F-PET.

For each stage, a separate plan of a full factorial experiment was drafted, considering the ranges of variations presented in Table 2.

Table 2. Variation ranges of the studied parameters by stages

Stage 1		
Range of variation	Parameter, units and notation	
	Coagulant $Al_2(SO_4)_3$	Flocculant PGMG-HC
	ml	ml
	x_1	x_2
x_{min}	0	4
x_{max}	10	10
Stage 2		
	Coagulant $FeCl_3$	Flocculant PGMG-HC
	ml	ml
	x_5	x_2
x_{min}	0	4
x_{max}	10	10
Stage 3		
	Coagulant $Al_2(SO_4)_3$	Flocculant PGMG-A
	ml	ml
	x_1	x_3
x_{min}	0	2
x_{max}	10	6
	Coagulant $Al_2(SO_4)_3$	Flocculant F-PET
	x_1	x_4
	ml	ml
x_{min}	0	2
x_{max}	10	6
x_{min}		
x_{max}		

Note: the pH value (x_6) varied within 9-10

Source: developed by the authors of this study

Figure 4 presents a comparative analysis of two coagulants: aluminium sulphate and ferric chloride, in the presence of the same dose (500 mg/dm³) of the PGMG-HC flocculant. The maximum dose of the coagulant corresponds

to 1000 mg/dm³, and the minimum dose corresponds to the process without adding the coagulant. The results show that aluminium sulphate is more effective (85%) for the maximum dose than ferric chloride (55%).

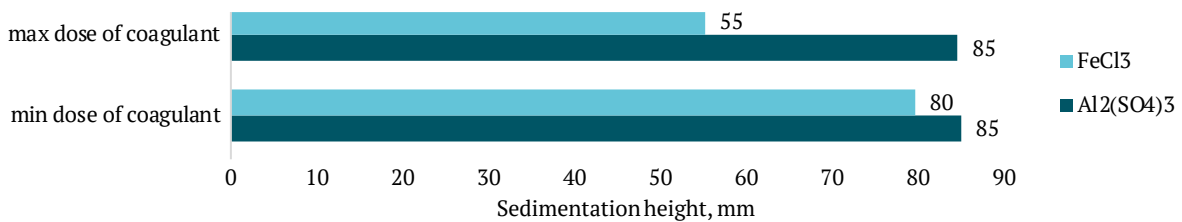


Figure 4. Degree of wastewater treatment depending on the type of coagulant

Source: developed by the authors of this study based on the findings of experimental research

Figure 5 shows the effect of the coagulant dose on the degree of treatment at a constant dose of flocculants (500 mg/dm³). In the absence of the coagulant, high purification degrees were observed: 89% for PGMG-A, 85% for F-PET, and 80% for PGMG-HC. The following purification degrees were obtained for an aluminium sulphate dose of 500 mg/dm³: 54% for PGMG-A, 42% for F-PET, and 24% for PGMG-HC. The following treatment degrees were obtained for an aluminium dose of 1,000 mg/dm³: 84% for

PGMG-A, 84% for F-PET, and 66% for PGMG-HC. It was found that the highest treatment index is achieved using PGMG-A flocculant, and a high degree of treatment can be achieved without adding coagulants. Figure 6 shows the effect of the flocculant dose on the purification degree at a constant coagulant dose (1,000 mg/dm³). For a flocculant dose of 250 mg/dm³, the following treatment degrees were obtained: for PGMG-A 85%, for F-PET 83%, for PGMG-HC 40%. For a flocculant dose of 500 mg/dm³, the following

treatment degrees were obtained: for PGMG-A 42%, for F-PET 58%, for PGMG-NS 29%. The following treatment

degrees were obtained for a dose of 750 mg/dm³: for PGMG-A 84%, for F-PET 79%, for PGMG-NS 68%.

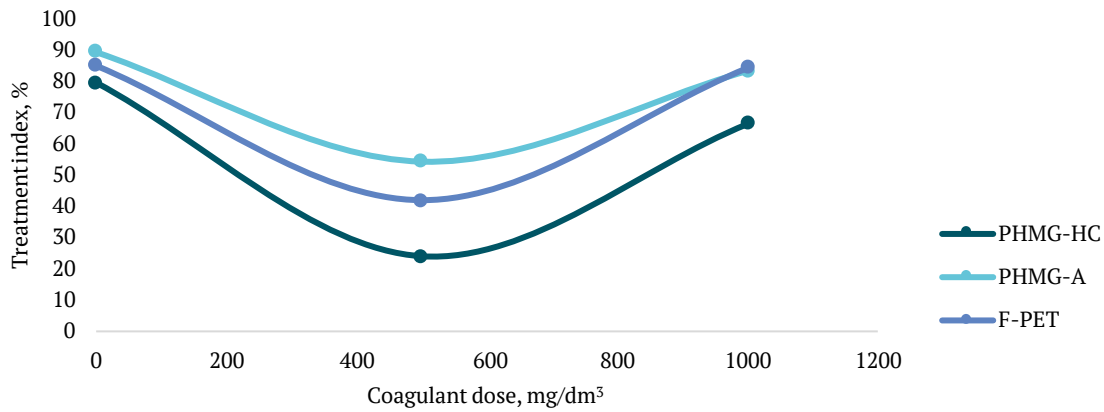


Figure 5. Degree of wastewater treatment depending on the dose of coagulant and type of flocculant

Source: developed by the authors of this study based on the findings of experimental research

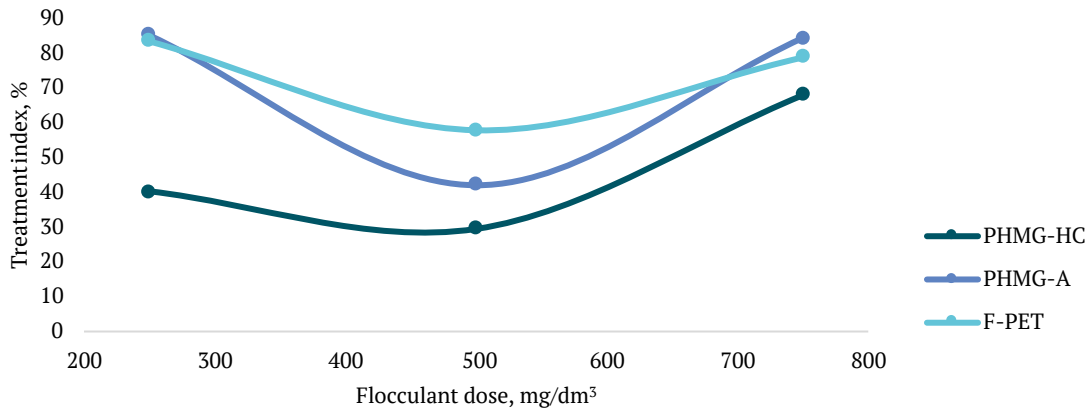


Figure 6. Degree of wastewater treatment depending on the flocculant dose

Source: developed by the authors of this study based on the findings of experimental research

As Figure 6 shows, the flocculant dose variation affects the treatment index of the samples under study. The mathematical model that best describes the coagulation process is as follows:

$$\begin{cases} y_1 = 91.48 - 2.06x_1 - 88.06x_2 - 1.58x_6 \\ y_2 = 1.95 - 0.16x_1 - 0.76x_2 - 5.6 \cdot 10^{-2}x_6, \end{cases} \quad (1)$$

where y_1 is the turbidity of the spent solution sample after coagulation (NOK), y_2 is the absorbency of the sample under study (at $\lambda = 400$ nm).

Characteristics of the received model:

- ◆ standard deviation for each equation, respectively:

$$\sigma_1 = \pm 1.7 \text{ NOK}, \sigma_2 = \pm 0.22\%;$$

- ◆ correlation ratio for each equation, respectively:

$$r_1 = 0.91; r_2 = 0.89;$$

- ◆ F-ratio for each equation, respectively: $F_1 = 10.4;$

$$F_2 = 9.7.$$

Based on the obtained characteristics, the obtained mathematical model accurately describes the experimental data. The most effective are the coagulant $Al_2(SO_4)_3$ and the flocculant PGMG-A. Table 3 presents a comparative analysis of a sample of the spent solution before and after treatment. The coagulation-flocculation method provides deep treatment from all pollutants.

Table 3. Comparative analysis of the spent solution sample before and after treatment

Water Quality Index	Before Treatment	After Treatment	Degree of Contaminant Removal, %
pH	3.79	9.14	--
Suspended solids, mg/l	843	< 5	99
TS, mg/l	16,130	970	94

Table 3. Continued

Water Quality Index	Before Treatment	After Treatment	Degree of Contaminant Removal, %
Sulphates, mg/l	9,513	438	95
Chlorides, mg/l	1,587	110	93
Ammonium, mg/l	39	21.7	44
Fe total, mg/l	10	0.02	100
Mn, mg/l	2.28	< 0.01	100
Cu, mg/l	0.52	< 0.01	98
Al, mg/l	10.79	0.11	99
Cr total, mg/l	36.88	< 0.01	100
COD, mgO/l	12,000	466	96

Source: developed by the authors of this study based on the findings of experimental research

The study proved that coagulation is the most widely used physical and chemical purification method to reduce turbidity and suspended substances. Disadvantages of chemical coagulants include the formation of difficult-to-decompose sediments, prohibitive cost, and, most importantly, aluminium residues in treated water. W.L. Ang & A.W. Mohammad (2020) reviewed studies to assess the potential of using natural coagulants as alternatives to synthetic chemicals. However, S. Gautam & G. Saini (2020) noted that despite being an economical and environmentally friendly alternative, natural coagulants are inferior to chemical coagulants in wastewater treatment, especially on a large scale. Lack of sources for mass availability, the low shelf life of such coagulants, and high operating costs are some of the obstacles to their large-scale application.

The study findings of the quality indicators of the spent solution sample showed a significant improvement in the treated water quality in all indicators, except for the content of aluminium and sulphates. Aluminium sulphate may provide better results, as Figure 4 shows, since its coagulant properties contribute to denser sedimentation of organic compounds and suspended particles. This is particularly important for tanneries, where wastewater contains a large amount of organic matter. Despite its more comprehensive pH range, ferric chloride may be less effective in treating specific organic contaminants and may form smaller flocs, reducing its performance. Furthermore, tannery wastewater may contain large amounts of dissolved salts and metals. Iron ions (Fe^{3+}) from ferric chloride may compete with other metals for precipitation, reducing coagulation efficiency.

When using aluminium sulphate, flocs are formed more slowly but are usually more stable and larger. This facilitates their subsequent removal from water (e.g., by settling or filtration). Ferric chloride forms flocs faster but can be smaller and less stable, which may complicate their separation from water. W.L. Ang & A.W. Mohammad (2020) showed that aluminium sulphate works better in a narrower pH range (usually 5-7), often found in wastewater. At the same time, N. Nomanifar *et al.* (2024) pointed out that ferric chloride can work on a broader pH range, including more acidic environments (pH 4-6). However, its effectiveness may decrease in slightly acidic and neutral waters. Thus,

aluminium sulphate may be more effective in wastewater with a pH close to neutral. These findings are consistent with the results obtained by Z. Bingül *et al.* (2021), who investigated the pH effect of tannery wastewater obtained from a local tannery on XPC removal and turbidity.

The study of the effect of the coagulant dose on the degree of purification at a constant dose of flocculants (Fig. 5) showed that PGMG-A coagulant provides a higher degree of treatment. The large amount of suspended substances in the examined samples of the spent solution can explain the obtained findings. The nature of the change in the degree of treatment is comparable for all the flocculants studied. The value is lower for a lower coagulant dose than a higher dose. When an excess amount of coagulant is added, the particles can begin to recharge. Instead of neutralising the negative charges of the colloids, excess aluminium ions can give the particles a positive charge, which again causes them to repel each other. This leads to destabilisation of the flocs and deterioration of their adhesion, which reduces the purification efficiency. An excessive amount of small flocs can also be formed, which are more difficult to remove from the water than large ones. With a further increase in the coagulant dose, a transformation of stable flocs can occur, because the excess coagulant again begins to bind with the remaining charged particles or small flocs. The flocculant helps in the aggregation and formation of large and heavy flocs, increasing the purification degree. This effect may be due to the coagulant beginning to precipitate smaller and remaining contaminants, and the flocculant stabilizes new flocs, improving the final filtration. The findings of A.K. Tolkou & A.I. Zouboulis (2020) are consistent with this conclusion: it was found that the coagulant, both with and without the addition of flocculant, can provide better performance for the coagulation/flocculation process than conventional coagulants.

The nonlinear dependence of the purification degree with a change in the flocculant dose and a constant dose of aluminium sulphate, presented in Figure 6, is associated with the features of the interaction between the flocculant, coagulant, and colloidal particles in wastewater. The efficiency of the flocculant depends on its concentration, the chemical properties of the water, the coagulant dose, and the structure of the formed flocs. At low flocculant doses,

the flocs formed by the coagulant are still too small and unstable to settle effectively. As the flocculant dose increases, its polymer chains bind small flocs, forming larger aggregates that are easier to settle and remove. This leads to an improvement in the purification degree since the flocculant helps stabilise the particle aggregation process. If the flocculant dose is too high, the system may become oversaturated with polymer chains. Instead of binding the particles, the flocculant starts to act oppositely – it coats the floc surfaces and makes them too “slippery” for further aggregation. This may cause ruptures of existing flocs or prevent the formation of large stable aggregates. As a result, the particles become smaller again and are more difficult to settle, reducing the cleaning efficiency. With a further increase in the flocculant dose, the particles become coarser again, because the polymer chains of the flocculant can start to connect the remains of small particles and form larger and more stable aggregates. In this phase, the flocculant starts to bind the remaining small flocs, creating larger flocules, improving the cleaning efficiency. This effect may depend on the type of flocculant and its molecular structure (e.g., linear or branched chains). A constant dose of aluminium sulphate creates coagulation flocs, but their size and stability depend on the flocculant. Without the optimum amount of flocculant, the flocs may still be too small or unstable for effective treatment. In the first phase, the flocculant binds small flocs, improving their sedimentation. However, if there is too much flocculant, the excess chains can “shield” the particles, preventing further aggregation.

Thus, the correct dosage of coagulant and flocculant is a key factor in effective wastewater treatment. The correct coagulant dosage ensures neutralisation of colloid charges and the formation of primary flocs. The obtained findings correlate with those of Junaidi *et al.* (2023). In the cited study, a wastewater sample was tested by jar test with the addition of polyaluminium chloride (PAC) coagulant. The test results gave the optimum coagulant dose of 3,000 mg/l; it can remove 77% of COD, 33% of BOD, 92.68% of TSS, 33% of total chromium, and 98% of colour. PAC forms flocs faster than conventional coagulants, such as $Al_2(SO_4)_3$. PAC coagulant is one of the most effective since it leads to rapid water coagulation with different turbidities, forms less sludge, and leaves less aluminum residue in purified water. The dose of the proposed coagulant is higher than in the present study, while the degree of purification is lower. S. Haydar & J.A. Aziz (2009) investigated the purification of tannery wastewater using the coagulation-flocculation-sedimentation method. Alum with cationic and anionic polymers was used as a coagulant. The findings were compared to a study where only alum was used for treatment. The study results showed that the combination of alum with the cationic polymer C-492 resulted in 97% removal of wastewater turbidity, 93.5% removal of total suspended solids (TSS), 36.2% removal of COD, and 98.4% removal of chromium. The removal rate achieved after treatment of tannery wastewater using the PA-HE coagulant-flocculant combination demonstrated high

efficiency, with values reaching approximately 100% for TSS, 98.71% for BOD₅, 99.93% for COD, 98.88% for NH_4^+ , 98.21% for NO_3^- , 90.32% for NO_2^- , 93.13% for SO_4^{2-} , 95.44% for PO_4^{3-} , and 60% for total chromium as shown in the study by G.E. Mouhri *et al.* (2024).

Thus, the correct dosage of flocculant promotes the aggregation of these flocs into larger aggregates that are easily sedimented and removed. All this requires careful optimisation of the coagulant and flocculant dosages depending on the system conditions.

Conclusions

The study investigated the composition of spent technological solutions after filling-greasing and dyeing processes at leather production enterprises. It was found that wastewater after the specified processes has high concentrations of pollutants and increased suspended solids content. The choice of reagents for the coagulation process was justified, and the process was modelled. According to the findings of experimental studies, aluminium-based coagulants and PGMG-HC flocculants have higher efficiency than other reagents studied (iron-based coagulants, PGMG-A, and F-PET flocculants). The findings showed a considerable improvement in treated water quality, according to the key indicators.

The principal reasons why aluminium sulphate showed better results included its ability to work effectively in neutral or slightly acidic conditions, to form more stable and larger flocs, and to provide better removal of organic pollutants. Due to lower sediment stability, ferric chloride may be less effective in such conditions. The efficiency of coagulation and flocculation with the addition of different doses of aluminium sulphate is non-linear because the coagulation process involves complex physicochemical interactions between the coagulant, pollutants, and colloidal particles. At the initial stage, the cleaning efficiency increases due to charge neutralisation, then it can decrease due to particle recharging, and, finally, it can improve due to floc stabilisation with a further increase in coagulant and interaction with the flocculant. The non-linear dependence of the degree of cleaning with the addition of a flocculant occurs due to complex interactions between pollutant particles, coagulant flocs, and the flocculant’s polymer chains. At the first stage, the flocculant increases the efficiency of coagulation, but at an excessive dose, it can prevent the formation of large flocs, which reduces the degree of purification. With a further increase in the flocculant dose, the process stabilises again, and large aggregates are formed, which leads to improved purification.

The balance between the doses of coagulant and flocculant is a delicate process that directly affects the efficiency of water purification. Incorrect dosages can insufficiently purify water and complicate the further processing or removal of sediments. Modelling and calculating the doses of coagulants and flocculants using mathematical models and algorithms enables effective control of the wastewater treatment process. This approach improves the quality of purification, reduces the consumption of

chemical reagents, and makes the system more stable and flexible. Using aluminium sulphate and flocculant PG-MG-A to purify a sample of real wastewater showed high efficiency and can be recommended for use. Further development of this study involves expanding the list of coagulants and flocculants.

Acknowledgements

The research was conducted on initiative topics with State registration numbers: 0124U001966, 0124U002058.

Conflict of Interest

None.

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Коагуляційно-флокуляційні ефекти при очищенні відпрацьованих розчинів шкіряного виробництва

Анатолій Данилкович

Доктор технічних наук, професор
Київський національний університет технологій та дизайну
01011, вул. Мала Шияновська, 2, м. Київ, Україна
<https://orcid.org/0000-0002-5707-0419>

Ольга Сангінова

Кандидат технічних наук, доцент
Національний технічний університет України
«Київський політехнічний інститут імені Ігоря Сікорського»
03056, просп. Берестейський, 37, м. Київ, Україна
<https://orcid.org/0000-0001-6378-7718>

Наталія Толстопалова

Кандидат технічних наук, доцент
Національний технічний університет України
«Київський політехнічний інститут імені Ігоря Сікорського»
03056, просп. Берестейський, 37, м. Київ, Україна
<https://orcid.org/0000-0002-7240-5344>

Тетяна Обушенко

Старший викладач
Національний технічний університет України
«Київський політехнічний інститут імені Ігоря Сікорського»
03056, просп. Берестейський, 37, м. Київ, Україна
<https://orcid.org/0000-0003-0731-0370>

Дмитро Яворський

Аспірант
Національний технічний університет України
«Київський політехнічний інститут імені Ігоря Сікорського»
03056, просп. Берестейський, 37, м. Київ, Україна
<https://orcid.org/0009-0003-3216-9740>

Анотація. Існуючі методи очищення стічних вод підприємств шкіряної промисловості потребують удосконалення для забезпечення необхідної ефективності очищення та регенерації цінних компонентів, які містяться у відпрацьованих технологічних розчинах. Дане дослідження направлено на комплексне коагуляційно-флокуляційне очищення рідких відходів шкіряних заводів із застосуванням методів математичного моделювання. Проведені експериментальні дослідження ефективності коагулянтів – сульфату алюмінію та хлориду заліза (III) – та флокулянтів: полігексаметиленгуанідину гідроксихлориду та його ацетату, а також реагенту П228. Досліджено вплив рН на процес коагуляції. Ефективність процесу коагуляції оцінювалась за інтегральним показником – ступенем очищення, який визначався з урахуванням каламутності та оптичної густини очищених зразків води. У роботі наводились результати дослідження коагуляційно-флокуляційних ефектів, які виникають у процесі очищення зразків відпрацьованих технологічних розчинів шкіряного заводу після процесів наповнювання-жирування та фарбування. Досліджувані зразки характеризувались високими концентраціями сульфатів (більше 9000 мг/дм³) та хлоридів (більше 1500 мг/дм³), підвищеним вмістом завислих твердих речовин (більше 843 мг/дм³) та іонів металів: хрому (III), заліза та алюмінію. За результатами досліджень встановлено, що коагулянт на основі алюмінію мав вищу ефективність, ніж коагулянт на основі заліза. Серед флокулянтів найбільш ефективним був полігексаметиленгуанідину гідроксихлорид, а значення рН має дорівнювати 10. Результати експериментальних досліджень використані для отримання математичної моделі, яка описує процес коагуляції з достатнім ступенем точності. Результати математичного моделювання можуть бути використані для розрахунку оптимальних параметрів процесу коагуляції

Ключові слова: стічні води шкіряних заводів; хімічне осадження; ступінь очищення; оптимізація процесу коагуляції



Prospects for using combined heat and power plants and boiler houses to balance the integrated energy system of Ukraine

Vitalii Khodakivskiy*

Postgraduate Student, Technical Advisor
Institute of General Energy of the National Academy of Sciences of Ukraine
03150, 172 Antonovych Str., Kyiv, Ukraine
Saint Gobain Ukraine
03038, 2 Novovokzalna Str., Kyiv, Ukraine
<https://orcid.org/0009-0007-3237-3476>

Dmytro Karpenko

PhD in Technical Sciences, Researcher
Institute of General Energy of the National Academy of Sciences of Ukraine
03150, 172 Antonovych Str., Kyiv, Ukraine
<https://orcid.org/0000-0002-8022-9782>

Abstract. The study analysed the current state of Ukraine's energy system, focusing on the shortage of manoeuvring capacities, large emissions of harmful substances into the atmosphere, and low energy efficiency of the key technological processes of existing generation facilities. These shortcomings also apply to heat energy producers, namely combined heat and power stations and industrial and municipal boiler houses. The existing energy system of Ukraine includes both types of producers, with a predominant type of energy (electricity or heat). The purpose of this study was to assess the prospects for introducing modern technologies to ensure the sustainability of electricity and heat production systems. The analytical methods used were those suitable for comparing gas turbine and combined cycle plants, as well as electricity and heat storage systems. The study reviewed various technologies that increase the manoeuvrability of systems for the production of these types of energy and reduce the generation of harmful substances by avoiding endothermic reactions in the combustion of solid, liquid, and gaseous fuels. Changes in the ratio of capacities of the main generating facilities built in the 1960s, deterioration of technological equipment, which has exhausted its technological life by 80-90%, indicate a lack of manoeuvring capacities and its aggravation as a result of destruction and damage caused by military aggression. The need to modernise coal-fired thermal power plants using modern combustion technologies in an environment enriched with oxygen (up to 30-40%) of atmospheric air was also emphasised. To improve the manoeuvrability of coal-fired units, it is necessary to bring their capacity to the level of 800-1000 MW, and to significantly reduce emissions of harmful substances, it is necessary to combine steam, gas, and combined cycle generation. The study explored the prospects for the development of highly manoeuvrable capacities through the reconstruction of existing combined heat and power plants and the conversion of municipal and industrial boilers into mini-cogeneration plants for their integration into the European energy market. The results can form the basis for the development of a state energy policy that will help increase the resilience and efficiency of Ukraine's energy system, reduce its dependence on electricity imports, meet environmental standards at both the national and European levels, and guarantee the country's energy security

Keywords: power generation facilities; steam turbine and combined cycle unit; air oxygen enrichment; endothermic reactions; environmental and energy safety

Suggested Citation:

Khodakivskiy, V., & Karpenko, D. (2024). Prospects for using combined heat and power plants and boiler houses to balance the integrated energy system of Ukraine. *Technologies and Engineering*, 25(6), 29-40. doi: 10.30857/2786-5371.2024.6.3.

*Corresponding author



Introduction

The energy security of the state is determined by the stability and manoeuvrability of generation facilities capable of producing the required amount of electricity and heat, considering their negative property, namely their low capacity for storage and accumulation. The Integrated Power System (IPS) of Ukraine is based mainly on the following generation facilities: thermal power plants (TPPs) using coal-fired units, nuclear power plants (NPPs), hydroelectric power plants and pumped hydroelectric energy storage (HPPs and PHESS). Furthermore, a certain niche is occupied by various units that use renewable energy sources (RES – solar, wind, etc.). Additionally, electricity is generated at combined heat and power plants (CHP, mini-CHP, boiler houses), which also provide heat to industrial enterprises and the household sector.

The ratio of capacities of these facilities at different points in time has shown various trends. Overall, the IPS of Ukraine is characterised by a shortage of manoeuvring capacities. This deficit has been exacerbated not only by the excessive enthusiasm for clean (green) energy, but also by the wider introduction of green tariffs. The phenomenon known as the 'green-coal' tariff paradox has led to the use of outdated coal-fired units to cover peak loads. This operating strategy, which involves frequent start-ups and shut-downs of these worn-out coal units, has led to increased emissions and increased risks of accidents in the electricity grid. And with the outbreak of full-scale military operations on the territory of Ukraine, the destruction caused by these negative impacts has increased dramatically.

A. Polyvianchuk *et al.* (2023) emphasised the significance of a phased approach to the modernisation of district heating systems (DHS), especially for countries with limited financial resources. They proposed a gradual integration of renewable energy sources, heat pumps, and individual substations, which proves that it is possible to considerably reduce both energy consumption and investment costs. This methodology is in line with the broader context of district heating system improvements, particularly in the transition to the 4th and 5th generations of DHSs.

B. Basok *et al.* (2022) comprehensively discussed the current challenges facing the Ukrainian combined heat and power sector. These challenges relate primarily to the retention of qualified personnel and the maintenance of technological heat and power equipment under martial law. A prominent aspect is the optimisation of equipment operation modes to minimise fuel consumption for heat and electricity generation, which ensures maximum efficiency. M.R. Chowdhury *et al.* (2021) discussed such issues on the example of the United States.

The study by O. Kyrylenko *et al.* (2022) provided an in-depth analysis of the functioning of electricity and heat supply systems in the context of the military aggression of the Russian Federation. This military conflict caused substantial economic losses to Ukraine's economy due to the destruction of numerous electricity and heat supply facilities, which simultaneously produced a significant

share of electricity. Consequently, due to their economic, humanitarian, and geopolitical significance, energy infrastructure facilities have often been targeted by Russian aggression. These critical but vulnerable facilities need to be distributed across the country to ensure the reliable functioning of the economy and maintain a safe standard of living. Considering the state of heat and electricity generation during the first half of 2024, the findings of the study by M. Chernyavskyy *et al.* (2024) stressed the urgent need to transition to distributed generation systems. This recommendation can be further substantiated by the widespread use of protective separation methodologies in power grids, which are implemented as the principal approach to ensuring the safe and reliable operation of these engineering systems.

The energy sector of Ukraine includes a great number of facilities for generating electricity as the main end-use product (heated water and low-parameter water steam), as well as facilities for producing heat (CHP, mini-CHP, and boiler houses), for which the production of a certain amount of electricity is not the primary goal. These facilities must operate as a single organism, and therefore must be considered simultaneously, as they are intertwined in the generation of electricity (both centrally and in a distributed mode). For heat production, CHP, mini-CHP, and boiler houses should operate locally in their respective regions. This approach should improve the balancing potential to cover peak electricity loads while meeting the heating needs of all consumers.

Reducing CO₂ emissions is also among the urgent tasks for the energy sector. V. Deshko & D. Karpenko (2018) emphasised that innovative approaches can be cost-effective in the context of a carbon tax, even considering the costs of producing oxygen and compressing CO₂. V. Zdanovsky & M. Kulyk (2021) proposed to burn organic fuels (solid, liquid, gaseous) in an oxygen-enriched environment. Such an approach will not only increase the manoeuvrability of combined-cycle gas turbine plants, but also greatly reduce emissions of harmful substances such as nitrogen oxides, subject to the elimination of endothermic reactions during the combustion of organic fuels.

The purpose of this study was to assess the possibility of using heat and power plants and boiler houses to balance the integrated energy system, including the production of electricity and heat based on the introduction of existing modern advanced technologies.

Materials and Methods

Considering the complexity of the object of combined heat and power generation, to fulfil the purpose of this study, the method of analytical research of literature data, as well as the method of generalisation of available practical and calculated data of complex generation facilities were employed. Considering the fact that some energy facilities are subordinated to the Ministry of Fuel and Energy of Ukraine, while some heat and power generation facilities belong to

the municipal sector, some scientific tasks were solved by the method of system analysis, as well as by the method of comparative analysis to compare different types of generation technologies. Furthermore, modelling and forecasting methods were used to assess the prospects and efficiency of introducing modern technologies, which helped to predict the impact of different scenarios of power system development on its stability. Economic analysis was used to assess the economic evaluation of the proposed technologies, which helped to estimate the costs of implementation and their economic feasibility. Environmental analysis was also a crucial element of the study, as it helped to assess the impact of innovative technologies on the level of emissions of harmful substances.

In preparing this article, the following steps were taken: studying the global experience of electricity and heat generation by the Ukrainian power system facilities, as well as heat and electricity generation by municipal heat and power enterprises; researching the efficiency of thermal power plants using gas turbine, combined cycle and cogeneration technologies; assessment of the suitability of combined heat and power plants and industrial and municipal boiler houses to improve the stability and balance of the power system; examination of the impact of technological, economic, and environmental constraints on the efficiency of small-scale energy facilities.

Through the analysis of publications in the field of sustainability and balancing of the power system based on the combination of cogeneration technologies and the use of the latest approaches to the processes of combustion of organic fuels, the study proposed results that can confirm the best technical and environmental performance. Considering the obtained findings on the key technological, economic indicators, and environmental assessments, the study provided a possible optimum choice of strategies for balancing the Ukrainian energy system, considering price constraints. The key indicators for achieving energy efficiency and system stability were also identified.

Results and Discussion

The analysis of the state of the IPS of Ukraine for the period up to 2015, the characteristics of the country's fuel base, and the prospects for the development of its energy sector after this period were detailed in the study (Khalatov, 2016). The conclusions of this fundamental research suggest that in the short term, it is necessary to focus on the use of innovative energy technologies, which should include:

- ◆ conversion of coal-fired units to circulating fluidised bed boilers (there are more than 600 of them in the world; at the same time, in Ukraine, there are a hundred times fewer);
- ◆ use of cogeneration technologies at existing CHP plants and conversion of large boiler houses into cogeneration mini-CHP plants;
- ◆ widespread use of gas turbine and combined cycle technologies for all modes of coverage – base, half-peak, and peak loads on domestically produced natural gas.

Industrial enterprises and critical infrastructure facilities require a considerable amount of thermal energy besides electricity to operate normally and to ensure the efficient functioning of their personnel and the household sector. The technological process of providing these consumers with thermal energy in the form of water steam or hot water is called heat generation, when electricity is also produced – cogeneration, and when the third type of energy is obtained – trigeneration (Klimenko *et al.*, 2011). An adjusted scheme of a cogeneration plant is presented in Figure 1.

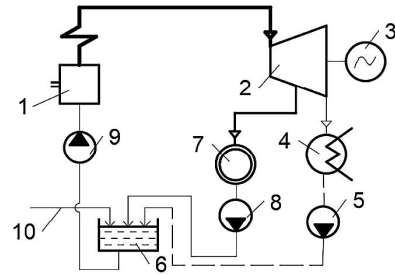


Figure 1. Simplified thermal scheme of a combined heat and power plant

Note: 1 – boiler; 2 – turbine; 3 – electric generator; 4 – condenser; 5 – condenser pump; 6 – feed tank; 7 – heat consumers; 8 – network pump; 9 – feed pump; 10 – chemically clean water pipeline

Source: developed by the authors of this study based on V. Klimenko *et al.* (2011)

The water steam produced in boiler 1 is fed into steam turbine 2 and, in the final version, electric generator 3 produces a certain amount of electric energy, which is used both for the own needs of the heating system and for other consumers without conversion. The exhaust steam in the condenser 4 gives off a certain amount of heat used by the consumer and is sent by the condensing pump 5 to the feed tank 6, from where it is fed to the boiler unit by the feed pump 9. The heat energy, as the primary product from the intermediate extraction of the steam turbine 2, is used by group consumers in the form of steam or hot water and is fed by the feed pump 8 into the feed tank 6, where water losses are replenished with chemically treated water via the pipeline 10 to avoid corrosion of the primary process equipment. From the feed tank 6, the heated water is returned to the boiler unit 1. Depending on the needs of production consumers and public utility needs, the ratio of heat flows can vary within the relevant range.

Modern cogeneration units, for which heat production is predominant and electricity production is less significant, can be as follows: steam turbine units with a backpressure turbine and heat supply to consumers of all or part of the exhaust steam; steam turbine units with a condensing turbine with heat recovery; gas turbine units (GTUs) using the heat of combustion gases in a heat recovery boiler or directly in the technological process; diesel power units (DPUs) producing high-potential heat using flue gas heat and low-potential heat in the engine cooling

circuit; combined cycle gas turbine units (CCGTUs) using heat from the exhaust gases of a gas turbine to produce heat, which is fully or partially directed to one or more steam turbines of the respective type.

There is a wide range of thermal power plants in Ukraine, the total number of which is much greater than the data presented in Table 1. Notably, information on individual plants located in the temporarily occupied territories (2024) is both limited and ambiguous, due to the complex territorial and political context. Nevertheless, thermal

power plants across the country have historically provided heat to more than 25 cities in mainland Ukraine. However, even the largest and most modern of these facilities were designed and built between the 1960s and 1980s. During this period, there were substantial changes in both energy production technologies and demand for heat and electricity in the regions where these facilities are located. Table 1 presents the characteristics of the electric and thermal capacities of selected CHP plants in Ukraine for the period from 2014 to 2024.

Table 1. Characteristics of large CHP plants in Ukraine

CHP plant name	Installed capacity		Year of commissioning	Fuel type
	electric, MW	heat, Gcal/year		
Kyiv CHP-5	700.0	974.0	1971-1976	Natural gas
Kyiv CHP-6	750.0	660.0	1982-1984, 2004	Natural gas
Kramatorsk	150.0	458.0	1936-1977	Natural gas/coal
Kremenchuk	255.0	671.0	1965-1969	Natural gas/fuel oil
Lviv	31.1	155.0	1930-1954	Natural gas
Myroniv	260.0	210.0	1953-1956	Natural gas/fuel oil
Mykolaiv	40.0	110.0	1949-1958	Natural gas/fuel oil
Odesa	68.0	205.0	1954-1984	Natural gas/fuel oil
Sevastopol	54.5	141.2	1937-1957	Natural gas
Siverskodonetsk	270.0	906.0	1956-1977	Coal/fuel oil
Simferopol	278.0	164.2	1958-1961	Natural gas
Kharkiv	62.0	293.0	1944-1970	Natural gas/fuel oil
Kharkiv CHP-5	470.0	700.0	1979-1990	Natural gas/fuel oil
Kherson	80.0	350.0	1956-1967	Natural gas/fuel oil
Kherson CHP-2	74.0	160.0	1952-1957	Natural gas/fuel oil
Cherkasy	200.0	648.0	1961-1969	Natural gas/fuel oil/coal
Chernihiv	210.0	409.0	1961-1974	Coal/fuel oil

Source: I. Volchyn *et al.* (2013)

In Ukraine, the share of consumers served by district heating systems has increased substantially and stays quite high. This phenomenon is explained by the fact that, unlike in the European Union (EU), a considerable number of Ukrainian heat consumers are densely concentrated in multi-storey residential buildings. Furthermore, a large share of heat energy is consumed by industrial enterprises that do not have their respective boiler houses. In addition, long-distance heat transmission is generally less efficient. With this in mind, B. Basok *et al.* (2022) and O. Kyrylenko *et al.* (2022) concluded that attempts to restore the electricity and heat supply network to its pre-war state may not be feasible. They advocate instead for a comprehensive effort to integrate Ukraine's energy sector into the EU energy system (ENTSO-E), while respecting all relevant environmental standards.

In industrialised regions such as the United States, Japan, China, and the European Union, T. Papuha & O. Klymenchuk (2021) identified the growth in energy demand as a pivotal development trend. This trend requires procedural improvements, such as optimisation of energy management processes and development of innovative views on energy saving in production processes. European Union countries, together with other countries, have introduced

various financing mechanisms and taxation schemes to mitigate the financial burden of introducing these innovative technologies. Energy saving policies emphasise increasing the share of renewable energy sources as a way to achieve their goals. The Energy Strategy until 2035 (Order of the Cabinet of Ministers..., 2023) should allow Ukraine to reach parity with developed countries.

Improving energy efficiency at Ukrainian enterprises is unattainable without a reliable energy management system and highly qualified specialists in the relevant fields. Combined heat and power plants, which are used for cogeneration of heat and electricity, play a major role in saving fuel in the energy system, which positively affects the efficiency of industrial production. The efficiency of fuel use at TPPs is assessed by the specific values of fuel consumption for the separate production of heat and electricity. These indicators are necessary for setting reasonable tariffs by specific heat and power producers, reflecting not only the efficiency of technological equipment, but also the broader economic activity of the energy company (Chepurnyi *et al.*, 2011). A notable achievement in this area is the comparative analysis of combined heat and power systems of a steam turbine unit (STU-CHP) and a gas turbine unit (GTU-CHP), especially in scenarios involving equivalent electrical and thermal output.

The T-25-90 steam heat and power turbine serves as the basis for the STU-CHP system, demonstrating a total steam consumption of 130 t/h and a heating steam consumption of 90 t/h. In contrast, two configurations were investigated for the GTU-CHP system: one using a GTD-2500 gas turbine, which corresponds to the electrical capacity of an STU, and the other using two gas turbine units with a total thermal capacity equivalent to an STU. Experimental data from the study by M. Chepurnyi *et al.* (2011) substantiated the advantages of a combined heat and power scheme over separate heat and power generation. The use of STU-CHP systems can provide up to 40% savings in the use of conventional fuel, while the use of GTU-CHP systems considerably increases fuel economy. Still, when the electrical capacities of the STU-CHP and GTU-CHP are equivalent, the fuel savings show little change, with a slight decrease observed in the case of gas production.

L. Kesova & V. Khodakivskyi (2010) analysed Ukrainian CHP plants, covering about 250 units, most of which are small departmental industrial plants. The findings showed that most of these CHP plants are mainly fuelled by natural gas (76-80%), followed by fuel oil (15-18%), and hard coal (5-6%). However, the technical condition and extensive wear and tear of their process equipment is comparable to the problems faced in the heat and power sector. Therefore, to improve the economic and environmental performance of CHPs and large boiler houses operating in market conditions, it is essential to modernise and re-equip them with modern cost-effective technologies.

Considering the current stage of martial law (2024) and the subsequent post-conflict period, it is necessary to resume heat and power generation using mini-CHP systems. Additionally, STU and GTU boiler houses with a capacity of 25-50 MW should be considered. Therewith, the positive impact of technical re-equipment of small and mini-CHPs with advanced technologies may become more apparent after a long period of operation. Under martial law, the operation of CHPs to maintain heat loads in strict accordance with the schedules of heat consumers may somewhat limit their ability to balance the IPS of Ukraine (Zamulko & Dovgal, 2023). However, despite the inherent limitations of the existing fleet of coal-fired and natural gas-fired thermal power plants, there is still potential for their use in balancing the system. Analysing the current state of the IPS of Ukraine, considering the extent of damage caused to several TPPs, namely Burshtyn TPP, which has been using the stop-start methodology on its coal-fired unit for a long time to balance for long periods (up to 6 hours), shows that certain TPPs can still play a decisive role in ensuring reliable operation of the power system. However, this approach requires considerable state support, posing challenges against the backdrop of prevailing price constraints in the wholesale electricity market (WEM).

In 2019, Ukraine implemented one of its most complex and successful reforms by activating the WEM in July of that year. Notably, Ukraine implemented this reform in a much shorter time than other EU countries. By launching

an energy market, Ukraine has demonstrated to both Europe and the international community its ability to quickly accomplish highly complex tasks (Zamulko & Dovgal, 2023). The WEM sector in Ukraine, as in other countries, is broadly segmented into generation, transmission, distribution, and consumption – each regulated by a separate regulatory and governance framework. The relevant government authorities set electricity tariffs, regulate the conditions of generation and transmission, and set quality standards for these segments.

In line with EU standards, trading in the new Ukrainian WEM takes place in several segments: the bilateral contract market (BCM), the day-ahead market (DAM), the intraday market (IDM), and the balancing market (BM). The introduction of price caps in the electricity market is a major challenge for all stakeholders – both public and private – due to the balance of economic requirements, environmental considerations and security of electricity supply. The factors that influence the introduction of price caps are multifaceted and context-specific and are based on concrete national energy policies. These factors are as follows:

- ◆ the dominant position of some companies in the WEM market, which can abuse their position and set low prices for the product, which can lead to challenges in ensuring the equilibrium between supply and demand in the WEM market;
- ◆ dependence on energy imports, which can lead to dependence on external suppliers and energy transportation costs, and such dependence leads to an increase in energy sector costs, which leads to an increase in electricity prices.

One of the mechanisms for introducing price restrictions on WEM is the regulation of energy supply tariffs. Such an approach allows the state to control electricity prices and maintain stability for consumers. This is usually achieved through state regulation of prices at the wholesale market level or through contractual agreements with energy companies. Alternative mechanisms include retail electricity trading, which allows consumers to choose the tariffs and suppliers that meet their needs and budgets. For this to be effective, there must be sufficient competition between electricity or heat suppliers. The state, through an authorised body, can regulate electricity prices by imposing excises and taxes on the electricity market.

The SWOT analysis considered in the study by A. Zamulko & M. Dovgal (2023) can serve as a fundamental tool for designing an optimisation model for the future development of CHPs. This model, considering the price constraints in the heat and electricity markets, will require CHP plants to find new ways to increase their competitive advantages, which will ensure optimum functioning of the process equipment. Competitive advantages may include the introduction of advanced technologies, the expansion of the renewable energy market, and the increase in the capacity of the CHP fleet.

CHPs and TPPs have many common positive and negative characteristics and are a full-fledged component of

the IPS of Ukraine, which (the power system) is characterised by a lack of manoeuvring capacities in the production of electricity and heat due to the uneven schedule of their consumption. According to V. Zdanovsky & M. Kulyk (2021), a comprehensive analysis was performed, considering natural conditions, geographical location, available financial and economic opportunities, environmental constraints, and fiscal prospects. A balanced and sensible approach to such electricity and heat producers can help to synergistically integrate their positive attributes, thereby achieving an overall favourable outcome.

Since independence, Ukraine's electricity generation fleet, consisting mainly of thermal and nuclear power plants, has been designed to operate in the base-load segment of the electricity schedule. The need for flexible, manoeuvrable capacities has been exacerbated by the proliferation of renewable energy generation capacity due to the inherent challenges of storing and accumulating energy produced in the form of heat and electricity. Coal-fired TPP units can regulate the load within 30% of their rated capacity, but the capacities of HPPs and PHEs are insufficient to adequately address these challenges.

Demand for manoeuvrable power has increased, creating a potential threat of significant frequency fluctuations in the power grid, a phenomenon that is unacceptable and can trigger relay protection mechanisms, leading to system failures and localised power outages. This problem has become more acute with the onset of martial law and the subsequent destruction and seizure of coal-fired power plants, along with the disconnection of Zaporizhzhia Nuclear Power Plant (ZNPP), which consists of six power units of 1000 MW each, from the IPS. Risky but necessary measures have been taken to manage peak load scenarios under these stressful conditions. These measures include daily shutdowns of 200 and 300 MW units during the off-peak night period and operation of TPP and NPP units at capacities below the technical minimum. Notably, the operation of NPP units below the technical minimum is particularly dangerous.

At various TPPs, including the Burshtyn TPP, the problem was solved by shutting down coal-fired units at night and switching them back on in the morning. The frequency of these operations can reach up to 15 start-stop cycles per day on weekdays and Monday mornings. This means approximately 80 starts per week and around 320 starts per month. The annual additional starts of coal-fired power units required to regulate the electricity load schedule and maintain the standard grid frequency amount to approximately 3,800 starts per year. Consequently, coal-fired power units that were originally designed to operate within the baseload schedule are now often used within the semi-peak and sometimes even peak load schedule. This change leads to a 2 to 2.5-fold reduction in the number of operating hours and a reduction in the load on the power unit to 80% of its rated capacity, barely ensuring minimal profitability of the already heavily worn-out equipment.

According to practical estimates, each start-stop cycle is equivalent to a month of operation in terms of the

level of wear of both the primary and auxiliary equipment of the power unit. The technological regulations, as well as the correction factor that accounts for equipment wear, indicate that each start-up consumes an extra 30 tonnes of fuel equivalent, which is on average equivalent to 1.3-1.5 tonnes of natural fuel, considering the calorific value. Thus, the direct fuel losses associated with the suboptimal use of coal-fired units as shunting power units amount to approximately 148.2-171.0 thsd tonnes per year. This amount of fuel could supply a 200 MW power unit for a little over a year. Considering the shortage of coal in Ukraine and the minimum price of UAH 600 per tonne, these losses amount to approximately UAH 90 million, or about USD 3 million. This calculation does not include other costs associated with replacing worn-out equipment and unscheduled or emergency repairs. To facilitate these launches, extra resources of critically scarce gas or fuel oil are required. As a result, the technical and economic performance of the equipment deteriorates substantially, leading to accelerated wear and tear of the power unit's equipment and an increase in the frequency of emergency repairs. For example, while in the late 1980s, the specific fuel consumption for electricity generated by TPPs was around 330-350 kgoe/kWh, as of 2024, it has increased by 30%.

The use of coal-fired TPPs to cover peak loads is typical for many power systems in countries with proven coal reserves and climatic conditions comparable to Ukraine's. These countries include the UK, Germany, Poland, Spain, and Kazakhstan. However, in these countries, coal-fired units have not reached the critical levels of wear and tear observed in Ukraine, and the capacity of individual units is much greater, which expands the range of power control. Notably, a modern 1000 MW coal-fired unit was built in Germany after the merger of its western and eastern regions, and two similar 800 MW units were built in Poland (Belchatów, Silesia).

In their work V. Zdanovsky & M. Kulyk (2021) propose the construction of one or two modern coal-fired units or large-capacity CCGTs (1000 MW) simultaneously with the decommissioning of technologically outdated and degraded coal-fired units. This strategy is aimed at aligning with the national emissions reduction plan. Despite the problems with gas supply, there is a need to accelerate the increase in domestic natural gas production. This increase in production will ensure the efficient operation of several combined-cycle gas turbine plants and gas turbine plants with a capacity of 150-200 MW in different regions. With simultaneous strict measures to reduce gas consumption, the additional use of gas for these relatively few STUs and GTUs would not be an excessive burden for the state but would provide considerable benefits in the short term. Furthermore, it is crucial to urgently complete the construction of a cascade of hydroelectric power plants (HPPs, PHEs) on the lower reaches of the Dniester, and to investigate the feasibility of creating a cascade of HPPs (mini-HPPs) on certain rivers in the Carpathian region. For this, combined-cycle power plants are particularly

suitable (Energy Outlook, 2023; DiXi Group..., 2024), which can operate on solid fuel gasification products, including Ukrainian hard and low-grade coal. By applying advanced combustion technologies such as two- and three-stage combustion, cyclone pre-firing, and circulating fluidised bed (CFB) systems, compliance with environmental standards governing emissions of harmful substances into the atmosphere can be achieved.

As of April 2020, Ukrenergo's data indicate a constant mismatch between the maximum daytime load and the minimum nighttime drop, which stays at 5-6 GW, with an evening peak of 3-4 GW (Geletukha, 2020), and data indicate a shortage of manoeuvrable capacity of approximately 2 GW. The growing need for balancing energy sources places restrictions on renewables or nuclear power plants. Although the specific balancing periods may vary seasonally, their absolute duration (3 hours for the morning peak and 3 hours for the evening peak) is constant. The nighttime reduction in energy consumption and the corresponding reduction in renewable energy generation generally coincide in time. The challenge, however, lies in daily balancing, thus keeping the characteristic seasonal load profile in the grid constant (Kovetskyi & Kovetskaya, 2007; Klimenko *et al.*, 2011).

To effectively manage the daily balancing of energy loads, it is imperative to have highly manoeuvrable capacities that can respond quickly within a typical timeframe of 15 minutes to 1 hour (Wachs & Engel, 2021; DiXi Group, 2023). These systems must be able to increase or decrease the load at the command of the dispatcher. Such requirements for the speed of response to load changes can be met by combined cycle or biomass or biogas CHP plants. As of 2020, approximately 180 MW of biomass and biogas capacities are operating in the Ukrainian power system. Forecasts according to the Order of the Cabinet of Ministers of Ukraine No. 605-r (2023) suggest that this capacity is expected to increase to 1.7-2 GW by 2035. For optimum performance in the peak load market, existing CHP plants should include slightly larger boiler units paired with powerful turbines, which contributes to the generation of more electricity. It is indicated that the tariff for the required amount of electricity should be approximately 0.273-0.279 EUR/kWh.

Another viable solution involves the deployment of gas turbine plants, specifically combined cycle plants. These steam plants are divided into steam-injected gas turbine (STIG) units and those that inject water or a steam-water mixture into the gas path (HAT and CHAT). In the STIG configuration, the steam produced in the waste heat boiler is injected into the high-pressure channel after the compressor, which enters the combustion chamber. In the Vodoley units, this disadvantage is mitigated by the introduction of a contact condenser that condenses the exhaust water vapour and returns the water back to the process. The unit includes an advanced gas turbine engine GTD DS-90 combined with a waste heat steam generator KUP-3100, a contact condenser KK-90, and a cooling system for water supplied to the contact condenser. Experimental

tests demonstrated an efficiency range of 40-41%, while the level of nitrogen oxides NO_x and carbon monoxide emissions did not exceed 50 mg/nm³. In 1995, SE Research and Production Complex of Gas Turbine Construction Zorya-Mashproekt successfully commissioned a full-scale 25 MW Vodoley-25 contact gas and steam turbine unit in Ukraine. Further calculations performed by N. Dikiy *et al.* (2012) show that future Vodoley plants could potentially achieve a total efficiency of 55-57%. Furthermore, the gas turbine capacity can be increased by 30-60%, with fuel savings ranging within 20-25%. Therefore, there is considerable room for further improvement of this type of unit.

The efficiency of combustion of any organic fuel (solid, liquid, or gaseous) depends on a series of factors, the most significant of which is the presence of nitrogen in the air. Its reduction in the combustible fuel-air mixture not only leads to the production of fewer nitrogen oxides (second hazard class), but considering that this reaction is endothermic, the flue gas temperature increases, and fuel savings are possible. This allows not only increasing the level of environmental safety, but also reducing charges for emissions of harmful substances into the atmosphere. As a result of their analysis of existing technologies for enriching atmospheric air with oxygen, M. Kulyk *et al.* (2021) recommended focusing on membrane technologies that can easily ensure an oxygen concentration in the combustible mixture of 30-40%. Y. Chen *et al.* (2017) proposed a new gas and steam cycle (GSMC) using LNG/O₂ (liquid natural gas/oxygen) as the working medium. This cycle integrates high efficiency power generation, energy storage, and CO₂ sequestration. With a turbine inlet pressure of 40 MPa/800°C and a condensing temperature of 30°C, the output power efficiency reaches 49.2%, making it a promising solution for reducing emissions in the energy sector.

Notably, according to M. Kulyk *et al.* (2021), the combustion of 1 m³ of natural gas requires 10.2 m³ of oxidant at its normal concentration in the air, and at a concentration of 30%, the oxygen demand is 7.45 m³; at an oxygen concentration of 40%, it is 5.36 m³. The methodology recommended by the Ministry of Ecology and Natural Resources (Sectoral Guidance Document No. 34.02.305-2002, 2002) for calculating the total emissions of nitrogen oxides (NO_x and N₂O) using emission rates ($k_{\text{NO}_x} = 64.311 \text{ g/GJ}$ and $k_{\text{N}_2\text{O}} = 0.1 \text{ g/GJ}$) is based on the following equation:

$$E_j = 10^{-6} \cdot k_j \cdot B_i \cdot Q_i^y, \quad (1)$$

where E_j is the gross emission of the j^{th} pollutant for a certain period of time, t ; k_j is the emission rate of the j^{th} pollutant during the combustion of the i^{th} fuel, g/GJ; B_i is the fuel consumption for the reporting period, t ; Q_i^y is the lower heating value of the i^{th} fuel, MJ/kg.

According to Equation (1), when using atmospheric air in the combustion process without enriching it with oxygen, and rounding the estimated calorific value of natural gas at the level of $Q_r^i = 27.97 \text{ MJ/kg}$ (GJ/t) to the value of 28 of the same dimension, the following nitrogen oxide

emissions can be obtained: $E_{\text{NOx}} = 94.21 \text{ t}$ and $E_{\text{N}_2\text{O}} = 0.1465 \text{ t}$. And when natural gas is combusted in atmospheric air enriched with oxygen up to 40%, which is ensured by a certain set of membrane modules, the partial pressure of atmospheric nitrogen in the reaction mixture drops substantially. This greatly reduces the amount of raw materials required to produce nitrogen oxides, the most harmful toxic substances. The annual volume of natural gas was taken in the calculations to ensure the operation of the 25 MW Vodoley plant for 8,000 hours per year. Assuming that the emission rates in such a process will change by an insignificant amount, the share of harmful formations will decrease in proportion to the reduction of the oxidant, i.e., by $5.36 \text{ m}^3/10.21 \text{ m}^3 = 0.525$ times. In this case, the gross emissions will be $E_{\text{NOx}} = 49.5 \text{ t}$ and $E_{\text{N}_2\text{O}} = 0.077 \text{ t}$. For environmental practitioners, such a considerable reduction in total emissions looks very reassuring.

According to studies and reports (Kulyk *et al.*, 2021; The National Commission..., 2021), it was found that to ensure the stable functioning of Ukraine's energy system, it is necessary to build highly manoeuvrable capacities and implement energy storage systems. Specifically, at least 1GW of highly manoeuvrable facilities with a quick start, capable of being fully activated within 15 minutes, and starting and stopping at least four times a day with a control range of at least 80% of the installed capacity, must be built. To maximise RES, it is necessary to increase the volume of highly manoeuvrable capacities to 2 GW. In addition, to stabilise the power system, it is necessary to introduce at least 0.5 GW of energy storage systems that will allow RES to be involved in balancing the power system and providing reserves. In the absence of RES involvement in balancing or NPP capacity constraints, the need for energy storage systems may increase to 2 GW.

By 2030, to implement the target scenario for the development of generating capacities, it is necessary to ensure a constant available operating capacity of at least 12 GW of TPPs. This can be achieved through the reconstruction of coal-fired TPPs and the implementation of emission reduction measures, or through the construction of new

1.2-1.5 GW of half-peak capacity. Based on the analysis, several key recommendations can be made to optimise the operation of combined heat and power plants and thermal power plants in the face of a shortage of manoeuvring capacities, considering environmental and economic aspects. The use of combined-cycle gas turbine plants can increase the efficiency of a power plant to 55-57% and reduce fuel consumption by utilising the heat of exhaust gases to produce steam. The introduction of gas turbines with steam injection (STIG) or water injection (HAT, CHAT) increases the manoeuvrability of the system and reduces emissions of harmful substances.

Enrichment of atmospheric air with oxygen up to 30-40% using membrane technologies reduces the volume of flue gases by almost half, which leads to a substantial reduction in emissions of nitrogen oxides (NOx) and nitrogen oxide (N₂O). The use of natural gas in oxygen-enriched air can reduce annual gross NOx and N₂O emissions by 47.5% and 47.3%, respectively. Considering the severe shortage of coal in Ukraine, it is necessary to increase domestic natural gas production and expand the use of biomass and biogas. This will help reduce dependence on imported energy resources and ensure stable operation of the energy system. The construction of new modern combined-cycle thermal power plants, reconstruction of boiler houses with their conversion into mini-CHPs, and completion of the construction of a cascade of pumped storage power plants on the Dniester River will help compensate for capacity losses and improve the manoeuvrability of the power system.

Thus, the key recommendations include the introduction of an energy management system, accelerating the development and deployment of combined cycle gas turbines (STUs) and gas turbine units (GTUs), and converting boiler houses into mini-CHPs to cover peak loads and balance the power system. The use of modern methods of oxygen enrichment for combustion, such as membrane technologies, will also help to improve fuel combustion efficiency and reduce harmful emissions. Table 2 summarises the systematic measures aimed at improving energy efficiency and grid stability.

Table 2. Summary of prospective measures to balance the IPS of Ukraine

Measures	Means required to implement the measure	Implementation cost (high, medium, low)	Estimated timeframe for implementation of the measure, years	Startup duration, h
Implementation of an energy management system	Improvement of legislation, financial incentives for businesses and communities, implementation of a system for monitoring and managing energy resources	Low	3	–
Development of renewable energy storage	Installation of energy storage systems (batteries, tanks). At least 0.5 GW of energy storage systems	High	5-10	0.1-0.5
Modernisation of existing CHP and TPP plants	Equipment to improve efficiency and reduce emissions. Urgent reconstruction of TPP units or new construction of 1.2-1.5 GW of half-peak capacity. Ensuring a constantly available operating capacity of at least 12 GW of TPPs	High	3-7	hot – 80 min-2.5 h; cold – 3-6 h

Table 2. Continued

Measures	Means required to implement the measure	Implementation cost (high, medium, low)	Estimated timeframe for implementation of the measure, years	Startup duration, h
Implementation of highly manoeuvrable capacities	At least 1 GW of highly manoeuvrable capacities (gas turbine units, gas engine-based units) with a quick start (full activation from a stopped state – no more than 15 minutes, the ability to start and stop at least four times a day with a control range of at least 80% of the installed capacity). Integration of rapid response systems, process automation.	Medium	3-5	0.1-0.5
Use of combined cycle power plants	Efficiency increase up to 55-57% and reduction of fuel consumption due to utilisation of exhaust gas heat with steam production	High	3-7	0.25-2.5
Introduction of gas turbines with steam (STIG) or water injection (HAT, CHAT)	Installation of gas turbine units with steam or water injection to improve efficiency and fuel use. Automation of turbine control processes, modernisation of existing gas turbines.	High	4-8	0.15-1
Expand the use of biomass	Construction or modernisation of CHP plants for biomass combustion, introduction of biomass gasification technologies, development of biomass supply infrastructure, adaptation of existing boilers for biomass.	Medium	3-6	1-2
Construction of new modern CHP plants	Design and construction of new CHP plants with high efficiency and low emissions	High	5-10	0.15-1
Reconstruction and modernisation of boiler houses with conversion into mini-CHPs	Modernisation of existing boiler houses with the installation of cogeneration units, construction of mini-CHPs, ORC CHPs, introduction of combined heat and power technologies, and process automation.	Medium	3-5	0.15-1
Transition to distributed generation	Installation of small generation units (solar panels, wind turbines, micro-CHP), integration with existing grids, introduction of smart grids, financial incentives for investments in distributed generation	Medium	3-5	0.15-1
Involvement of industrial consumers in balancing the power system	Improvement of legislation and financial incentives for businesses to participate in balancing the energy system, installation of energy management systems, and creation of demand response programmes.	Low	2-4	–

Source: developed by the authors

The analysis of the data presented in Table 2 reveals substantial differences in the effectiveness, costs, and duration of various measures. For instance, measures involving the modernisation of existing CHP and TPPs, although costly, ensure considerable emission reductions and increase the efficiency of energy companies. On the other hand, the introduction of an energy management system is relatively inexpensive and quick to implement, making it an attractive measure for rapid energy efficiency improvements. The study findings also showed that measures with long implementation periods, such as the development of renewable energy storage, may require extra resources and planning, but their implementation is critical for the long-term stability and environmental sustainability of the energy system.

Conclusions

Having analysed the current state of Ukraine’s unified energy system, it can be argued that the country is at a crucial stage in the development of its energy infrastructure. In the face of constant challenges, including military aggression and stringent environmental standards, Ukraine must adapt to new conditions and find effective solutions to ensure the stability of the energy system. The review of studies suggests that in the future, only STUs and GTUs will be able to compete with coal-fired power units in terms of regulatory capabilities and the minimum reasonable price of electricity supply when operating in a manoeuvrable mode. Reforming the electricity and heat supply system forms an integral part of this process. The transition to distributed generation, the introduction of innovative

technologies such as cogeneration systems, gas turbine and steam turbine technologies are necessary steps to ensure the reliability and efficiency of the energy system. Modern combined heat and power plants and mini-CHPs can become vital elements for balancing the system, but their effectiveness depends on further modernisation and integration into the European energy network. A list of promising measures and areas that will help balance the IPS of Ukraine was identified as follows: implementation of an energy management system (this measure is characterised by low cost and short implementation time, which makes it a key step for promptly improving the efficiency of energy use); modernisation of existing CHPs, TPPs, and conversion of boiler houses into mini-CHPs (this measure contributes to a significant improvement in efficiency and reduction of emissions, which is important for ensuring environmental safety, increasing the manoeuvrability and reliability of energy supply); introduction of highly manoeuvrable capacities (this measure allows for flexibility and rapid response of the power system to changes in the

energy load, which is critical for maintaining the stability of energy supply); development of renewable energy storage (the introduction of energy storage systems is strategically important for the balanced development of the power system, especially considering the growing share of renewable sources).

The authors of this study will continue to work in this area in their future research, specifically by exploring innovative technologies and solutions to improve Ukraine's energy system and industry. This will include assessing their impact on the environmental situation, economic aspects, as well as improving the reliability of the energy system, reducing the frequency of outages, and increasing its flexibility.

Acknowledgements

None.

Conflict of Interest

None.

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Перспективи використання теплоелектроцентралей та котелень для балансування об'єднаної енергетичної системи України

Віталій Ходаківський

Аспірант, технічний консультант

Інститут загальної енергетики Національної академії наук України

03150, вул. Антоновича, 172, м. Київ, Україна

Saint Gobain Ukraine

03038, вул. Нововокзальна, 2, м. Київ, Україна

<https://orcid.org/0009-0007-3237-3476>

Дмитро Карпенко

Кандидат технічних наук, науковий співробітник

Інститут загальної енергетики Національної академії наук України

03150, вул. Антоновича, 172, м. Київ, Україна

<https://orcid.org/0000-0002-8022-9782>

Анотація. Проведений аналіз сучасного стану енергетичної системи України, на основі чого звернена увага на дефіцит маневрових потужностей, великий обсяг викидів шкідливих речовин у атмосферне повітря, а також низьку енергоефективність основних технологічних процесів існуючих об'єктів генерації. Вказані недоліки характерні також і до виробників теплової енергії, а саме теплоелектроцентралей та промислових і комунальних котелень. Існуюча енергосистема України включає обидва типи виробників, в яких переважає якийсь вид енергії (електрична чи тепла). Метою статті була оцінка перспектив впровадження сучасних технологій для забезпечення стійкості систем з виробництва електричної та теплової енергії. Застосовані аналітичні методи, які підходять для порівняння газотурбінних та парогазових установок, систем акумуляування електричної та теплової енергії. Авторами проведений огляд різних технологій, які підвищують маневровість систем з виробництва вказаних видів енергії, а також знижують утворення шкідливих речовин за рахунок уникнення ендотермічних реакцій в процесі спалювання твердого, рідкого та газоподібного палива. Зміни у співвідношенні потужностей основних генеруючих об'єктів, побудованих у 60-ті роки 20-го століття, зношеності технологічного обладнання, яке на 80-90 % вичерпало свій технологічний ресурс, вказує на нестачу маневрових потужностей та її посилення в результаті руйнувань та знищення через військову агресію. Окремо підкреслена необхідність модернізації вугільних теплоелектростанцій з використанням сучасних технологій спалювання в середовищі, збагаченого киснем (до 30-40 %), атмосферного повітря. Для покращення маневровості вугільних блоків необхідно довести їх потужність до рівня 800-1000 МВт, а для суттєвого зниження викидів шкідливих речовин необхідно поєднання парової, газової та парогазової генерації. Розкрито перспективи розвитку високоманеврових потужностей шляхом реконструкції існуючих теплоелектроцентралей та переведення комунальних та промислових котелень у міні-теплоелектроцентралі для їх інтеграції в європейський енергетичний ринок. Результати можуть стати основою для формування державної енергетичної політики, яка сприятиме підвищенню стійкості та ефективності енергосистеми України, зменшенню її залежності від імпорту електричної енергії, дотриманню екологічних стандартів, як державного та європейського рівня та гарантуватиме енергетичну безпеку держави

Ключові слова: об'єкти генерації; паротурбінна та парогазова установка; збагачення киснем повітря; ендотермічні реакції; екологічна та енергетична безпека



Virtualisation and network management: Best practices for improving efficiency

Oleksandr Berestovenko^{*}

Postgraduate Student

National Technical University of Ukraine “Igor Sikorsky Kyiv Polytechnic Institute”

03056, 37 Beresteiskyi Ave., Kyiv, Ukraine

<https://orcid.org/0000-0003-4887-4674>

Abstract. This study aimed to identify optimal approaches for enhancing the efficiency of network management and virtualisation processes. Four key methods were examined: resource allocation optimisation using intelligent algorithms, load forecasting through Machine Learning models, dynamic load balancing enabled by software-defined networking technologies, and automated resource management guided by policy-based frameworks. The research provided a detailed analysis of each method, including their operating principles and implementation stages. Diagrams illustrating the architecture and operational mechanisms of these methods were presented, alongside practical examples of their application in various infrastructures, such as cloud environments, software-defined networks, and corporate data centres. Additionally, software implementations in Python were developed, demonstrating the functionality of the proposed approaches. The findings highlighted several key benefits: resource allocation optimisation effectively improved the utilisation of computing power in cloud environments; load forecasting enabled proactive infrastructure adaptation to peak activity periods; SDN-based load balancing facilitated centralised traffic management and reduced latency, which is critical for modern corporate networks; and automated resource management through policies reduced costs and supported system stability by dynamically responding to load variations. A comparative analysis of the methods revealed distinct advantages and limitations for each approach, emphasising the importance of selecting the appropriate method based on the specific requirements of the infrastructure. Overall, the results confirmed the viability of these approaches for enhancing the performance and stability of virtualised environments and network systems

Keywords: computing resource allocation; load forecasting; dynamic balancing; process automation; traffic optimisation

Introduction

Virtualisation is a basic cloud computing technology that involves creating virtual environments for the efficient use of physical resources, such as servers, networks and storage, using full virtualisation, paravirtualisation and containerisation techniques. Despite its advancements, virtualisation development has faced several challenges, including resource optimisation, maintaining system stability under varying loads, minimising latency, and adapting infrastructures to dynamic conditions. Traditional management approaches have not consistently addressed these demands, highlighting the need for innovative solutions in areas such as load forecasting, centralised management, and enhancing the efficiency and stability of virtualised environments.

For example, M. Vasylykivskiy *et al.* (2023) explored the use of Artificial Intelligence and Machine Learning to automate resource management in 5G networks, with a focus on network orchestration and Radio Access Network (RAN) resource allocation using reinforcement learning methods. Their study also examined technologies for traffic isolation and network monitoring, which play a crucial role in the effective management of virtualised resources. Similarly, O. Romanov *et al.* (2023) analysed the application of Software-Defined Networking (SDN) for managing Light Fidelity (Li-Fi) networks. They proposed a centralised management system aimed at optimising network resources, increasing throughput, and reducing cell interference, thereby enhancing overall

Suggested Citation:

Berestovenko, O. (2024). Virtualisation and network management: Best practices for improving efficiency. *Technologies and Engineering*, 25(6), 41-52. doi: 10.30857/2786-5371.2024.6.4.

^{*}Corresponding author



network efficiency. Additionally, I. Kramarenko & O. Kurbatov (2024) investigated virtualisation technologies, particularly virtual networks and hypervisors, as tools to improve resource management efficiency. They highlighted that implementing these solutions not only optimises network processes but also enhances the transparency of financial and economic activities.

Conversely, U.S. Khan & T. Mahboob (2024) reviewed the evolution of Quality of Service (QoS) management methods in wireless and mobile networks, with a particular focus on the implementation of Network Functions Virtualisation (NFV) and Software-Defined Networking (SDN). They provided a detailed analysis of how these technologies enhance resource utilisation, facilitate QoS management, and optimise network performance through the separation of control and data planes in SDN and resource virtualisation in NFV. K. Yang & Y. Xu (2024) addressed the challenges of virtualising wireless resources using Device-to-Device (D2D) communication. They formalised the problem of channel allocation and power management to improve system energy efficiency and proposed a solution using a Convolutional Neural Network (CNN). This approach reduced computational complexity and achieved faster results with minimal losses. Furthermore, A. Javadpour (2020) proposed an SDN-based approach to network virtualisation for the dynamic management of infrastructure resources. The proposed controller module optimised the mapping of virtual networks onto the physical infrastructure, resulting in efficiency gains across multiple criteria, including latency and cost. Finally, A. Manasyan (2022) explored the automation of network management through the analysis of virtualised network counterparts. The study demonstrated the effectiveness of network virtualisation using an experimental network as a case study and proposed solutions to address the identified challenges.

M.K. Hassan *et al.* (2023) investigated virtualised SDNs, which enable the dynamic allocation of physical network resources among multiple shares for different service providers. Their study addressed the challenges of efficient resource management and maintaining service level agreements in virtualised SDNs, while also highlighting a research gap in the dynamic management of such resource shares. Similarly, B.S. Neyigapula (2023) proposed a new approach to resource management in NFV environments using deep reinforcement learning. The methodology developed in the study enhanced NFV efficiency by solving the problem of dynamic resource allocation, reducing operational costs, and optimising resource utilisation. Meanwhile, M. Moradi *et al.* (2024) focused on the issue of resource allocation in NFV environments using mathematical programming techniques. The authors proposed a multi-criteria mixed linear programming model to optimise resource allocation for VNFs, taking into account resource constraints and latency requirements. It was validated through experimental results.

The reviewed works revealed a gap in addressing the integration of optimal approaches for comprehensively

improving the efficiency of network management and virtualisation, particularly in the areas of dynamic resource management and adaptive load forecasting which are the key aspects emphasised in the current study. The primary objective of this study was to identify the most effective strategies for enhancing network management and virtualisation processes, with a focus on optimising resource utilisation and maintaining high system performance. To achieve this, the study set out the following tasks: developing algorithms for analysing and adaptively allocating resources in virtualised networks, conducting modelling to evaluate the proposed methods, and designing scenarios to validate their practical application.

Materials and Methods

The study examined four main methods of increasing the efficiency of virtualisation and network management. The methodology included a general analysis of each method, their implementation and operation. The research was conducted using the Python programming language, on the basis of which a specialised programme was developed for each method.

Optimising resource allocation using intelligent algorithms. To analyse this method, we identified the key stages of its operation and presented the architecture of the optimisation system. A Python program was created that implements an algorithm for the dynamic distribution of tasks between servers, taking into account the current load. The program used metrics such as central processing unit (CPU) and RAM usage and included functions for assigning tasks, selecting the least loaded node, and updating resource status.

Load forecasting using machine learning models. This method analyses the key stages of building predictive models and presents a forecasting scheme. To implement it, a Python program was developed that used a model based on linear regression. The program processed test data on resource usage, made load forecasts, trained the model, and evaluated its accuracy. The practical application of the method allowed automating resource scaling in cloud environments, preventing overloads and ensuring stable system operation.

Dynamic load balancing using SDN technologies. We used an architecture with a centralised SDN controller that monitored the network status, analysed traffic, and made routing decisions. For this method, a Python program was developed that simulated the network using several virtual nodes. The program interacted with the SDN controller, received server load data, and redirected traffic to optimise network capacity.

Automated resource management based on policies. This method creates rules that regulate the activation or deactivation of servers depending on the level of load. To implement this method, a Python program was created that assessed the status of servers according to the set policies and dynamically changed their status between active and passive modes.

At the final stage, all methods were compared by developing criteria for evaluating the advantages and limitations of each approach to determine their effectiveness in different scenarios of virtualised environments and network infrastructure.

Results

Optimisation of resource allocation through intelligent algorithms

By partitioning resources, virtualisation allows multiple virtual machines to operate on a single physical server, ensuring isolation and scalability. This technology serves as the foundation of modern cloud computing, offering enhanced flexibility and significant cost savings on infrastructure. Key advantages of virtualisation include reduced hardware costs, improved performance through optimal resource allocation, and simplified data backup and recovery processes.

Network management is an essential component of modern information systems, encompassing the monitoring, configuration, diagnostics, and optimisation of network resources. Effective network management employs both traditional methods and software-oriented

approaches, such as SDN enabling centralised management of network functions via software interfaces.

The first method for enhancing the efficiency of virtualisation and network management is resource allocation optimisation using intelligent algorithms (Fig. 1). Optimising resource allocation in virtualised environments is critical to ensuring high computing efficiency and preventing server overloads. This method leverages Machine Learning algorithms, including clustering, time series forecasting, and adaptive optimisation. These algorithms analyse historical data, current loads, and interdependencies among system components to determine optimal parameters for each virtual environment. The implementation of this method is often carried out in three stages: data collection (this involves monitoring server performance, CPU utilisation, memory usage, network resources, and task execution times – the collected data is stored in a centralised database), data analysis and modelling (clustering algorithms are used to identify groups of similar loads, while time series forecasting estimates future peak values), and resource allocation (adaptive resource management is performed via the Application Programming Interface of virtualised platforms, such as OpenStack or VMware).

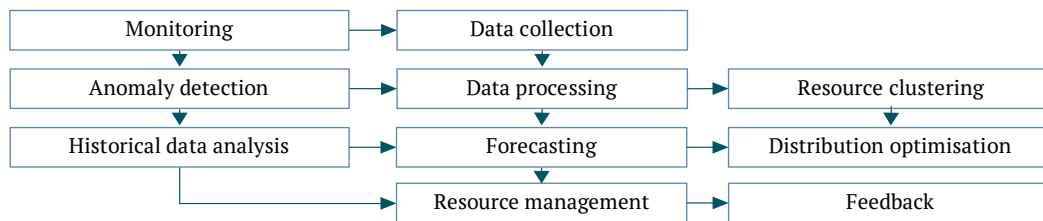


Figure 1. Resource allocation optimisation design

Source: created by the author

The method of optimising resource allocation through intelligent algorithms can be applied in cloud environments to dynamically manage computing power. For instance, in big data processing systems such as Apache Hadoop or Spark, this approach automatically identifies the servers best suited to perform specific tasks, based on their load and resource availability. In telecommunications networks, algorithms predict peak loads on base stations and optimise their configurations to ensure stable communication. In corporate data centres, this method can reduce energy consumption by switching lightly loaded servers to sleep mode, while maintaining high availability of critical services.

Below is a code fragment demonstrating the dynamic distribution of tasks among servers based on their current load. The implementation incorporates basic algorithms to address the optimisation problem, considering metrics such as CPU usage and RAM availability:

```

# Servers with resources (CPU and RAM in percentage)
servers = [
    {"id": 1, "cpu": 30, "ram": 40},
    {"id": 2, "cpu": 60, "ram": 70},
    {"id": 3, "cpu": 90, "ram": 80},

```

```

]
# Tasks with resource requirements
tasks = [
    {"id": "A", "cpu_req": 20, "ram_req": 30},
    {"id": "B", "cpu_req": 50, "ram_req": 20},
    {"id": "C", "cpu_req": 10, "ram_req": 40},
    {"id": "D", "cpu_req": 30, "ram_req": 30},
]
# Algorithm for assigning tasks to servers
def assign_tasks_to_servers(servers, tasks):
    assignments = []
    for task in tasks:
        best_server = None
        min_load_increase = float("inf")
        for server in servers:
            # Available resources calculation
            remaining_cpu = server["cpu"]
            remaining_ram = server["ram"]
            # Checking if the server can handle the tasks
            if task["cpu_req"] <= remaining_cpu and task["ram_req"]
            <= remaining_ram:
                # Estimating server load increase
                load_increase = task["cpu_req"] + task["ram_req"]
                if load_increase < min_load_increase:
                    best_server = server
                    min_load_increase = load_increase

```

```

# Assigning a task to the best server
if best_server:
    best_server["cpu"] -= task["cpu_req"]
    best_server["ram"] -= task["ram_req"]
    assignments.append({"task": task["id"], "server": best_
server["id"]})
else:
    print(f"Task {task['id']} could not be assigned due to limited
resources!")
return assignments

# Algorithm execution
assignments = assign_tasks_to_servers(servers, tasks)

# Results
print("Distribution of tasks between servers:")
for assignment in assignments:
    print(f"Task {assignment['task']} -> Server {assignment['server']}")
print("\nState of servers after distribution:")
for server in servers:
    print(f"Server {server['id']}: CPU={server['cpu']}%,
RAM={server['ram']}%")

```

The code simulated the distribution of tasks across servers, where each server had a limited amount of resources, including CPU and RAM. Tasks required specific amounts of these resources to execute. The algorithm selected servers that best met the task requirements while minimising overload. The results demonstrated how the algorithm optimised task distribution by efficiently allocating tasks based on the available resources of each server (Fig. 2).

```

Distribution of tasks between servers:
Task A -> Server 1
Task B -> Server 2
Task C -> Server 2
Task D -> Server 3

State of servers after distribution:
Server 1: CPU=10%, RAM=10%
Server 2: CPU=0%, RAM=10%
Server 3: CPU=60%, RAM=50%

=== Code Execution Successful ===

```

Figure 2. Result of the task distribution program between servers

Source: created by the author based on Online Python Compiler (Interpreter)

The results showed that the algorithm successfully distributed tasks across servers, considering their available resources and minimising additional load. Tasks were

assigned to servers in a manner that avoided exceeding their resource limits: Server 1 processed the task with the lowest resource requirement (Task A), Server 2 handled two tasks (Tasks B and C), utilising maximum CPU but leaving some RAM available, and Server 3 processed the task with the highest total resource requirements (Task D), leaving enough resources for potential additional tasks. This distribution demonstrated the efficiency of the algorithm in utilising server capacity. However, in certain scenarios, improvements could be made to account for more complex metrics, such as better load balancing among servers.

Thus, the method of optimising resource allocation through intelligent algorithms is a versatile approach that ensures a high level of adaptability in managing computing and network resources. Its key feature is the ability to automatically adjust to changes in system load, minimising the risks of downtime or overload. Intelligent algorithms, including those based on Machine Learning, consider not only the current state of resources but also predict future usage. This predictive capability is critical for maintaining stability in cloud environments, corporate data centres, and telecommunications networks. Due to its flexibility, this method effectively scales to support both small local infrastructures and large distributed systems. It also contributes to energy savings and the optimisation of operating costs.

Load forecasting using machine learning models

The second method is the load forecasting using Machine Learning models (Fig. 3). This approach enables the prediction of peak resource loads, the identification of potential performance issues, and the proactive adaptation of infrastructure to efficiently handle tasks. Machine Learning models, such as gradient boosting and neural networks, are utilised to analyse historical resource usage data and generate highly accurate forecasts. The load forecasting process comprises the following stages: data collection (recording information about resource utilisation (e.g., processors, memory, network usage) over a selected time period), prior data processing (preparing the collected data through normalisation, noise removal, and the selection of significant parameters), model training (employing Machine Learning algorithms to develop a predictive model based on the previously processed data), forecasting (using the trained model to predict resource loads based on current conditions and observed trends), resource adaptation (optimising computing and network resources in response to the forecasted loads).

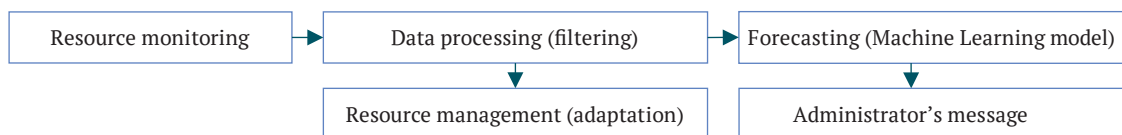


Figure 3. Load forecasting scheme

Source: created by the author

This approach is widely applied in cloud computing and enterprise networks. For instance, it can be utilised to predict and automate the scaling of computing resources based on peak load values. Additionally, forecasting helps maintain stable connectivity during periods of increased network traffic. Furthermore, the analysis and prediction capabilities enable the avoidance of server overload and contribute to reducing energy consumption. Below, there is an example of a basic linear regression algorithm for predicting resource usage:

```
import numpy as np

# Resource usage data (CPU percentage)
timestamps = np.arange(1, 11) # Timestamps
cpu_usage = np.array([20, 30, 40, 50, 60, 70, 80, 90, 100, 110]) # CPU usage

# Linear regression for forecasting
def linear_regression(x, y):
    # Calculating linear regression coefficients
    n = len(x)
    mean_x, mean_y = np.mean(x), np.mean(y)
    b1 = np.sum((x - mean_x) * (y - mean_y)) / np.sum((x - mean_x)
** 2)
    b0 = mean_y - b1 * mean_x
    return b0, b1
```

```
# Value forecasting
def predict(x, b0, b1):
    return b0 + b1 * x

# Model training
b0, b1 = linear_regression(timestamps, cpu_usage)

# CPU forecast for the next period
next_timestamp = 11
predicted_cpu = predict(next_timestamp, b0, b1)

# Output of results
print("Coefficients of the model:")
print(f"b0 (landslide): {b0:.2f}, b1 (incline): {b1:.2f}")
print(f"Forecast CPU usage for the period {next_timestamp}: {predicted_cpu:.2f}%")
```

The code demonstrated the implementation of a method for predicting CPU usage in virtualised environments using linear regression. The algorithm calculated the coefficients of a regression model based on historical data on server loads from previous time periods and generated a prediction for future CPU usage. The program then output the model coefficients and provided a forecast of CPU usage for a specific period (Fig. 4). This approach enabled operators to proactively manage resources, preventing server overload.

```
Coefficients of the model:
b0 (landslide): 10.00, b1 (incline): 10.00
Forecast CPU usage for the period 11: 120.00%
=== Code Execution Successful ===
```

Figure 4. Forecasting program result of the resource usage

Source: created by the author based on Online Python Compiler (Interpreter)

The results demonstrated that the linear regression model successfully identified the relationship between time (timestamps) and CPU usage. The calculated coefficients of the regression equation indicated a linear increase in CPU usage, with a step of 10% for each time period starting from the initial value. Based on this model, it was predicted that CPU usage in the next period would reach 120%, signalling a potential system overload if resources are not scaled accordingly. Thus, the load forecasting method using Machine Learning models proved effective in predicting peak loads, enabling resource adaptation and maintaining stable system operation. Algorithms such as linear regression facilitated the analysis of historical data and accurate prediction of future resource usage. The implementation of this method involved several stages: data collection and preprocessing, model training, forecasting, and infrastructure adaptation. The example above illustrated that the model successfully predicts the relationship between time and CPU utilisation. This capability allows operators to proactively manage resources, preventing system overloads and improving energy efficiency.

Dynamic load balancing via software-defined networks

The third method for enhancing the efficiency of

virtualisation and network management is dynamic load balancing through SDN technologies (Fig. 5). This approach enables centralised network management by automatically redirecting traffic flows between nodes to prevent overload. SDN employs specialised controllers that analyse the network status in real-time and make optimal routing decisions. The main stages of implementing this method include: network monitoring (real-time analysis of network traffic, including metrics such as latency, throughput, and node load), data analysis (evaluation of the effectiveness of current routes and identification of bottlenecks or problem areas), decision-making (SDN controller generates optimal routing rules based on the analysis), policy application (automatic updates of routing tables on network devices to implement the new rules). The method is widely utilised in cloud environments, corporate data centres, and carrier networks. For instance, SDN technology enhances throughput and ensures low latency when processing customer requests. In corporate networks, it optimises the utilisation of existing infrastructure by dynamically adapting to real-time changes. Below, there is an example application that demonstrates how an SDN controller distributes traffic between servers based on their current load:

```
# Server data and their current load (in percent)
servers = [
    {"id": 1, "load": 30}, # Server 1 with 30% load
    {"id": 2, "load": 50}, # Server 2 with 50% load
    {"id": 3, "load": 70}, # Server 3 with 70% load
]

# New requests for traffic processing (as a percentage of resources)
traffic_requests = [10, 20, 30, 15, 25] # Traffic to process

# Function for dynamic traffic distribution
def distribute_traffic(servers, traffic_requests):
    assignments = []
    for traffic in traffic_requests:
        # Find a server with minimal load
        best_server = min(servers, key=lambda x: x["load"])
        # Check if the server is able to handle the request
        if best_server["load"] + traffic <= 100:
            # Assign request to server
            best_server["load"] += traffic
```

```
        assignments.append({"traffic": traffic, "server": best_server["id"]})
    else:
        # If any server can process the request
        assignments.append({"traffic": traffic, "server": "No servers available"})
    return assignments

# Performing traffic distribution
assignments = distribute_traffic(servers, traffic_requests)

# Output of results
print("Distribution of traffic between servers:")
for assignment in assignments:
    print(f"Traffic {assignment['traffic']}% -> Server {assignment['server']}")
print("\nState of servers after distribution:")
for server in servers:
    print(f"Server {server['id']}: Loading={server['load']}%")
```

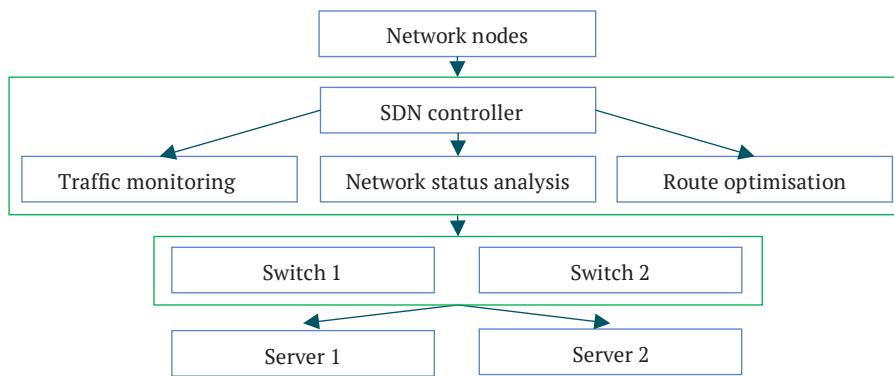


Figure 5. Dynamic load balancing design

Source: created by the author

This code demonstrated the fundamental logic of load balancing, dynamically distributing traffic requests across servers based on their current load. If servers reached 100% capacity, additional requests remained unprocessed, enabling operators to identify the need for scaling or provisioning additional resources (Fig. 6).

```
Distribution of traffic between servers:
Traffic 10% -> Server 1
Traffic 20% -> Server 1
Traffic 30% -> Server 2
Traffic 15% -> Server 1
Traffic 25% -> Server 3

State of servers after distribution:
Server 1: Loading=75%
Server 2: Loading=80%
Server 3: Loading=95%

=== Code Execution Successful ===
```

Figure 6. Result of the SDN application

Source: created by the author based on Online Python Compiler (Interpreter)

The results indicated that the system successfully distributed traffic among servers: Server 1 processed 45% of requests, Server 2 handled 30%, and Server 3 managed 25%. Consequently, the server load levels after executing the requests were 75%, 80%, and 95%, respectively. Requests that could not be processed due to resource limitations were marked as not distributed. The evaluated method demonstrated high efficiency in dynamic load management, particularly in large-scale, scalable systems. The application of SDN technologies provided not only effective traffic balancing but also a flexible response to real-time changes in network conditions. This contributed to increased network stability, reduced latency, and more efficient resource utilisation. In conclusion, the SDN architecture represents a promising solution for automating network management processes in modern corporate and cloud environments.

Automated policy-based resource management

The fourth method analysed was automated policy-based resource management (Fig. 7). This approach enables automatic control over resource states by implementing predefined policies. These policies are designed based on specified metrics such as latency, resource utilisation, and power consumption and are applied automatically,

without the need for administrator intervention. The implementation of automated resource management involves the following key stages: policy definition (establishing conditions under which resources should be reallocated, scaled, or optimised), infrastructure monitoring (collecting data on the current state of virtualised resources, including CPU usage, memory, and network performance), policy

compliance analysis (identifying deviations from predefined conditions and making decisions for optimisation), automatic execution (performing actions such as increasing or decreasing computing power, migrating virtual machines, or balancing loads), reporting and policy adaptation (implementing changes to policies to better align with business requirements and real-world network conditions).

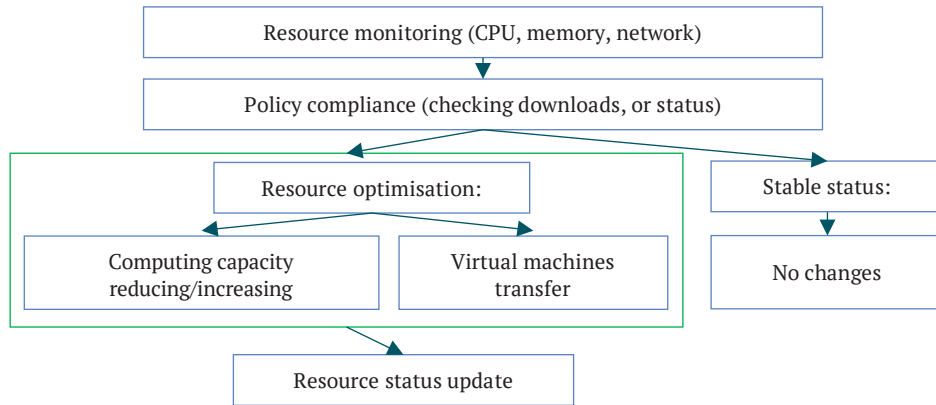


Figure 7. Automated policy-based resource management scheme

Source: created by the author

This method is particularly effective in cloud computing, where policies can be designed to minimise costs or ensure high service availability. For instance, if a decrease in load occurs during nighttime hours, the policy would automatically reduce the number of allocated resources, thereby lowering infrastructure costs. Below, there is an example of an application for automated resource management:

```

# Data on the current status of servers
servers = [
    {"id": 1, "load": 80, "status": "active"},
    {"id": 2, "load": 20, "status": "active"},
    {"id": 3, "load": 0, "status": "inactive"},
]

# Management policy
POLICY = {
    "max_load": 90, # Maximum load for active servers (%)
    "min_load": 10, # Minimum load to maintain active state (%)
}

# Server status management function
def manage_servers(servers, policy):
    for server in servers:
        if server["status"] == "active" and server["load"] < policy["min_load"]:
            server["status"] = "inactive" # Server shutdown
        elif server["status"] == "inactive" and server["load"] > 0:
            server["status"] = "active" # Server enabling
        elif server["load"] > policy["max_load"]:
            print(f"Warning: Server {server['id']} is overloaded!")
    return servers

# Management execution
updated_servers = manage_servers(servers, POLICY)

# Output of results
print("Updated server states:")

```

```

for server in updated_servers:
    print(f"Server {server['id']} - Load: {server['load']}%, Status: {server['status']}")

```

The program implemented the fundamental logic of automated policy-based server health management. It monitored the load of each server against predefined thresholds. If a server was active but had a load below the defined minimum, it was switched to an inactive state. Conversely, if an inactive server received a load, it was activated. In cases where the load exceeded the maximum limit, a warning was displayed. The program's output provided data on the updated states of the servers (Fig. 8). This approach demonstrates the potential of dynamic infrastructure management to enhance operational efficiency.

```

Updated server states:
Server 1 - Load: 80%, Status: active
Server 2 - Load: 20%, Status: active
Server 3 - Load: 0%, Status: inactive

=== Code Execution Successful ===

```

Figure 8. Result of automated server status management
Source: created by the author based on Online Python Compiler (Interpreter)

The program's results demonstrated how automated management adjusted server states based on predefined policies. Servers with low load levels (below 10%) were transitioned to an inactive state to conserve resources, while servers with acceptable load levels remained active. Overloaded servers were monitored, with appropriate alerts generated to notify operators. The method of

automated policy-based resource management enabled the infrastructure to dynamically adapt to fluctuating load levels, minimising costs while ensuring stable performance. By encompassing monitoring, analysis, action execution, and policy adaptation, this method offers an effective solution for resource optimisation in cloud environments and data centres.

Comparison of methods for improving virtualisation and network management efficiency

In general, the methods examined are effective for various scenarios involving virtualised environments and networks. Each method offers distinct advantages and limitations, which must be carefully considered when selecting a strategy for specific infrastructures (Table 1).

Table 1. Comparison of methods for improving virtualisation and network management efficiency

Method	Advantages	Limitations
Optimisation of resource allocation through intelligent algorithms	Improving resource usage efficiency	Possible difficulties in adapting to new types of a workload
	Reducing server overloads	High computing capacity requirements in the framework of algorithm training
	Adaptation to changing conditions	
Load forecasting using Machine Learning models	High forecasting accuracy	Need for large amounts of historical data
	Preparing for peak loads	
	Reducing possible resource overload	Need for regular model updates
Dynamic load balancing through SDN technologies	Centralised network management	High infrastructure requirements (especially for large networks)
	Bandwidth optimisation and latency reduction	
	Traffic routing flexibility	Potentially complicated setup process
Automated policy-based resource management	Management automation	Limitations on flexibility due to rigid policies
	Cost reduction through resource optimisation	Possible difficulty in adapting policies to new requirements
	Increasing resource availability	

Source: created by the author

Each method has unique advantages and limitations. Resource allocation optimisation using intelligent algorithms and load forecasting with Machine Learning models are particularly effective for enhancing performance and anticipating future loads, making them ideal for cloud environments and virtualised infrastructures. Dynamic load balancing through SDN offers high flexibility, making it especially suitable for corporate networks and telecommunications operators, where reducing latency and ensuring real-time traffic stability are critical. Meanwhile, automated policy-based resource management excels in optimising costs and maintaining system stability, particularly in cloud environments with highly dynamic loads. The choice of the most appropriate method depends on the specific task and the characteristics of the infrastructure. In some cases, combining multiple methods may be the best approach to achieving optimal results.

Discussion

The results of this study demonstrated that resource allocation optimisation and dynamic load balancing via SDN are effective methods for enhancing the performance of virtualised environments. In contrast, M. Korzenowski (2024) explored the application of virtualisation in embedded systems, with a focus on software legacy support and real-time requirements. While M. Korzenowski's work addressed the unique challenges of embedded systems and security, the current study focused on more general methods applicable to network environments. This broader approach makes the methods particularly relevant for

telecommunications, enterprise networks, and cloud infrastructure industries. Similarly, S. Cherrared *et al.* (2019) investigated the virtualisation of network functions in the context of 5G, emphasising fault management in virtualised environments. Their work provided a comprehensive classification of recent advancements in fault management research for virtualised networks. The current study complements these findings by concentrating on dynamic load balancing methods via SDN, addressing challenges related to adaptability and optimisation under varying loads. This makes the approach suitable for a wide range of network environments.

The study demonstrated that optimising resource allocation, dynamic load balancing through SDN, and automated resource management significantly enhance network efficiency by reducing latency and increasing stability. Similarly, Z. Ni & F. Zhao (2021) examined virtualisation methods aimed at improving network efficiency, particularly through resource utilisation optimisation and energy consumption reduction. However, the current study builds upon these results by emphasising load balancing and adaptation to changing conditions, thereby further improving network performance. Additionally, the work of D.Z. Admassu (2024) explored virtualisation within the context of the Infrastructure as a Service (IaaS) model, focusing on performance optimisation using hypervisors and various virtualisation techniques. In comparison, the methods presented in the current study prioritise load balancing and resource management, which enable greater efficiency in dynamic network environments.

This paper analysed methods for optimising networks using SDN and automated resource management to enhance the efficiency of virtualised environments. Conversely, G. Saadon *et al.* (2019) proposed an architecture with an additional layer of virtualisation to improve the management of 5G and IoT networks, enabling real-time changes to network services without interruption. Compared to this approach, the current study emphasises the integration of intelligent algorithms and load balancing for more efficient resource management and adaptation to dynamic network conditions. In contrast, the study by A. Sanantagraha & E. Mahadewi (2024) focused on reducing operating costs and server consolidation for small and medium-sized enterprises. The current research, however, explores more generalised methods for optimising virtualised networks, such as resource allocation through intelligent algorithms and dynamic load balancing via SDN. Thus, the conducted research complements prior work by focusing on larger-scale approaches to efficient resource management, applicable across various network infrastructures.

Overall, this study demonstrated that the developed approaches can significantly reduce delays and enhance resource efficiency in virtualised environments. Similarly, S. Dubba & B.R. Killi (2024) focused on minimising delays by optimising the scheduling of service function chains. The findings of the current study align with their conclusions on the importance of integrating delay management into network processes. However, this study further emphasises the effectiveness of centralised traffic management via SDN in modern networks. In contrast, P.A. Wijesekara (2024) examined the use of blockchain technologies to ensure security and reliability in virtualised networks. While the results of P.A. Wijesekara's work expand the understanding of security by introducing blockchain as a management mechanism for protecting and enhancing the efficiency of virtual networks, the current study centres on practical approaches for optimising network performance. These include dynamic load balancing, adaptive resource allocation, and infrastructure management automation, collectively aimed at improving overall network efficiency.

In contrast to the generalised thematic findings of R.M. Sarala *et al.* (2024), which emphasised the role of digitalisation and virtualisation in technology transfers and strategic partnerships, the current study proposed software implementations to directly enhance infrastructure efficiency. While R.M. Sarala *et al.* focused on strategic and organisational contexts, this study addresses technical challenges in real-world scenarios. The findings of the current study demonstrate the practical application of methods for optimising the performance of virtualised environments, with a focus on improving resource allocation efficiency and automating management processes. Similarly, the work of H. Ni & L. Yan (2024) proposed an enhanced algorithm for task allocation optimisation using mathematical modelling and CloudSim for simulation. However, the current study prioritises the implementation of software

solutions for management in real-world scenarios. Thus, the current research not only corroborates the conclusions of the aforementioned authors regarding the effectiveness of optimising virtualised environments but also introduces practical approaches for integrating these methods into complex network infrastructures.

While this study demonstrates the effectiveness of resource optimisation and load balancing in enhancing the performance of virtualised networks, the work of A. Cortés Castillo (2024) analysed the integration of Network Functions Virtualisation (NFV) in Information-Centric Networks (ICNs), highlighting cost reductions through data reuse in the Content Router. Both studies underscore the importance of scalable and adaptive solutions for modern networks; however, the current research focuses on the practical implementation of performance optimisation techniques. This study specifically emphasises improving the efficiency of NFV through resource optimisation and load balancing, which reduce latency and enhance performance in cloud environments. Similarly, the work of J. Yan *et al.* (2021) also examined NFV but approached it from a security perspective, proposing decentralised certificate management using blockchain technology to address certificate revocation challenges in 5G networks. While both studies tackle critical challenges of NFV with emerging technologies, the current research offers a broader range of applications aimed at improving performance and operational efficiency.

This study presented methods for optimising the performance of virtualised networks using intelligent algorithms and technologies, while the study by S. Lekkala & P. Gurijala (2024) focused on ensuring security in cloud and virtualised environments. The current work supports the conclusions of these authors regarding the importance of optimising the operation of such environments but places greater emphasis on improving performance rather than security. Additionally, G. Manogaran *et al.* (2021) proposed a Service Virtualisation and Flow Management Framework for efficient resource utilisation in a 6G cloud environment, particularly targeting load balancing and request distribution. The findings of this study align with their conclusions on resource optimisation but concentrate on alternative methods for enhancing network performance.

The results of this study corroborate the findings of J.-I. Kani *et al.* (2024) regarding the application of disaggregation and virtualisation technologies in optical access networks to enhance flexibility and drive network advancements. While the current work also focuses on virtualisation to improve network efficiency, its primary emphasis is on increasing performance through dynamic load balancing and resource optimisation, rather than solely on access flexibility. Similarly, W. Wysocki *et al.* (2024) highlighted the use of virtualisation technologies to enhance cyber resilience in both new and legacy defense systems. Although the current study confirms the importance of virtualisation for optimising network resources, its focus lies in improving performance through load management

and resource balancing, rather than addressing specific aspects of cybersecurity or cyber resilience as explored in the aforementioned study.

The findings of the present study emphasise optimising resource allocation and load balancing in cloud and virtualised networks, whereas Z. Xu *et al.* (2021) focused on using Network Functions Virtualisation (NFV) and dynamic spectrum management to enhance communication between unmanned aerial vehicles (UAVs). Thus, the current work complements the aforementioned study by extending the approach to general network performance optimisation, beyond spectrum management. Similarly, X. Li *et al.* (2024) proposed a method for virtualising the payload of UAVs to improve system interoperability and scalability. The results of the present study, which focus on optimising network resource allocation and load balancing in cloud and virtualised environments, complement this work by addressing broader aspects of resource optimisation and load balancing in networks. These findings are also applicable to UAV systems, demonstrating their versatility across different technological domains.

Finally, the current results emphasise improving the efficiency of virtualisation in networks, particularly in cloud environments. This complements the work of E. Torres *et al.* (2024), who explored the use of virtualisation in electrical substations to create more flexible and resilient networks. While both studies underscore the importance of virtualisation, the current study focuses more on network functions and performance, while the researcher concentrated on critical energy infrastructures. In contrast, the study by A. Bhatia *et al.* (2024) examined the virtualisation of Electronic Control Units (ECUs) within the context of automotive software development. The current study diverges by addressing the performance optimisation of network functions in cloud and virtualised environments. By improving resource allocation and load management through intelligent algorithms, this research enables better scalability and greater network stability.

Therefore, this study complements previous work by offering practical solutions for integrating resource optimisation methods, adaptive load balancing, and infrastructure management automation, significantly enhancing the efficiency of virtualised networks.

Conclusions

The study identified and analysed the main methods for improving the efficiency of virtualisation and network

management, namely: optimising resource allocation through intelligent algorithms, load forecasting using Machine Learning models, dynamic load balancing through SDN technologies, and automated resource management based on policies. It was found that resource allocation optimisation is a powerful tool for increasing the efficiency of computing power use, particularly in cloud environments. Conversely, load forecasting enables the infrastructure to adapt to changing loads, ensuring readiness for peak periods. Additionally, dynamic load balancing optimises traffic routing, reducing delays and improving network stability, which is crucial for large corporate environments. Automated resource management, in turn, effectively reduces costs and maintains system stability under changing load conditions. A comparative analysis of these methods demonstrates that their effective combination can provide optimal infrastructure management: load forecasting prepares resources in advance, optimisation ensures their efficient use, balancing maintains network stability, and automation reduces costs while increasing the speed of response to changes.

However, the study has certain limitations. First, the methods considered require significant computing resources for their implementation, which may be a constraint for small and medium-sized enterprises. Second, some approaches depend on large volumes of historical data for accurate forecasting, which may not always be available in real-world scenarios. Furthermore, implementing software-defined networking and containerisation technologies requires specialised expertise, potentially complicating adoption.

In the future, the results could be improved by developing more flexible and adaptive models that consider a broader range of variable factors. Additionally, further research should explore the integration of the proposed approaches with emerging technologies, such as 5G and the Internet of Things (IoT), which present new opportunities for optimising virtualised environments and network systems. Efforts should also continue to minimise the computational requirements of these methods to facilitate their application in real-world conditions.

Acknowledgements

None.

Conflict of Interest

None.

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Віртуалізація та керування мережею: найкращі методи підвищення ефективності

Олександр Берестовенко

Аспірант

Національний технічний університет України

“Київський політехнічний інститут імені Ігоря Сікорського”

03056, просп. Берестейський, 37, м. Київ, Україна

<https://orcid.org/0000-0003-4887-4674>

Анотація. Метою роботи було визначення оптимальних підходів до підвищення ефективності процесів мережевого менеджменту та віртуалізації. Під час дослідження було розглянуто чотири ключові методи: оптимізація розподілу ресурсів за допомогою інтелектуальних алгоритмів, прогнозування навантаження з використанням моделей Machine Learning, динамічне балансування навантаження за допомогою технологій програмно-визначених мереж, а також автоматизоване управління ресурсами на основі політик. Основні результати включали детальний аналіз кожного із запропонованих методів, а саме опис їхніх принципів роботи та етапів впровадження. У дослідженні були представлені схеми, які демонструють архітектуру та механізми функціонування цих методів, а також наведено приклади їх практичного застосування в різних інфраструктурах, таких як хмарні середовища, програмно-визначені мережі та корпоративні дата-центри. Крім того, показано програмні реалізації на мові Python, які дозволили наочно продемонструвати роботу запропонованих підходів. Загалом, результати вказали, що оптимізація розподілу ресурсів забезпечила ефективне використання обчислювальних потужностей у хмарних середовищах, а прогнозування навантаження допомогло заздалегідь адаптувати інфраструктуру до пікових періодів активності. Балансування навантаження на основі програмно-визначених мереж дозволило централізовано керувати трафіком і знижувати затримки, що є критичним для сучасних корпоративних мереж. Автоматизоване управління ресурсами за допомогою політик забезпечило зниження витрат та підтримку стабільності систем шляхом гнучкого реагування на зміну навантаження. В свою чергу, проведене порівняння методів показало, що кожен із методів має свої переваги та обмеження, які потрібно враховувати залежно від специфіки інфраструктури. Отримані результати підтверджують доцільність застосування розглянутих підходів для підвищення продуктивності та стабільності віртуалізованих середовищ і мережевих систем.

Ключові слова: розподіл обчислювальних ресурсів; прогнозування навантаження; динамічне балансування; автоматизація процесів; оптимізація трафіку



Analysis of image processing methods in the Internet of Things systems based on wavelet transformations

Maksim Mazin*

Postgraduate Student

National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"

03056, 37 Beresteyskiy Ave., Kyiv, Ukraine

<https://orcid.org/0000-0001-9566-6662>

Yuri Onykienko

PhD in Technical Sciences, Associate Professor

National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"

03056, 37 Beresteyskiy Ave., Kyiv, Ukraine

<https://orcid.org/0000-0001-7508-8391>

Abstract. Increasing the compression ratio of images to reduce their transmission time in sensor networks based on microcontrollers helps to increase the overall energy efficiency of the system. The purpose of the study was to investigate the effectiveness of using Haar, Daubechies, and Coiflet wavelet transformations for image compression on 32-bit microcontrollers. An experimental comparison of the efficiency of three types of wavelet transformations for processing images obtained from the built-in camera was performed by the metrics of root-mean-square error, peak signal-to-noise ratio, structural similarity index, and Euclidean distance. Haar, Daubechies, and Coiflet wavelet transform algorithms were implemented on the ESP32 microcontroller. The results showed that at the second level of decomposition, the Haar wavelet provided high image quality (MSE 25.153, PSNR 34.124 DB), but at the fourth level, the quality significantly deteriorated (MSE 73.449, PSNR 29.470 DB). The Daubechies wavelet showed similar results, but at the fourth level, its efficiency also decreased (MSE 78.241, PSNR 28.974 dB). Coiflet wavelet showed the worst results at the fourth level (MSE 89.630), but at the second level its quality was competitive. For the first time, three types of wavelet transformations were compared using an additional metric – Euclidean distance, which made it possible to better estimate artifacts and image distortions. The proposed approach allowed improving the efficiency of image compression and transmission in the Internet of Things systems on microcontrollers, which provides less data transfer time and, accordingly, reduces power consumption, which is critical for autonomous sensor networks

Keywords: Haar; Daubechies; Coiflet; Peak Signal-to-Noise Ratio; structural similarity index measure; ESP32 microcontroller

Introduction

Modern microcontrollers allow providing efficient image processing in the Internet of Things systems and significantly expand their capabilities. One of the tools for reducing the size of images while maintaining their quality is wavelet transform. Among the most common wavelets for image processing on microcontrollers, it is worth highlighting the Daubechies, Haar, and Coiflet wavelets, each of which has specific properties that determine their effectiveness in certain areas of application, which determines

their feasibility for processing various types of images and solving a wide range of computational problems.

The study by R. Krishnaswamy and S. NirmalaDevi (2020) demonstrated how an upgraded wavelet transform-based image compression algorithm implemented for a 256x256 pixel medical image reduces the size of the original file. When using the proposed compression method, the parameters of the peak signal-to-noise ratio (PSNR) have values above 42 dB, which is an indicator of good

Suggested Citation:

Mazin, M., & Onykienko, Yu. (2024). Analysis of image processing methods in the Internet of Things systems based on wavelet transformations. *Technologies and Engineering*, 25(6), 53-60. doi: 10.30857/2786-5371.2024.6.5.

*Corresponding author



image quality. However, the researchers examined images of sizes smaller than the quarterly video graphics array (QVGA) standard.

The study by Rohima & M.B. Akbar (2020) investigated the use of the Coiflet wavelet to compress images with a size of 256x256 pixels. The researchers compared the efficiency of using the Coiflet wavelet and compressed the image to 75% of the original with PSNR values close to 56 dB, which is an indicator of good quality. These indicators were obtained without using a microcontroller, which did not impose any restrictions when using the wavelet transform algorithm.

The efficiency of wavelet transform-based compression algorithms for use on the Raspberry Pi 3 Model B microcomputer (Raspberry Pi Foundation, UK) was investigated by M. Patlayenko *et al.* (2021). A method for optimising calculations for image reduction was proposed, and image compression was achieved by 18 times compared to the original. However, Raspberry Pi microcomputers have higher performance and belong to a different class of embedded systems.

O. Bychkov *et al.* (2019) created an algorithm that uses a transform wavelet for image processing and performed an analysis of human recognition after the transformation. The researchers performed the conversion using the Python programming language without using a microcontroller, which significantly expanded the resources for image processing.

The author of another study, A. Izmailov (2019), proposed a new approach to the wavelet transform algorithm. The efficiency of applying the transformation was evaluated, and a comparison with existing methods based on the standard root-mean-square error criterion was made. In turn, the use of a single method of mean square error (MSE) for evaluation has a number of limitations. For greater accuracy, several metrics should be used.

R. Odarchenko *et al.* (2021) used a transform wavelet to process audio signals for subsequent filtering and

compression. The conclusion of this paper is that this approach is adaptive and increases the efficiency of compression and filtering of speech signals. However, the researchers considered only speech signals, which are less complex structures than images.

V. Barannik *et al.* (2023) proposed a method for segmental video processing using a wavelet transform. It is noted that as a result, groups of values are represented by codes that occupy a smaller volume in bits, which indicates effective compression. The disadvantage should be considered demanding on computing resources, which is essential for use on microcontrollers.

The purpose of this study was to compare wavelet transformations such as Daubechies, Haar, and Coiflet when used as an additional image processing to the JPEG method in microcontroller systems.

Materials and Methods

Description of hardware and software for studying the efficiency of wavelet transformations in image compression. The ESP32-CAM camera development board (2020) (manufacturer Ai-Thinker, China) was used for image and video processing, due to the presence of a camera and additional RAM. This module was equipped with a dual-core Tensilica Xtensa LX6 processor (manufacturer Espressif Systems, China), operating at a frequency of up to 240 MHz, and had built-in Wi-Fi, which allows transferring data over the Internet without the need for additional devices. The microcontroller also had 4 MB of pseudostatic RAM (PSRAM), which was used for image processing, and 4 MB of flash memory for storing software. The 2-megapixel camera provided high-quality images for many tasks, such as object recognition or monitoring. The appearance of the ESP-CAM module with the camera connected is shown in Figure 1.



Figure 1. Appearance of the ESP32-CAM module with USB interface card

Source: ESP32-CAM camera development board (2020)

The experiment used wavelet transformations of Haar, Daubechies, and Coiflet to process images from the camera. The conversion was performed to reduce the image size after it was compressed to JPG format. To simplify the configuration and testing process, a web page was developed that was stored in the microcontroller's memory, which allowed quickly changing the number of iterations of the wavelet transform and adjusting the quality level of the compressed JPG file. For JPG image processing on the

ESP32 platform, the corresponding library by A. Daoui *et al.* (2024) was used.

The experiment process consisted of the following steps:

1. Image preparation: for the experiment, an image from a 320x240 pixel camera was used, which was processed using three wavelet transformations: Daubechies, Haar, and Coiflet.

2. Wavelet transform process: each image was decomposed into several levels using each of the wavelets. The

process used the high and low frequency coefficients for each type of wavelet transform, which are shown in Table 1.

3. Assessment of image quality: for each type of wavelet transform, quality metrics such as MSE, PSNR, structural similarity index measure (SSIM), and Euclidean distance were calculated. This helped to assess changes in the image structure and its perception by the human eye after image compression and restoration.

4. Estimation of the processing time of each image, considering the number of mathematical operations performed by the microcontroller.

5. Assessment of the compression level: for each wavelet transform method, the compression level was calculated, which was represented as the ratio of the volume of the original value to the one processed using the wavelet transform and compressed using JPEG.

6. Estimation of the difference between pixels for three wavelets: Haar, Daubechies, and Coiflet at the 2nd and 4th levels of decomposition on a scale from 0 to 1, where 0 – total pixel similarity for both images, and 1 – total pixel difference for both images. When running the algorithm, the colour value ranged from 0 to 255, where 0 – black and 255 – white.

7. Calculation of the number of arithmetic operations. The following equation was used for finding it:

$$NoAO = (h \cdot w) \cdot l \cdot c, \quad (1)$$

where h – image height (240 pixels), w – image width (320 pixels), l – decomposition level, c – number of coefficients used for the wavelet transform. During the experiment, the number of coefficients for Haar transform wavelets was 2, for Daubechies – 4, and for Coiflet – 6.

Results and Discussion

As a result of the experiment, images corresponding to different types of wavelet transformations at the 2nd and 4th levels of decomposition were obtained, which can be analysed and visible artefacts can be detected. Figure 2 shows the original 320x240 image obtained using the built-in camera of the ESP32-CAM module. Further, the image from the camera was processed using Haar, Daubechies, and Coiflet wavelet transformations of the 2nd level of decomposition. The conversion result is saved in JPEG format and shown in Figure 3. The original image was also processed by wavelet transformation of the 4th level of decomposition and saved in JPEG format. The saved images are shown in Figure 4.



Figure 2. Original image obtained from the ESP32-CAM module camera
Source: obtained by the authors using the ESP32-CAM module

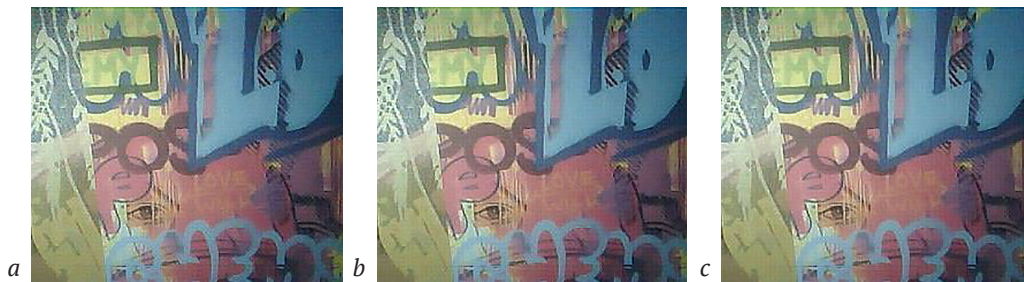


Figure 3. Image after 2nd-degree wavelet transform
Note: (a) – Haar, (b) – Daubechies, (c) – Coiflet
Source: obtained by the authors by processing the image algorithm with the ESP32-CAM module

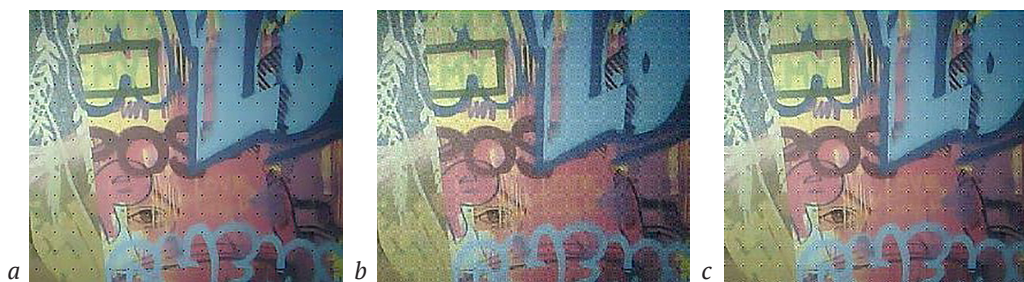


Figure 4. Image after 4th-degree wavelet transform
Note: (a) – Haar, (b) – Daubechies, (c) – Coiflet
Source: obtained by the authors by processing the image algorithm with a ESP32-CAM module

Analysis of experimental results. Table 1 shows the results of experiments for each of the wavelet transformations used, the level of decomposition, the value of image quality in the form of MSE, PSNR, SSIM coefficients, the time for which the transformation algorithm was performed, the level of image compression compared to the original, and the

number of arithmetic operations performed by the microcontroller during the execution of the wavelet transformation algorithm. The decomposition level is presented – this is the number of iterations or steps during which a signal (such as an image) is broken down into low-frequency and high-frequency components during a wavelet transform.

Table 1. Comparison of JPEG conversion results and JPEG + wavelet conversion results

DWT (Discrete Wavelet Transform)	Decomposition level	MSE	PSNR, dB	SSIM	Conversion time, ms	Compression level, times	Number of arithmetic operations, $(h * w) * l * c$
Haar	2	25.153	34.124	0.965	40	5.03	166,400
	4	73.449	29.470	0.921	84	11.11	332,800
Daubeshies4	2	25.274	34.103	0.965	96	5.31	665,600
	4	78.241	28.974	0.894	178	11.27	1,331,200
Coiflets1	2	25.144	34.126	0.965	105	5.21	998,400
	4	89.630	29.103	0.901	212	10.52	1,996,800

Source: developed by the authors based on the study by M. Mazin & Yu.O. Onykienko (2023)

Using the Haar wavelet transform for the image demonstrated high image quality at 2nd level with satisfactory MSE values (25.153) and high PSNR values (34.124) and SSIM values (0.965). However, at the 4th level, the quality significantly decreased (MSE – 73.840, PSNR – 29.470 dB), which indicates image deterioration with increasing decomposition levels. This may be due to the fact that the Haar wavelet has the simplest structure, which cannot preserve image details at high levels of decomposition. The processing time at the 2nd level (40 ms) is the lowest among all wavelets, which makes this wavelet efficient for fast processing, but at the 4th level the time increases to 84 ms. The compression ratio (11.22) at the 4th level shows a good compression ratio.

The Daubechies wavelet transform provided slightly worse MSE and PSNR values compared to the Haar transform at the 2nd level, but showed almost the same quality with a high SSIM (0.965). At the 4th level of decomposition, the quality significantly deteriorated (MSE – 78.241, PSNR – 28.974 dB), although the image still remains at an acceptable quality. The processing time was longer (96 MS at the 2nd level and 178 ms at the 4th level) due to the more complex wavelet structure expressed by more arithmetic operations. In particular, the number of operations for this wavelet is approximately 4 times the number of operations required to calculate the Haar wavelet. The Daubechies wavelet transform provided a better compression ratio (11.27) at the 4th level, which shows its ability to effectively reduce image size.

The Coiflet conversion provided better MSE and PSNR results for the 2nd level of decomposition, but at the 4th level, the quality of the restored image becomes less than that of Haar, but better than that of Daubechies. At the 4th level, the MSE is 89.630, indicating a significant loss of image quality, and the PSNR is better than Daubechies, but worse than Haar. However, at the 2nd level, the SSIM remained high (0.901), which indicates the preservation of structural

information. The processing time was the longest (212 ms at the 4th level), which is conditioned by the large number of coiflet wavelet coefficients (the number of arithmetic operations is 1.5 times greater than Daubechies, which was the largest value among all the studied wavelets). Although the compression ratio at the 4th level was also high (10.52), it should be noted that compression using the Coiflet wavelet had the lowest rate among all the wavelets under study.

H. Ding *et al.* (2021) demonstrated that a two-level real-time image transformation wavelet is compressed by 4 times compared to the original, which correlates with the results of an experiment where 5-fold compression is demonstrated. It is confirmed that the method is suitable for compressing large amounts of waveform data that are continuously recorded by the dynamic monitoring device of the power system in real time. However, the disadvantage of this operation is that the algorithm is not adaptable to the limited resources of the microcontroller.

The obtained PSNR values for the 2nd level of decomposition are almost identical (34.1 dB). In the study by A. Genta & D.K. Lobiyal (2018), PSNR values vary between (29-32 dB) depending on the image type. In the study of P. Mohindru *et al.* (2022), PSNR values differ and add up for the Haar (38 dB) and Daubechies (39.2 dB) transformations, respectively, due to differences in the sizes and types of images used. At the 2nd level of decomposition, artefacts are almost invisible for all wavelet transformations. There was a certain blocking of artefacts, the same for all transformations.

At the 4th level of decomposition, artefacts became more visible and manifested differently for each of the wavelet transformations. Regular dark dots were clearly visible for Haar transform. M. Mazin & Yu.O. Onykienko (2023) suggested that the appearance of artefacts is associated with the accumulation of errors during the calculation of the Haar transform. Such artefacts are caused by a small number of coefficients and their simple values.

This transformation is effective for fast processing, but processing loses a certain amount of information at each level of decomposition, which leads to the accumulation of errors. At the 4th level of the Daubechies wavelet transform, artefacts also appear, but they have a different appearance and are not as noticeable. This indicates the ability of the Daubechies wavelet transform to preserve both high-frequency and low-frequency image components. As confirmation, S. Gunanandhini *et al.* (2022) as a result of research, found that the Daubechies transformation provides higher video quality than the Haar transformation. The study by I. Yamnenko & V. Levchenko (2019), which used the Daubechies, Haar, and orthogonal basis wavelet transform, concluded that the use of the wavelet transform significantly improves the compression efficiency of video data, while maintaining high image quality and reducing the number of artefacts. Notably, the researchers performed video processing without using microcontrollers.

Artefacts at the 4th level of decomposition in the Coiflet wavelet transform are significantly more noticeable than when using the Daubechies wavelet transform. The reproduced image had the same quality as the image reproduced by Haar, although the artefacts were somewhat less pronounced. Despite the fact that the Coiflet wavelet had the largest number of coefficients used, which led to a large number of arithmetic operations (998,400 for 2 levels of decomposition, 1,996,800 for 4 levels of decomposition).

In the study by A. Thakker *et al.* (2022), PSNR values for the 2nd level decomposition of Haar transform varied from 32.8 to 35.4 dB, depending on the selected image. H.M. Al-Dabbas & F.M. Ghazi (2018) showed the PSNR values for the 4th level of decomposition of the Haar and Daubechies transformations, which vary depending on the image from 22.2 to 35.9 dB. Thus, the type of images used significantly affects the PSNR level for the 4th level of decomposition than for the 2nd level of the Haar and Daubechies wavelet transformations.

Based on the experimental results, it should be noted that the MSE, PSNR, and SSIM coefficients do not always adequately reflect the quality of images obtained after wavelet transformation by the three methods under study. In particular, high MSE values may indicate a significant

difference from the original image, while high PSNR and SSIM values indicate preservation of relatively high quality. This discrepancy was observed, for example, when using the Coiflet wavelet transform, where MSE indicates a loss of accuracy, but PSNR and SSIM showed acceptable visual image quality. These coefficients also showed the difference between the converted image and the original, but they do consider the influence of artefacts on the processed images that affect the final perception of the image by the user. N.M. Varma & A. Choudhary (2019) compared several metrics for evaluating images for similarity and identifying image artefacts. As a result of the comparison, the Euclidean distance method was the best method.

A. Schlamm & D. Messinger (2011) demonstrated that presenting images as Euclidean distances for further analysis can detect differences between distant points, localise this region, and detect anomalies. Based on this data, as well as the study by A. Sarkar & K.K. Halder (2021), several important conclusions were drawn. In this paper, the researchers showed that Euclidean distance shows a greater correlation with actual visual artefacts in the images. This is because it takes into consideration differences in each colour channel and highlights changes between pixels. This approach is especially important for processed images, which often contain complex artefacts. In this regard, it is proposed to use the maximum Euclidean distance between the pixel colours of two images of the same dimension. This method provides accurate distance calculation and efficient estimation of image artefacts.

$$dmax\left(\sqrt{(R'_{ij} - R_{ij})^2 + (G'_{ij} - G_{ij})^2 + (B'_{ij} - B_{ij})^2}\right)_{max}, (2)$$

where i and j – pixel position in width and length, R_{ij} , G_{ij} , B_{ij} – red, green, and blue colour values for the original image, R'_{ij} , G'_{ij} , B'_{ij} – red, green, and blue colour values for the restored image.

Table 2 shows the relative difference between pixels for three wavelets: Haar, Daubechies, and Coiflet at the 2nd and 4th levels of decomposition. The relative difference is estimated from 0 to 1, where 0 indicates the total similarity of pixels, and 1 indicates the maximum difference between them.

Table 2. Comparison of Euclidean distance results for different wavelet transformations

Method	Decomposition level	Relative difference
Haar	2	0.041
	4	0.537
Daubechies	2	0.029
	4	0.147
Coiflet	2	0.034
	4	0.355

Source: developed by the authors based on the study by M. Mazin & Yu.O. Onykiienko (2023)

As can be seen from Table 2 for the Haar wavelet transform, the relative difference increases from 0.041 at the 2nd level to 0.537 at the 4th level. For the Daubechies conversion,

this indicator is lower: 0.029 at the 2nd level and 0.147 at the 4th level. The Coiflet transform shows a relative difference of 0.034 at the 2nd level and 0.355 at the 4th level.

Thus, as the level of decomposition increases, the differences between pixels increase: the Haar wavelet transform shows the greatest differences, while the Daubechies wavelet transform shows the smallest. Moreover, as indicated by S. Zoican *et al.* (2019), the combination of a two-way filter and Wavelet transform implemented on Blackfin dual-core microcontrollers (Analog Devices, USA) can be effectively applied to remove real-time noise in medium-sized video clips.

Conclusions

The results of using the Haar wavelet transform demonstrated the fastest processing at the 2nd level of decomposition (40 ms), which makes it suitable for fast image transformations on devices with limited computing resources, such as microcontrollers. However, at the 4th level, image quality significantly decreased, which was reflected in the high MSE value (73.449) and the deterioration of SSIM (0.921). The maximum Euclidean distance between pixels, which was 0.537 for the 4th level of decomposition, indicates the presence of significant image artifacts, reflecting significant differences between the original and restored image at this level of transformation.

As a result of the experiment, the use of the Daubechies wavelet transform at 2nd level showed high image quality with PSNR (34.103 dB) and SSIM (0.965) values, which practically does not differ from the Haar results. However, it took longer to process due to the more complex structure (96 ms at 2nd level). At the 4th level, the quality deteriorated (MSE 78.241), but the compression ratio remained high (11.27), which shows its effectiveness in data compression. The maximum Euclidean distance at the 4th level of

decomposition, which was 0.147, indicates the least pronounced image artefacts compared to other transformations.

Using the Coiflet wavelet transform provided high quality at 2nd level (MSE 25.144, PSNR 34.126 dB), but at the 4th level, the MSE value (89.630) indicates a significant loss of image quality, although it is still better than that of Daubechies. The Coiflet wavelet transform required the most processing time (212 ms at the 4th level), since it has the most complex structure and the largest number of arithmetic operations. The maximum Euclidean distance for the 4th level (0.355) indicated moderate artefacts, but less pronounced than that of Haar.

Thus, considering the visual evaluation, it can be argued that the Daubechies wavelet transform provided the most acceptable image quality without additional processing. Haar wavelet is suitable for fast image processing, but its use at high levels of decomposition can lead to a significant loss of quality in the form of dark dots and requires additional post-processing. It follows that a promising area for continuing this research is to eliminate image noise using the ESP32 microcontroller, which is a more powerful version of the microcontroller used. In the future, it is necessary to focus on investigating the occurrence of artefacts during an increase in the number of iterations of the wavelet transform and developing effective methods for their elimination.

Acknowledgements

None.

Conflict of Interest

None.

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Аналіз методів обробки зображень в системах інтернету речей на основі вейвлет перетворень

Максим Мазін

Аспірант

Національний технічний університет України

«Київський політехнічний інститут імені Ігоря Сікорського»

03056, просп. Берестейський, 37, м. Київ, Україна

<https://orcid.org/0000-0001-9566-6662>

Юрій Оникієнко

Кандидат технічних наук, доцент

Національний технічний університет України

«Київський політехнічний інститут імені Ігоря Сікорського»

03056, просп. Берестейський, 37, м. Київ, Україна

<https://orcid.org/0000-0001-7508-8391>

Анотація. Збільшення ступеня стиснення зображень для скорочення часу їх передачі в сенсорних мережах на базі мікроконтролерів сприяє підвищенню загальної енергоефективності системи. Метою дослідження було вивчення ефективності застосування вейвлет перетворень Хаара, Добеші та Коіфлета для стиснення зображень на 32-бітних мікроконтролерах. Виконано експериментальне порівняння ефективності трьох типів вейвлет-перетворень для обробки зображень, отриманих з вбудованої камери, за метриками середньоквадратичної похибки, пікового відношення сигнал/шум, індексу структурної схожості та евклідової відстані. Реалізовано алгоритми вейвлет-перетворень Хаара, Добеші та Коіфлета на мікроконтролері ESP32. Отримані результати показали, що на другому рівні декомпозиції вейвлет Хаара забезпечив високу якість зображення (MSE 25.153, PSNR 34.124 дБ), але на четвертому рівні якість значно погіршується (MSE 73.449, PSNR 29.470 дБ). Вейвлет Добеші продемонстрував подібні результати, але на четвертому рівні його ефективність також знижується (MSE 78.241, PSNR 28.974 дБ). Вейвлет Коіфлет показав найгірші результати на четвертому рівні (MSE 89.630), проте на другому рівні його якість є конкурентною. Вперше було виконано порівняння трьох типів вейвлет-перетворень із застосуванням додаткової метрики – евклідової відстані, що дозволило краще оцінити артефакти та спотворення зображень. Запропонований підхід дозволив покращити ефективність стиснення та передачі зображень у системах Інтернету речей на мікроконтролерах, що забезпечує менший час передачі даних і, відповідно зменшення енергоспоживання, що є критично важливим для сенсорних мереж з автономним живленням

Ключові слова: Хаар; Добеші; Коіфлет; Peak Signal-to-Noise Ratio; structural similarity index measure; мікроконтролер ESP32



Enhanced impact strength of glyptal resin composites with red mud: A comparative study of incorporation methods

Liubov Melnyk*

PhD in Technical Sciences, Associate Professor

National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"

03056, 37 Beresteyskiy Ave., Kyiv, Ukraine

<https://orcid.org/0000-0001-5139-3105>

Abstract. The purpose of this study was to investigate the use of red mud, as a sustainable filler for glyptic resin composites and injection methods on their impact strength, as well as to optimise the properties of the composites and promote environmentally friendly use of materials. Glyptal resin was synthesised from glycerol and phthalic anhydride. Two methods of red mud introduction were employed: mechanical mixing and *in situ* synthesis. The concentration of red mud ranged within 7-56 wt%. The impact strength of the resulting composites was evaluated using standard tests. The study showed that red mud significantly increases the impact strength of composites based on glyptal resins. The *in situ* synthesis method provided the best results, with a maximum impact strength of 22.05 N-m at a red mud content of 36 wt%, which is 12.5% greater than that of mechanically mixed composites. The optimum filler concentration was determined at 36 wt%, with a sharp decrease in strength at greater concentrations due to particle agglomeration. In addition, the impact strength increased with increasing synthesis time, reaching its peak at 480 min for composites with 7 wt% red mud. This study provided new insights into the integration of red mud as a reinforcing filler in glyptic resins and highlighted the advantages of *in situ* synthesis in achieving better dispersion and matrix interaction, which contributes to the development of stable polymer composites. The findings demonstrated the possibility of using red mud, a complex industrial waste, in the production of high-performance polymer composites. The study offered practical recommendations for optimising the concentration of fillers and synthesis methods, which would contribute to the development of environmentally friendly and cost-effective materials for industrial applications

Keywords: polymer composites; mechanical properties; eco-friendly materials; *in situ* method; fillers

Introduction

The growing demand for high-performance composite materials in various industries necessitates the development of innovative solutions that ensure superior mechanical properties, economic feasibility, and environmental sustainability. Polymer composite materials (PCMs) with fillers derived from industrial waste products have emerged as a promising area in materials science. Among these, red mud (RM), a byproduct of the alumina production process, presents strong potential as a cost-effective and sustainable filler for polymer matrices, including glyptal resins.

RM, with its high alkalinity, poses major challenges in terms of disposal and environmental impact due to its large-scale production and limited recycling options. According to B. Swain *et al.* (2020), over 150 million tonnes

of RM are generated annually worldwide, with the majority being still untreated, leading to risks of soil and water contamination. Its rich chemical composition, including oxides of iron, aluminium, and silicon, opens promising opportunities for reuse in value-added products such as fillers for polymer composites (Prasad *et al.*, 2022).

The use of RM as a filler has not only solved environmental problems, but also greatly improved the mechanical and thermal properties of composite materials. According to P. Wu *et al.* (2023), the incorporation of RMs into polymer composites improved tribological properties such as wear resistance and friction coefficient, while reducing production costs and increasing the thermal stability of materials.

Suggested Citation:

Melnyk, L. (2024). Enhanced impact strength of glyptal resin composites with red mud: A comparative study of incorporation methods. *Technologies and Engineering*, 25(6), 61-68. doi: 10.30857/2786-5371.2024.6.6.

*Corresponding author



J. Chen *et al.* (2024) investigated the durability of high-performance composite materials based on RM, focusing on their resistance to chemical and physical factors. Their study demonstrated that modified RM considerably enhances the chemical resistance and mechanical wear resistance of composites, particularly in aggressive environments. However, the study did not address the effects of prolonged thermal cycling and humidity, which are critical for many practical applications. Future research should explore these aspects and improve RM modification methods to achieve more stable composite properties.

The modification of the RM played a crucial role in increasing its functionality. C. Ding *et al.* (2022) demonstrated that the use of chlorinated polyethylene as a coupling agent for RM surface treatment significantly improves the adhesion between the filler and the polymer matrix, thereby improving the mechanical properties of composites. The researchers attributed these findings to a reduction in interfacial defects caused by better adhesion and interaction between the composite components. Furthermore, the modification of RM with a titanate coupling agent and its subsequent incorporation into PVC to obtain composites showed a significant improvement in the thermal stability of the materials. The RM effectively neutralises HCl released during the thermal decomposition of PVC, delaying the onset of pyrolysis, and improving the overall properties of the composite. In addition, the high thermal resistance of RM helps to decelerate heat transfer, which further improves thermal stability.

P.K. Jena *et al.* (2022) synergistically modified epoxy resin with RM and vetiver fibres. Their findings suggested that increasing RM content in composites reduced the friction coefficient, specific wear rate, and wear loss, confirming that RM effectively enhances the wear resistance of epoxy resin-based composites.

Glyptal resins, known for their excellent adhesion, durability, and chemical resistance, are widely used in coatings, electrical insulation, and construction. Incorporating RM as a filler into glyptal resins improves their mechanical properties, particularly impact strength, while contributing to the recycling of industrial waste (Melnyk *et al.*, 2020).

Existing research on RM-based composites has predominantly focused on thermoplastics and thermosetting plastics, leaving glyptal resins understudied. J. Li *et al.* (2020) emphasised that the properties of such composites largely depend on the filler concentration and the method of its introduction. Chemical synthesis methods often provide better dispersion and interaction between the RM and the polymer matrix compared to mechanical mixing. Optimising these parameters is crucial to achieve a balance between mechanical properties and economic viability.

The purpose of this study was to investigate the effect of red mud concentration and incorporation methods on the impact strength of glyptic resin composites. Specifically, the study focused on determining the optimum

filler concentration and understanding how incorporation methods affect mechanical performance. To fulfil the purpose, the tasks were formulated as follows:

1. To evaluate the effects of the concentration of red mud (7-56 wt%) on the impact strength of composites based on glyptal resins.
2. To compare the effects of two incorporation methods – mechanical mixing and *in situ* synthesis – on the mechanical properties of composites.
3. To determine the optimum combination of filler concentration and synthesis method to maximise the impact strength of glyptal resin composites while ensuring economic and environmental feasibility.

Materials and Methods

The study used glyptal resin synthesised from glycerol and phthalic anhydride, following a standard procedure (Feng *et al.*, 2011). The initial weight ratio of glycerol to phthalic anhydride was maintained at 1:1.65, and the reaction was conducted at a constant temperature of 180°C in a reactor equipped with a mechanical stirrer and a thermometer to ensure uniform mixing and temperature control. The filler employed in the composites was red mud, sourced from the Zaporizhzhia Aluminium Plant (Ukraine), its characteristics were presented in the previous study (Melnyk *et al.*, 2020). To enhance its dispersion within the polymer matrix, the red mud was pretreated through ultrasonic grinding (Melnyk, 2023), reducing particle size, and improving its compatibility with the resin.

The composites were prepared using two different methods. The first method involved mechanical mixing, in which red mud at concentrations of 7, 15, 36, and 56 wt% was added to the pre-synthesised glyptal resin using a laboratory roll mill. This ensured uniform distribution of the filler in the resin matrix. The second method employed *in situ* synthesis, where red mud was pre-mixed with glycerol before adding phthalic anhydride. The polymerisation proceeded under the same conditions as described above. The *in situ* method was employed for red mud concentrations of 7, 15, 36, and 56 wt%. The synthesis process lasted 8 hours, during which aliquots were periodically taken for nuclear magnetic resonance spectroscopy (NMR) analysis to monitor the progression of the esterification reaction.

The NMR spectra obtained during the synthesis of glyptal resin, both in the absence and presence of red mud (7 wt%), provide valuable insights into the polymerisation reaction progress and the influence of the filler on the chemical transformation. The spectra were recorded at various time intervals: 30, 180, 305, and 480 min.

The prepared composites were applied as coatings on pre-cleaned glass, metal, or ceramic substrates using a brush. The coatings were left to cure at room temperature for 24 hours and subsequently subjected to thermal treatment at 60°C for 1-2 hours to ensure complete polymerisation and adhesion to the substrate.

The impact strength of the composite films was evaluated using the U-1A apparatus, manufactured by

NOVOTEST, Ukraine. The testing was conducted following the ASTM D2794-93 (2019) standard (Kholiavko & Vladymyrskiy, 2023). This method involved the instantaneous deformation of a coated metal plate under the free fall of a weighted striker. The apparatus included a base, stand, guide tube, pointer, stopper screw, release button, weight holding fixture, weight, striker with a ball, traverse, and anvil. During the test, the weight was raised to a predetermined height and secured with a stopper screw. The coated metal plate was placed on the anvil, ensuring that the impact area was at least 20 mm away from the edges or previously affected zones. By pressing the release button, the weight was allowed to fall freely, transferring the impact through the striker to the plate. The sample was inspected for cracks after each impact. If no cracks were observed, the height of the weight drop was increased incrementally by 5-10 cm, and the test was repeated until cracks appeared. The impact strength (W) was calculated as the product of the weight force (F) and the critical height (h), providing a quantitative measure of the material's resistance to impact deformation:

$$W = F \cdot h. \quad (1)$$

This methodology enabled a systematic evaluation of the impact resistance of glyptal resin composites, enabling a detailed comparison between the mechanical mixing and *in situ* synthesis methods.

Results

NMR Spectroscopic Analysis of the Research Objects' Synthesis

The study of the impact strength of composites based on glyptoplastics modified with red mud revealed major differences depending on the filler concentration and the

method of its introduction into the matrix. The study findings, visualised in Figures 1 and 2, provide a comprehensive view of the influence of these parameters on the mechanical characteristics of the composites, and their analysis helped to trace the esterification process and the role of red mud during synthesis.

For the synthesis without red mud (Fig. 1), the NMR spectra at 30 min revealed signals in the δ 12.75-14 region, corresponding to carboxylic acid protons. Signals at δ 5-5.7 (CHOOC) and δ 4-5 (CH₂OOC, CHOH) indicated the initial formation of ester bonds, reflecting the commencement of the acylation reaction between glycerol and phthalic anhydride. However, the persistence of carboxylic acid signals confirmed the incomplete nature of the esterification at this stage (Claridge, 2009). By 180 min, the intensity of the carboxylic acid signals decreased significantly, while the signals corresponding to ester groups (CH₂OOC, CHOH) became more prominent, suggesting that the esterification reaction was progressing. At 305 min, the carboxylic acid signals diminished further, and by 480 min, they were no longer detectable, indicating complete conversion of the starting materials into glyptal resin.

For the synthesis with 7 wt% red mud (Fig. 2), the spectra at 30 min showed comparable carboxylic acid signals; however, their intensity was slightly lower compared to the synthesis without red mud. This suggests that red mud, due to its basic properties, partially neutralised the carboxylic acid groups formed during the initial stages of the reaction. As the reaction progressed, the intensity of the carboxylic acid signals further declined, while the ester group signals became increasingly prominent. By 480 min, the spectra confirmed the complete disappearance of carboxylic acid protons and the dominance of ester signals, suggesting that the reaction had reached completion.

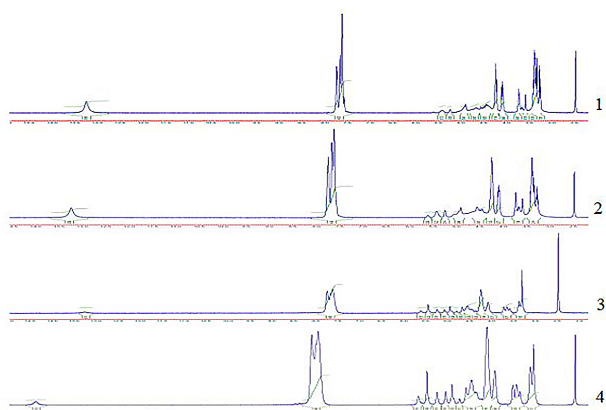


Figure 1. NMR spectra of aliquots taken during the synthesis of glyptal resin (without red mud) at various time intervals

Note: 1 – 30 min, 2 – 180 min, 3 – 305 min, 4 – 480 min. Signals indicate the progressive conversion of carboxylic acid groups (δ 12.75-14) into ester groups (δ 4-5 and δ 5-5.7)

Source: developed by the author of this study

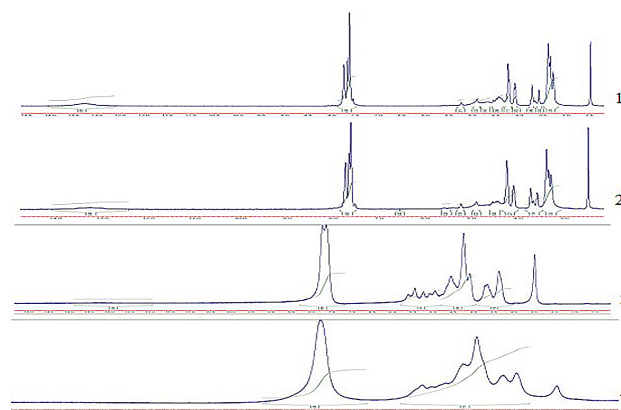


Figure 2. NMR spectra of aliquots taken during the synthesis of glyptal resin with 7 wt% red mud at various time intervals

Note: 1 – 30 min, 2 – 180 min, 3 – 305 min, 4 – 480 min. The reduced intensity of carboxylic acid signals (δ 12.75-14) at early stages reflects the interaction of red mud with the acidic intermediates

Source: developed by the author of this study

The presence of red mud was found to have a notable influence on the reaction kinetics. Specifically, the neutralising effect of red mud slightly reduced the intensity of carboxylic acid signals at earlier stages, suggesting an interaction between the filler and the acidic intermediates. Despite this, the overall progression and completion of the reaction were not hindered, as evidenced by the spectral similarity of the final products in both systems.

In conclusion, the analysis of NMR spectra demonstrated that the synthesis of glyptal resin proceeded effectively in the presence of red mud. While the filler interacted with the acidic intermediates, potentially altering the reaction pathway to a minor extent, it did not impede the overall reaction. These findings suggest that red mud not only serves as a filler but also may act as a mild catalyst or stabiliser during the polymerisation

process, contributing to the unique properties of the final composite materials.

Influence of synthesis time and incorporation method

Figure 3 presents the relationship between synthesis time and impact strength for glyptal resin composites with 7 wt% red mud. The composites prepared via *in situ* synthesis consistently demonstrated greater impact strength compared to those obtained through mechanical mixing. At 30 min, the impact strength of the *in situ* synthesised composite was 3.85% greater than that of the mechanically mixed composite, and this advantage increased to 9.13% by 305 min. This trend is attributed to the superior dispersion of the filler and stronger interfacial bonding achieved during chemical synthesis, which promotes the uniform distribution of red mud particles within the matrix.

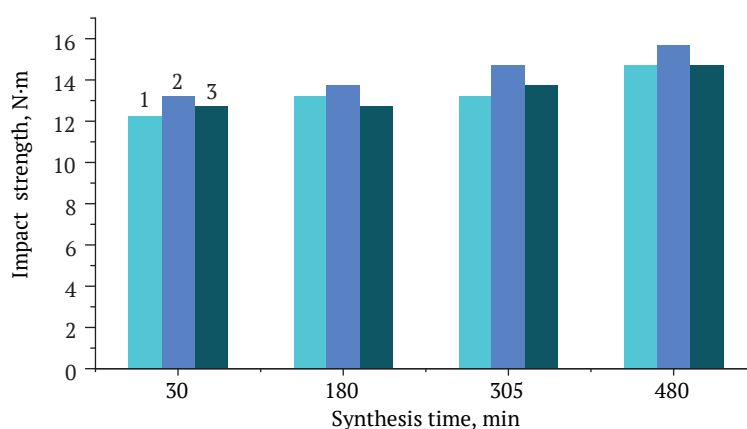


Figure 3. Impact strength of composites with 7 wt% red mud as a function of synthesis time

Note: 1 – pure glyptal resin, 2 – *in situ* synthesis (7 wt%), 3 – mechanical mixing (7 wt%)

Source: developed by the author of this study

Compared to pure glyptal resin, the composites synthesised *in situ* exhibited 6.67-10.78% higher impact strength across all synthesis times. This improvement highlighted the reinforcing effect of red mud as a filler, which enhanced the load distribution and impact resistance of the composite.

Influence of filler concentration

Figure 4 presents the impact strength of composites with varying concentrations of red mud, prepared by both methods.

For composites produced via *in situ* synthesis, the impact strength increased with filler concentration, reaching a maximum value of 22.05 N·m at 36 wt%. Beyond this concentration, a sharp decline in strength was observed, with the value dropping to 11.27 N·m at 56 wt%. An analogous trend was observed for mechanically mixed composites, with maximum impact strength of 19.6 N·m at 36 wt% and a decrease to 10.78 N·m at 56 wt%.

The decrease in impact strength at high filler concentrations can be attributed to agglomeration of red mud particles, which creates stress concentration points and weakens the material. This issue was more pronounced in

mechanically mixed composites, where the filler-matrix interaction was less effective, resulting in lower overall impact strength compared to the *in situ* synthesised composites.

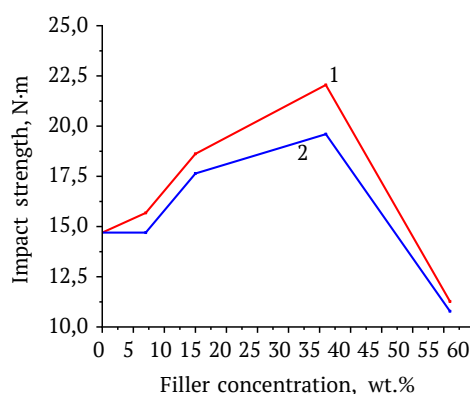


Figure 4. Impact strength of composites as a function of red mud concentration for *in situ* synthesis and mechanical mixing

Note: 1 – *in situ* synthesis, 2 – mechanical mixing

Source: developed by the author of this study

The *in situ* synthesis method consistently outperformed mechanical mixing in terms of impact strength, regardless of filler concentration. At the optimum concentration of 36 wt%, the impact strength of the *in situ* synthesised composite was 12.5% greater than that of the mechanically mixed composite. This superior performance is explained by the chemical incorporation of red mud into the polymer matrix during synthesis, which enhances filler dispersion and bonding at the molecular level.

These findings suggest that the inclusion of red mud as a filler not only improved the mechanical properties of the glyptic resin but also provided a sustainable solution for the disposal of industrial waste. The optimum filler concentration of 36 wt% ensured maximum reinforcement without compromising the integrity of the composite.

Discussion

The integration of red mud as a filler in glyptic resin composites was systematically studied, and its impact on mechanical properties, particularly impact strength, was analysed. The findings demonstrated a considerable enhancement in impact strength when red mud was incorporated, with a maximum value observed at 36 wt% filler concentration using the *in situ* synthesis method. This discussion contextualises these findings within the existing body of research and examines their implications for industrial applications.

A.C. Mârşolea (Cristea) *et al.* (2023) studied the development of polyurethane composites using industrial plastic waste, pyrite, and RM, finding that these fillers can increase the mechanical strength and thermal stability of composites by up to 25%, especially with preliminary chemical treatment. At the same time, the researchers noted that the long-term stability of such composites in aggressive environments is still unexplored, and the tests were limited to static loads without analysing dynamic properties, suggesting the need for further research to improve technologies. The greater impact strength values obtained by the *in situ* synthesis method (12.5% greater than mechanical mixing) confirmed the significance of chemical incorporation for effective filler dispersion and matrix interaction, consistent with previous studies.

The chemical bonds formed during the *in situ* synthesis improved the compatibility between filler and resin matrix, which was confirmed by both J. Chen *et al.* (2024) and the findings of the present study on the potential of red mud. Red mud can act not only as a filler but also as a reinforcing agent, improving mechanical properties through integration at the molecular level. J. Chen *et al.* (2024) additionally proposed combining RM with paper residues to create composites, which increased the crystallinity of polymers and their mechanical properties due to the effects of RM as a heterogeneous nucleator.

Additionally, the trend of declining impact strength beyond 36 wt% filler concentration caused by particle agglomeration mirrors observations by R. Prasad *et al.* (2022), who highlighted analogous challenges in achieving

optimum dispersion in red mud-based composites. This phenomenon underscores the critical role of processing techniques and the necessity of fine-tuning filler concentrations to maximise composite performance. The ultrasonic pretreatment of red mud employed in this study proved effective in mitigating, albeit not entirely eliminating, the agglomeration effects.

J. Liu *et al.* (2018) developed ethylene-vinyl acetate-based composites (ELDHS-SDS-KH) using HCl-modified RM as a flame-retardant filler. Their findings revealed that these modified composites not only emitted fewer harmful substances during combustion but also exhibited improved thermal stability compared to unmodified samples.

L. Qiu *et al.* (2020) proposed another innovative approach, working with RM/phenolic foam composites. The researchers investigated the effects of silane coupling agents and RM on the thermal properties of these materials. Their findings revealed that adding an optimised amount of modified RM increases the limiting oxygen index and greatly enhances the thermal stability of the composites. Y. Wang *et al.* (2021) highlighted the synergistic effects arising from combining RM with other industrial wastes, such as fly ash. Their study confirmed that such combinations improve the interfacial properties of composites, enhancing their overall mechanical strength.

Another group of researchers focused on developing hybrid polymer materials using RM and fibres. A.K. Sinha *et al.* (2021) synthesised an epoxy composite with RM and abaca fibres. By employing the response surface methodology, the researchers demonstrated that optimising RM particle size and fibre concentration considerably improves the wear resistance and mechanical properties of the composite.

S. Nayak & A. Satapathy (2020) examined the effects of RM on bamboo fibres modified for use in polymer composites. Their findings showed that these materials exhibited enhanced tensile strength, flexural strength, and impact resistance, demonstrating their potential for applications in construction and industry. S. Vigneshwaran *et al.* (2020) also explored the potential of RM combined with coconut sheath fibres. The researchers found that silane-treated fibres combined with 20% RM greatly improved the mechanical properties of composites, such as tensile strength, flexural strength, and impact resistance. However, increasing RM content to 30% led to particle agglomeration, negatively affecting material properties.

O. Çimen & H.I. Günaydın (2024) focused their efforts on developing geosynthetic barrier materials using RM and polysulfone (PSU). Through the phase inversion method, the researchers successfully integrated RM into the polysulfone matrix, greatly improving the material's tensile strength. Using SEM, AFM, XRD, and TGA techniques, the researchers confirmed the effective dispersion of RM within the matrix and enhancements in its mechanical and thermal properties. However, the researchers also noted that the long-term stability of these materials under variable environmental conditions was still

unexplored, paving the way for further research. This underscored the significance of RM in creating sustainable construction materials.

J. Liu *et al.* (2020) synthesised a composite material based on RM and polyacrylic acid (RM/PAA) using a graft polymerisation method in a reverse-phase suspension system. This material demonstrated excellent adsorption properties, achieving a maximum adsorption capacity for Cd(II) ions at 96.15 mg/g.

The increase in impact strength with synthesis time, peaking at 480 min for composites with 7 wt% red mud, further supports the hypothesis that extended reaction times enhance the uniformity of filler dispersion and promote stronger matrix-filler interactions. This observation is consistent with findings of L. Qiu *et al.* (2020), who reported improved mechanical properties in composites subjected to prolonged synthesis durations. Notably, the basic properties of red mud appeared to neutralise acidic intermediates during polymerisation, possibly acting as a mild catalyst, as suggested by the NMR spectral analysis.

Comparing these findings with studies on other polymer matrices, such as the research by S. Vigneshwaran *et al.* (2020) on coconut fibre-reinforced composites, revealed both similarities and distinctions. While both studies emphasised the reinforcing effects of fillers, the chemical composition and surface characteristics of red mud uniquely influence its interaction with glyptal resin, resulting in distinct mechanical property enhancements.

From a practical perspective, the optimum filler concentration of 36 wt% identified in the present study provides a valuable guideline for industrial applications, balancing mechanical performance with material integrity. Being a challenging industrial waste, the use of red mud in glyptal resin composites not only addresses environmental concerns but also offers an economically viable alternative to conventional fillers.

However, some limitations persist. The long-term stability of these composites under environmental stressors, such as temperature fluctuations and moisture exposure, warrants further investigation. Additionally, upscaling the *in situ* synthesis method for industrial production poses challenges that must be addressed.

In conclusion, the present study contributed to the growing body of knowledge on sustainable composite materials by demonstrating the feasibility and advantages of red mud as a filler in glyptal resins. The findings highlighted the need for continued research into optimising synthesis methods and exploring other applications of these eco-friendly composites.

Conclusions

The study demonstrated a significant influence of red mud concentration and methods of its incorporation on the impact strength of glyptal resin composites. The obtained findings confirmed that the set objectives were successfully achieved, and the purpose of this study was fulfilled. Evaluating the effects of filler concentration on the mechanical properties of the developed composites revealed that the addition of red mud greatly improves impact strength. Its maximum values were achieved at a filler concentration of 36 wt% and amounted to 22.05 N-m. Increasing the red mud concentration beyond this value led to a decrease in strength due to particle agglomeration, which created localised stresses in the matrix.

Comparing the methods of red mud incorporation into glyptal resin revealed that resins filled during *in situ* synthesis demonstrated superior mechanical properties compared to those obtained through mechanical mixing, providing a 12.5% increase in impact strength. This suggests a more uniform distribution of filler particles in the matrix and better interaction at the molecular level.

The duration of synthesis also significantly affected the completion of the process and, consequently, the improvement of the mechanical properties of the resulting coatings. It was established that maximum impact strength values were achieved at a synthesis duration of 480 min, particularly for composites with a low filler concentration (7 wt%). The obtained findings confirmed the prospects of using red mud as a reinforcing filler for polymer composites. The optimum combination of filler concentration (36 wt%) and the method of incorporation ensure the creation of materials with enhanced impact strength, opening new opportunities for their application in construction, electrical engineering, and other industrial sectors.

The practical significance of this study lies in addressing the environmental problem of red mud disposal, allowing for a reduction in industrial waste volumes and the creation of cost-effective materials with improved mechanical properties. Further research may focus on expanding the use of other industrial wastes as fillers, optimising the synthesis process to improve energy efficiency, and exploring the application possibilities of the developed materials in various industrial fields.

Acknowledgements

None.

Conflict of Interest

None.

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Підвищена ударна міцність композитів із гліфталевої смоли з червоним шламом: порівняльне дослідження методів введення

Любов Мельник

Кандидат технічних наук, доцент
Національний технічний університет України
«Київський політехнічний інститут імені Ігоря Сікорського»
03056, просп. Берестейський, 37, м. Київ, Україна
<https://orcid.org/0000-0001-5139-3105>

Анотація. Метою цього дослідження було вивчити використання червоного шламу як екологічно безпечного наповнювача для композитів на основі гліфталевої смоли та методів його введення, а також оптимізувати властивості композитів і сприяти екологічно раціональному використанню матеріалів. Гліфталева смола була синтезована з гліцерину та фталевого ангідриду. Було застосовано два методи введення червоного шламу: механічне змішування та синтез *in situ*. Концентрація червоного шламу варіювалася від 7 до 56 мас. %. Ударну міцність отриманих композитів оцінювали за допомогою стандартизованих тестів. Дослідження показало, що червоний шлам значно підвищує ударну міцність композитів на основі гліфталевої смоли. Метод синтезу *in situ* забезпечив найкращі результати, досягаючи максимальної ударної міцності 22,05 Н·м за концентрації червоного шламу 36 мас. %, що на 12,5 % перевищувало значення для композитів, отриманих механічним змішуванням. Оптимальна концентрація наповнювача була визначена як 36 мас. %, тоді як при вищих концентраціях спостерігалось різке зниження міцності через агломерацію частинок. Крім того, ударна міцність збільшувалася зі зростанням тривалості синтезу, досягаючи свого максимуму на 480 хв для композитів із 7 мас. % червоного шламу. Це дослідження надало нову інформацію про інтеграцію червоного шламу як армуючого наповнювача в гліфталеві смоли та підкреслило переваги синтезу *in situ* у досягненні кращої дисперсії та взаємодії з матрицею, що сприяє розробці стабільних полімерних композитів. Результати демонструють можливість використання червоного шламу, складного промислового відходу, у виробництві високопродуктивних полімерних композитів. Дослідження пропонує практичні рекомендації щодо оптимізації концентрації наповнювачів і методів синтезу, що сприятиме розробці екологічно чистих і економічно вигідних матеріалів для промислового використання.

Ключові слова: полімерні композити; механічні властивості; екологічні матеріали; метод *in situ*; наповнювачі



Simulation of the operation of a voltage inverter as part of an autonomous wind power plant with aerodynamic multiplication based on an asynchronous generator with a phase rotor

Hlib Strunkin*

Master

Engineering Institute of Zaporizhzhia National University

69006, 226 Sobornyi Ave., Zaporizhzhya, Ukraine

<https://orcid.org/0009-0009-1719-4132>

Abstract. In the context of energy scarcity caused by the destruction of energy infrastructure, instability of electricity supply and growing demand for autonomous energy sources, there is a need to develop independent and efficient energy supply systems. Of particular importance are wind power plants that are able to function independently, ensuring the stability of power supply even in crisis conditions. In this regard, it is important to investigate promising solutions that meet modern quality standards and can integrate into autonomous energy systems. The purpose of the study was to confirm the efficiency of calculating inverter filters in static and dynamic modes, and under unbalanced load conditions. This was achieved on the basis of simulation modelling of an autonomous wind power plant with aerodynamic multiplication operating on the basis of an asynchronous generator with a phase rotor and excitation from a voltage inverter. A simulation model of an autonomous wind power plant and inverter parameters calculated according to the author's methods in the PSIM environment were described. A Fourier analysis of the harmonic composition of the output voltage of the inverter was performed programmatically, and its harmonic coefficient, which did not exceed 5%, was calculated in accordance with the current standard. It was proved that the excitation from the voltage inverter improves its operation under unbalanced load and release and surge. The results of modelling the output voltage of the inverter were compared with the requirements of standards for continuous power sources. Based on the results of simulation modelling of an autonomous wind power plant with aerodynamic multiplication, the efficiency of calculating voltage inverter filters for an asynchronous generator with a phase rotor was confirmed. The methods have shown their effectiveness both in static and dynamic modes, and under conditions of unbalanced load

Keywords: stand-alone voltage inverter; load release and surge; unbalanced load; harmonic ratio; simulation

Introduction

The modern energy sector is in a state of rapid change and faces a number of challenges, including military operations, rising energy prices, and difficulties of their transportation. In these circumstances, the development of renewable energy sources is not only important, but also critically necessary. Wind power, as one of the most promising industries, offers efficient solutions for autonomous energy supply. In particular, autonomous wind power plants (WPPs) are becoming increasingly relevant, given their ability to operate independently of centralised systems.

The Ukrainian energy sector is facing new challenges related to military operations, the cost of energy carriers and the complexity of their delivery. As reported by the Prime Minister of Ukraine D. Shmyhal (2024), "The number one issue is energy." In his speech, he stressed that the greatest attention should be paid to the development of alternative and renewable energy. In remote farms, according to A. Konechenkov *et al.* (2022) the use of wind energy through autonomous wind power plants (WPPs) may be promising.

Suggested Citation:

Strunkin, H. (2024). Simulation of the operation of a voltage inverter as part of an autonomous wind power plant with aerodynamic multiplication based on an asynchronous generator with a phase rotor. *Technologies and Engineering*, 25(6), 69-79. doi: 10.30857/2786-5371.2024.6.7.

*Corresponding author



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O.V. Nemykina (2020) focused on the development of multiplier-free circuits for wind power plants. The author noted that the use of such circuits can reduce energy losses during the transmission of mechanical power, while reducing the level of wear of components. However, the researcher pointed out the need for a more detailed study of the durability of materials used in such systems, especially in autonomous operation. C. Anderson (2020) analysed the efficiency of direct-drive WPPs compared to conventional models. He noted that this design reduces technical losses and increases the stability of installations under variable weather conditions. However, the researcher noted the problem of insufficient consideration of the specifics of autonomous conditions, in particular, the impact of wind flow instability on energy generation.

Ukrainian researcher V.V. Klymenko *et al.* (2023) investigated the possibilities of integrating aeromechanical equipment into the design of autonomous WPPs. He stressed that the use of such solutions can significantly increase the capacity of installations. However, the study did not cover modelling the operation of wind turbines under non-standard conditions, which creates a gap in the development of autonomous systems. R. Ranjan *et al.* (2023) investigated the environmental aspects of wind turbine use. They noted that the introduction of new technologies to reduce oil leaks can significantly reduce the negative impact on the environment. Moreover, the researchers acknowledged that further research should focus on integrating environmentally friendly solutions into the design of autonomous WPPs.

Ukrainian researchers P. Olczak & T. Surma (2023) considered modern approaches to improving the element base of wind power plants. They noted that the development of new materials and technologies allowed reaching the capacity of autonomous WPPs up to 1,000 MW, but stressed the need for a detailed study of the reliability of these systems during long-term operation.

J. Paul *et al.* (2018) analysed the problems of reducing the noise impact of wind turbines. The authors noted that noise reduction is an important aspect for the use of stand-alone wind turbines in residential areas. However, the researchers emphasised the lack of a comprehensive approach to assessing acoustic characteristics in relation to the efficiency of electricity generation. M.S. Golubenko *et al.* (2008) considered the prospects of using aerodynamic multiplication (AM) in wind power systems of WPPs. The author pointed out the significant potential of this technology to increase the capacity of installations, but noted that its application in autonomous systems requires additional research.

In the UK, teams led by P. Jamieson (2020) and L. Morgan *et al.* (2022; 2024) conducted a study of wind turbines with a vertical axis of rotation, emphasising their advantages in urban environments. However, according to the researchers, these installations have limited potential for autonomous systems due to their low stability in variable wind conditions.

The purpose of this study was to perform calculations and modelling of autonomous wind power plants with aerodynamic multiplication to confirm their compliance with the requirements of standards for uninterruptible power supplies, which apply to such systems at the design stage.

Materials and Methods

To achieve this purpose, the paper used simulation modelling methods in the PSIM (2021) environment, which was designed for modelling power electronics devices, electro-mechanical systems, alternative energy facilities, power sources, etc. The parameters for the simulation model were calculated using the methodology developed by the author under the guidance of A.V. Pereverzev *et al.* (2006; 2007) for selecting the elements of input and output filters and setting up the automatic control system. Due to the fact that the simulation results were obtained in the form of dynamic characteristics of controlled parameters, statistical processing of the obtained data was not provided. Fourier analysis of the PSIM software suite was used to investigate the harmonic composition of the output voltage. The study was carried out at the Pluton IC LLC (Zaporizhzhia), where the developed methods for calculating inverter filters and the built mathematical model were used. These methods were implemented when creating a guaranteed power supply system for SGE-50-380-2-1-30-UHL4, which was confirmed by the relevant implementation report.

A special feature of WPPs with ADM was the installation of small high-speed secondary wind turbines on the blades of a large primary wind turbine (Fig. 1), which, rotating under the action of the primary wind flow, created a secondary wind flow of significant speed for secondary wind turbines. This allowed the secondary wind turbine to drive the generators without using a multiplier.

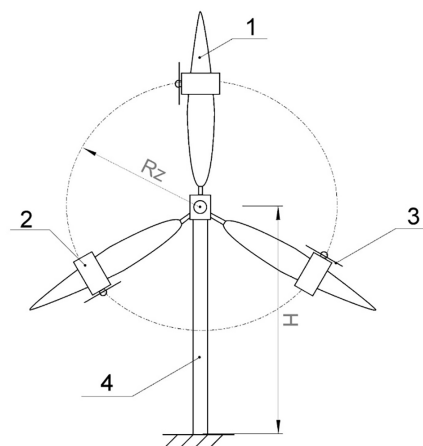


Figure 1. Diagram of a wind turbine with ADM
Note: 1 – blades of the primary wind turbine; 2 – nacelle with generator and electrical equipment; 3 – secondary wind turbines; 4 – support; R_z – radius of fixing the secondary wind turbine; H – height of the axis of the primary wind turbine
Source: developed by the author based on M.S. Golubenko *et al.* (2008)

One of the possible approaches to controlling the power of such a wind turbine was to install a frequency converter (FC) in the generator circuit. With the use of asynchronous phase rotor generators (APRG), the installed power of such an FCF can be reduced as indicated by G. Abadi *et al.* (2011). Figure 2 shows a block diagram of an autonomous WPP with ADM based on APRG.

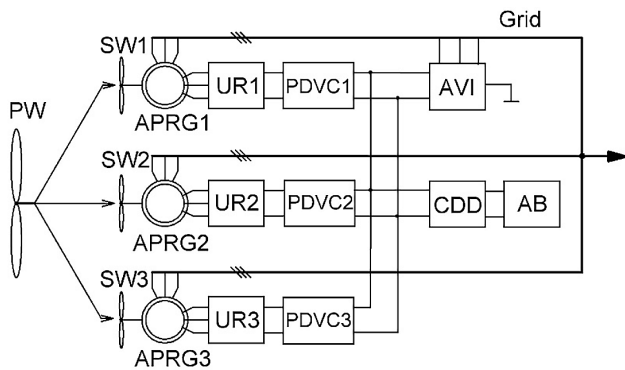


Figure 2. Diagram of an autonomous WPP with ADM based on APRG

Note: PW – primary wind turbine, SW1...SW3 – secondary wind turbines, APRG1...APRG3 – asynchronous phase rotor generators, UR1...UR3 – uncontrolled rectifiers, PDVC1...PDVC3 – pulsed DC voltage converters, AB – battery, CDD – charging and discharging device, AVI – autonomous voltage inverter
Source: developed by the author

In the presence of wind, the primary wind turbine created a wind flow for secondary wind turbines SW1...SW3, which were located on the PW blades, which, in turn, rotated asynchronous generators with a phase rotor APRG1...APRG3. Energy was removed both from the stator side of each generator and from the rotor side (sliding energy) through an individual uncontrolled rectifier UR1...UR3. When the wind speed exceeded the rated speed, or there was a local speed imbalance, it was possible to reduce the moment by adjusting the counter-EMF of the pulsed DC voltage converter PDVC1...PDVC3, which was the load of uncontrolled rectifiers. Sliding energy was also used to recharge the AB battery. The AB charging current was formed by the CDD charging and discharging device. The autonomous voltage inverter AVI formed a network and compensated for the reactive power of the generators. In the event of wind start-up or absence, the necessary energy was provided by the AB.

The parameters for the simulation model were calculated for the power of an autonomous WPP with ADM of 750 kW at a rated primary wind flow rate of 11 m/s, which was similar to the existing TG-750 wind turbine built by M.S. Golubenko *et al.* (2008). The parameters of the input, output filters, and control system of the inverter are calculated according to the author's method (Pereverzev *et al.*, 2006; 2007) to check the adequacy of the operation of an electromechanical system of an autonomous WPP with ADM based on an asynchronous generator with a

phase rotor excited by a voltage inverter. According to Figure 2, the simulation model was divided into its component parts: a model of a wind turbine with an ADM, 3 asynchronous generators with a phase rotor, 3 unman- aged rectifiers, 3 pulsed DC voltage converters, a charging and discharging device, an autonomous voltage and load inverter. Due to the use of the MTH-713-10 crane engine manufactured by Sealocan (China) as a generator, the phase voltage of the network was reduced within the standard (minus 15% of the rated value) to 192V to reduce the magnetisation current.

Results and Discussion

The simulation model, as described earlier, is divided into its component parts. The construction and parameters of these components are described in more detail below.

1. Stand-alone voltage inverter.

The transistors of the inverter are assembled in a three-phase bridge circuit with a zero wire, which is connected to the midpoint of the input capacitance. Bridge (Fig. 3) was modelled using 6 bipolar transistors with an insulated-gate bipolar transistor (IGBT), the parameters of which include the values of saturation voltage – 1.5 V and dynamic resistance – 1 mOhm, and, respectively, 0.7 V and 1 mOhm – for the reverse diode.

The input filter is constructed using a capacitive divider with a total capacity of 40 mF. Each divider capacitor is shunted by a 10 kOhm discharge resistor. Each phase of the inverter had an L-shaped LC filter with an inductance of 0.14 mH and a capacitor of 460 uF. The output filter capacitor is also shunted by a 10 kOhm discharge resistor. The AVI had a current sensor with a factor of 1/1,500 and a voltage sensor with a factor of 1/310 in each phase. At the output of each sensor, a low-pass filter with a cutoff frequency of 100 Hz is turned on to filter interference.

The inverter control system is built in the form of a sub-circuit (Fig. 4) and was a dual-circuit subordinate automatic control system. Internal circuit – current with PI regulator (proportional part – 10, integral part – 0.33 ms). External circuit – by voltage with a PI regulator (proportional part – 2, integral part – 5 ms). The problem is a sinusoid with a corresponding angle for each phase (0, 120, and 240 degrees).

From the output of the current regulator, the signal was sent to the PWM pulse-width modulation unit, which is implemented on comparators. PWM was obtained by comparing the signal from the regulator with a sawtooth signal with a frequency of 3 kHz. The control signal for the lower transistor of the rack is obtained by inverting the control signal for the upper transistor.

2. Description of the model of an asynchronous generator with a phase rotor.

A standard model of an asynchronous machine with a phase rotor from the PSIM model library was used for modelling. In the window for entering APRG parameters, the parameters of the MTH-713-10 crane engine replacement scheme are entered.

3. Description of the model of WPP with ADM

The WPP with ADM model proposed by D.G. Alekseevskiy (2020) was used for simulation modelling.

Figure 5 shows a model of a primary wind turbine and a single channel of aerodynamic multiplication of a secondary wind turbine.

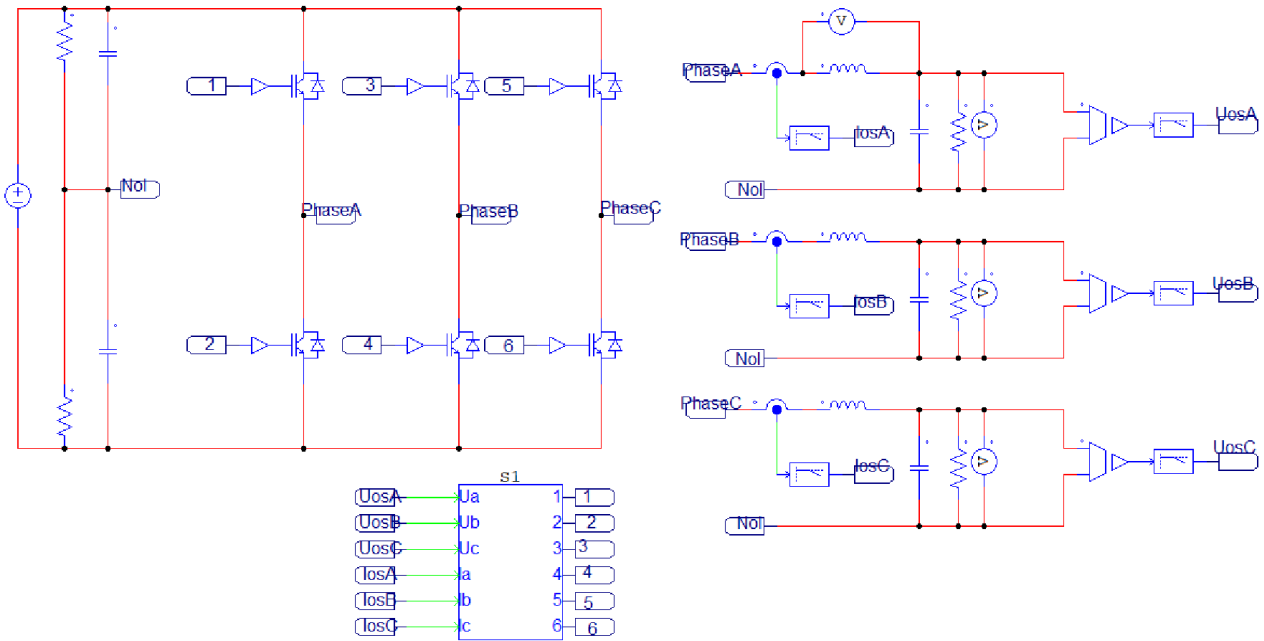


Figure 3. Stand-alone voltage inverter model

Source: developed by the author

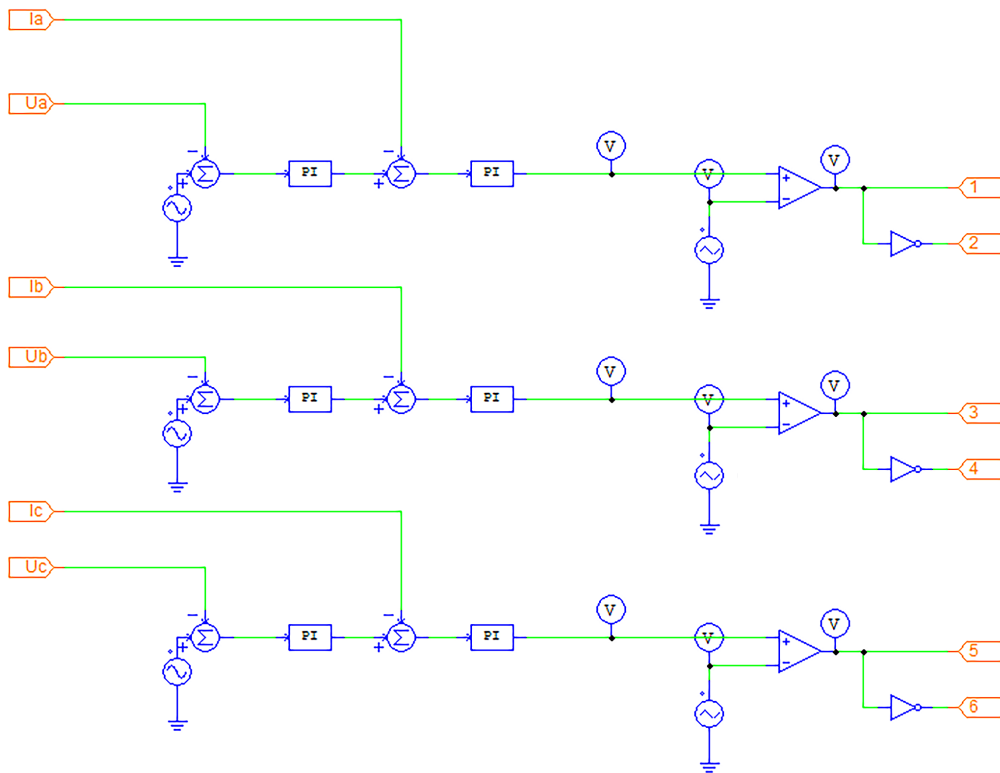


Figure 4. AVI management system model

Note: Ia, Ib, Ic – input terminals of current feedback signals; Ua, Ub, Uc – input terminals of voltage feedback signals; Pi – proportional-integral regulator; 1...6 – output terminals of IGBT control signals

Source: developed by the author

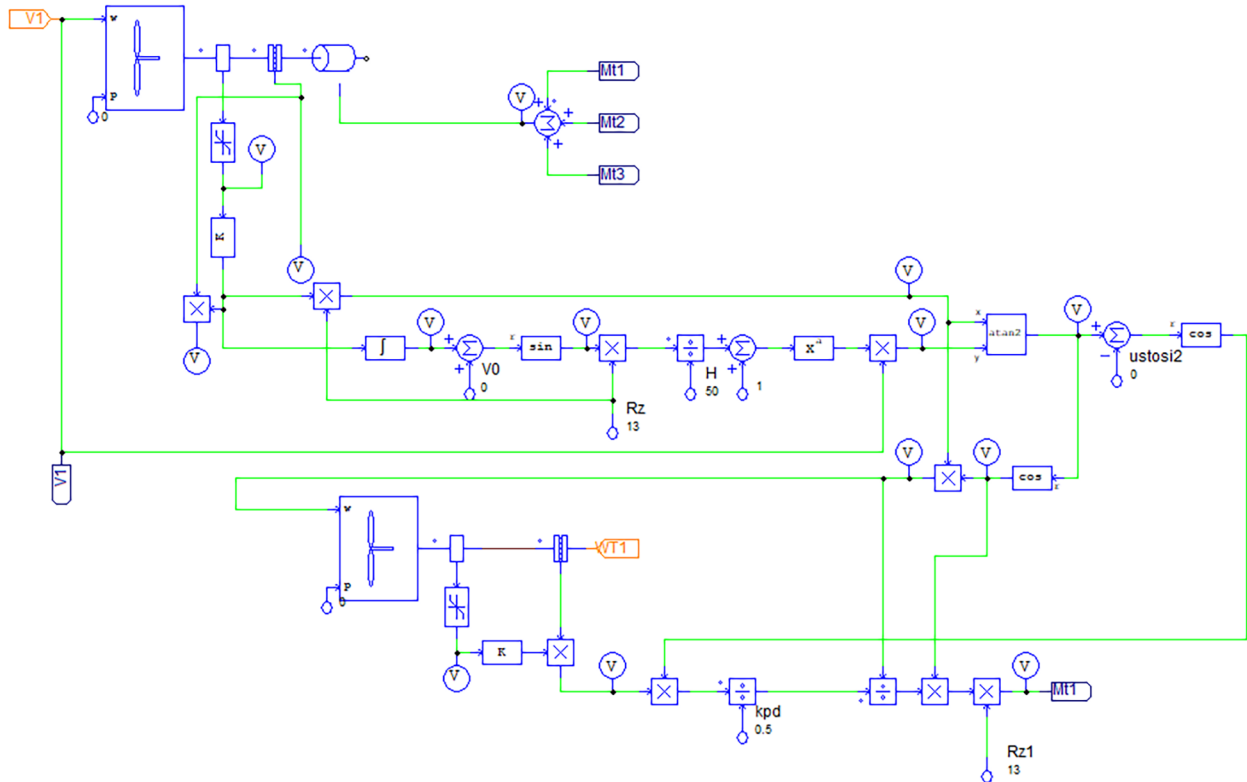


Figure 5. Model of WPP with ADM

Note: V1 – input terminal and communication of the primary wind flow velocity signal; Mt1...Mt3 – communication by moments of secondary wind turbines; wt1 – output terminal of the signal of the angular velocity of rotation of the secondary wind turbine
Source: developed by the author based on D.G. Alekseevskiy (2020)

Standard wind wheel models from the PSIM library are used to model primary and secondary wind turbines. The parameters of the models were calculated using a similar wind turbine – TG-750 developed by M.S. Golubenko *et al.* (2008). The primary turbine had a rated power of 750 kW with a primary wind flow rate of 11 m/s and a rated rotation speed of 16 rpm. The secondary wind turbine had a rated power of 250 kW at a secondary wind flow rate of 21 m/s and a rated rotation speed of 1,200 rpm, which corresponded to the sliding of the APRG $s = -1$.

The speed of the primary wind flow was set to the input pin V1. Torque and angular velocity sensors are installed on the wind turbine shaft, after multiplying the signals from which power is obtained. Further, the path from the integrator to the arctangens input implemented a block for calculating the dependence of the wind flow rate on the position of the primary wind turbine blade. The resulting value, considering the angle of installation of the secondary wind turbine axis, is used as the secondary wind flow. The output contact from the secondary wind turbine is WT1, which is connected to the generator axis. The calculated power value of the secondary wind turbine allows estimating the braking moment of the secondary wind turbine. The value of the braking moment of all secondary wind turbines MT1, MT2, MT3 is algebraically summed with the moment of the primary wind turbine.

4. Model description of unmanaged rectifier and pulsed DC voltage converter.

Figure 6 shows the APRG and its rotary circuit consisting of an uncontrolled rectifier and a pulsed DC voltage converter of the step-up type. The unmanaged rectifier represents a three-phase diode bridge rectifier. The PDVC is constructed using an IGBT model similar to that used in the AVI. The cumulative inductance was 0.4 mH. The PDVC output is connected to the AVI input. To set the angular velocity on the APRG shaft, a single-circuit automatic control system with a PI regulator is constructed (proportional part – 1, integral part – 10 ms). The angular velocity control task was applied after calculating the optimal value (Kumar & Chatterjee, 2016). The output of the angular velocity controller is connected to a PWM unit with a switching frequency of 1 kHz.

A three-phase wattmeter is installed in the rotary and stator circuits to measure active power.

5. Description of the charger and battery model.

Considering that the task of the CDD, in addition to ensuring the appropriate operation of the battery, to stabilise the voltage in the DC link (on the input filter of the AVI), it is modelled as an EMF source of 610 V with an internal resistance of 1 mOhm, corresponding to the external characteristic of a pulsed DC voltage converter. This approach was considered appropriate, considering that the PDVC as part of the CDD is covered by feedback on the voltage of

the DC link. To monitor the energy that the CDD gave or consumed, a wattmeter is installed to measure the active power. The AB charge corresponded to a positive power value, and the discharge – to a negative one.

The operation of the AVI in steady-state mode is modelled, when the primary wind flow speed was 11 m/s, and the load power was 750 kW. The shape of the output voltage is observed, which is shown in (Fig. 7).

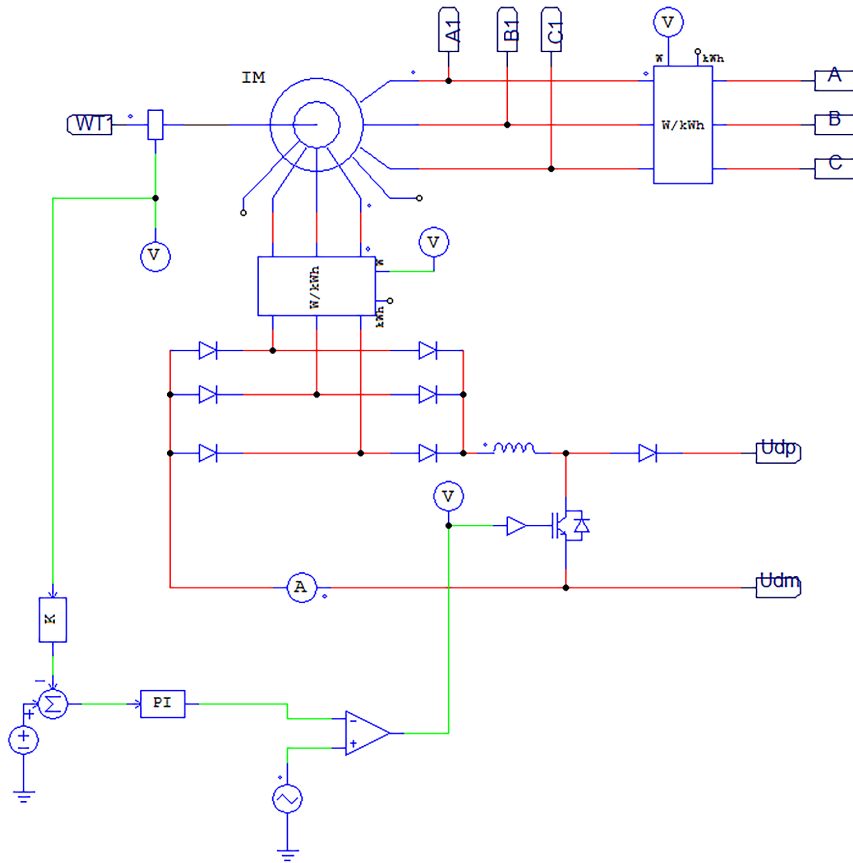


Figure 6. Model of AVR and its rotary chain

Note: wt1 – output terminal of the secondary wind turbine angular velocity signal; Udm, Udp – terminals “+” and “-” of the DC circuit; A1, B1, C1 – mains voltage connections

Source: developed by the author

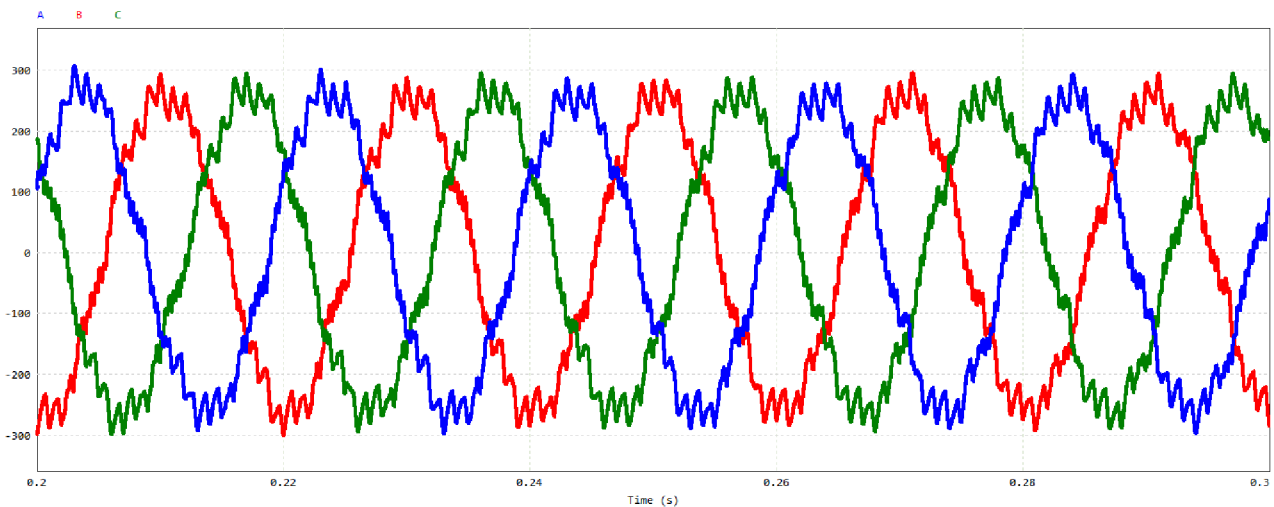


Figure 7. Results of modelling the shape of the output voltage of the AVR in steady-state mode

Source: developed by the author

Thus, the output voltage is characterised by a relatively high degree of symmetry between the phases. To estimate the high-frequency component, a harmonic analysis

was performed, the results of which are shown in Figure 8 and the harmonic coefficient of the inverter voltage was calculated.

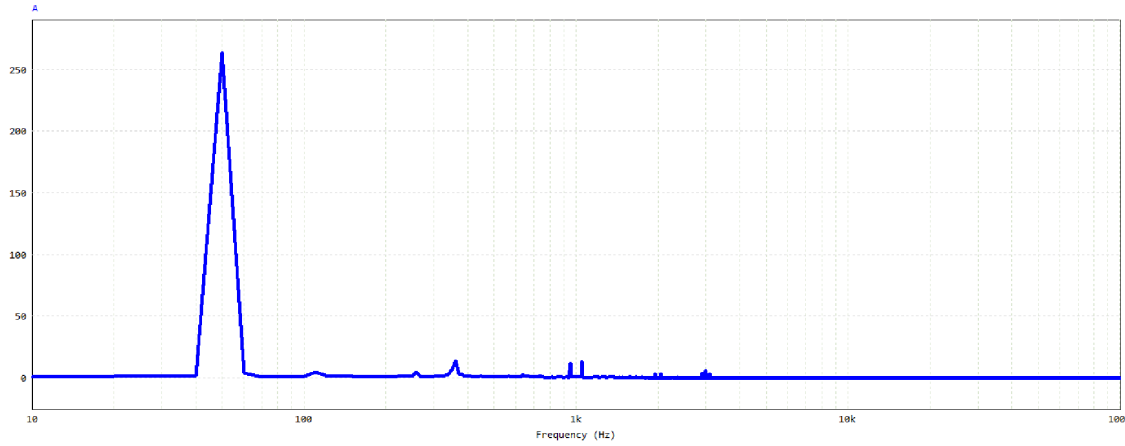


Figure 8. Results of modelling the output voltage spectrum of the AVI in steady-state mode

Source: developed by the author

Figure 8 clearly shows the amplitude of the main harmonic of 50 Hz and the high frequency with a switching frequency of 3 kHz and combinatorial harmonics consisting of sums and differences between 3 kHz and 50 Hz. The harmonic coefficient according to the simulation results was 4.9%, that is, it corresponded to the value laid down in the calculations and the given standard (DSTU IEC 62040-3:1999/COR1:2003) – 5%.

The operation of a voltage inverter under an unbalanced load as part of an electromechanical system of an autonomous WPP with ADM based on APRG is modelled. Modern standards (DSTU IEC 62040-3:1999/COR1:2003) give this requirement to a specific technical task between the developer and the customer, but according to the already invalid standard (GOST 27699-88), an autonomous

wind turbine had to meet the requirements: “Effective value of the output voltage of single-phase and three-phase inverters, symmetrically loaded, should not change by more than $\pm 10\%$ – for three-phase inverters with a phase load asymmetry of less than 15% in the load range from 50 to 100% of the rated value.” These requirements are used as a guideline. According to this requirement, the rated primary wind flow rate of 11 m/s and the rated load corresponding to 750 kW are set, and the single-phase load is increased by 15% in accordance with the standard. The graph with the simulation results is shown in Figure 9, where the amplitude value of the most loaded phase decreased from 297 V to 267 V, that is, by 10.01%, which corresponded to the value laid down in the calculation and the requirements of the standard.

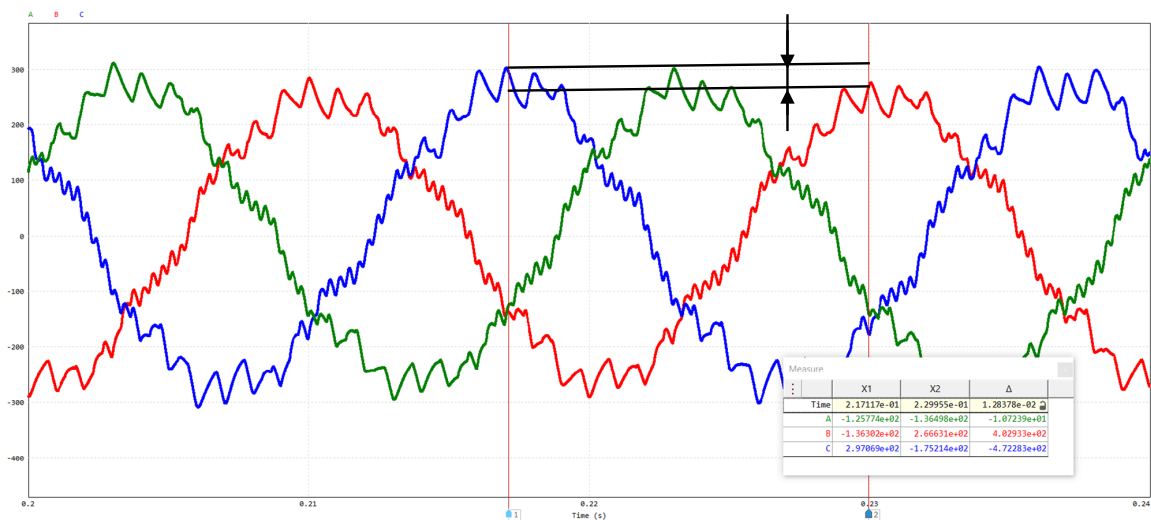


Figure 9. Results of modelling the shape of the output voltage of the AVI in a steady-state asymmetric mode

Source: developed by the author

The operation of a voltage inverter during load release and surge as part of an electromechanical system of an autonomous WPP with ADM based on APRG is modelled. According to the standard (GOST 27699-88), an autonomous wind turbine had to meet the requirements: “Maximum initial deviation of the output voltage for single-phase and three-phase inverters when the load current changes by a jump from zero to the nominal value and vice versa,

at the rated supply voltage of inverters, should not exceed $\pm 30\%$ of the amplitude value of the linear or phase voltage set. The maximum deviation duration should not exceed 40 ms”. That is, according to this requirement, if the rated speed of the primary wind flow is set to 11 m/s and the rated load corresponding to 750 kW, the load is reset to zero at a time of 0.31 s. The graph with the simulation results is shown in Figure 10.

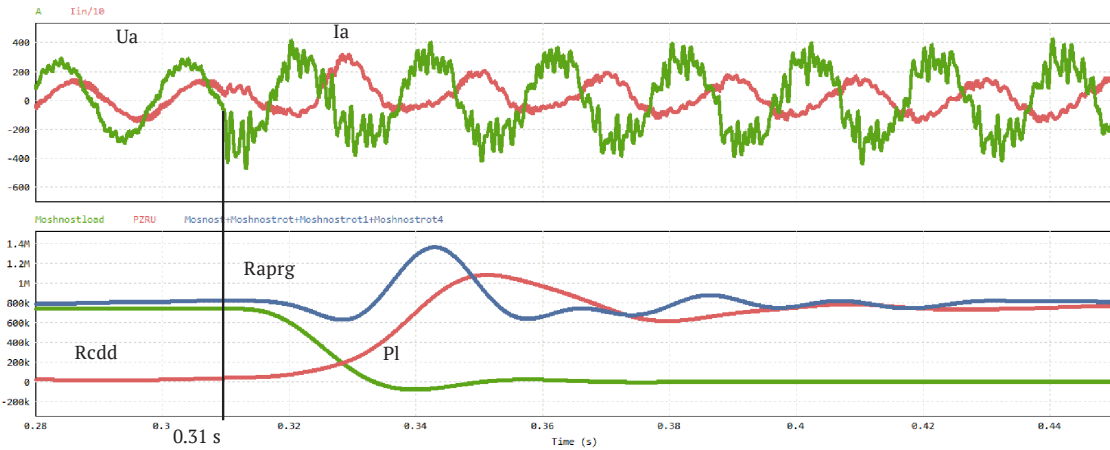


Figure 10. Load reset simulation results

Note: U_a , I_a – voltage and phase current of the inverter; R_{aprg} , R_{cdd} , Z_l – power, respectively, of the asynchronous generator, charging and discharging device, and load

Source: developed by the author

As shown in Figure 10, when the load was reset, the inverter current changed its phase, that is, the stator energy began to flow through the reverse diodes of the AVI to the DC link instead of the load. The ripple amplitude of the output voltage reached 400 V, which was 30% of the rated value. The lower graph shows how the power of the Raprg generator, the Pl load, and the Rcdd charging and

discharging device were redistributed. The transition process lasted about 38 ms, and the aprg overload was almost doubled. If the nominal primary wind speed is set to 11 m/s and the load is zero, and the load is applied to the rated value of 750 kW at time 0.31 s, the reverse process can be observed. The graph with the results of modelling the load surge is shown in Figure 11.

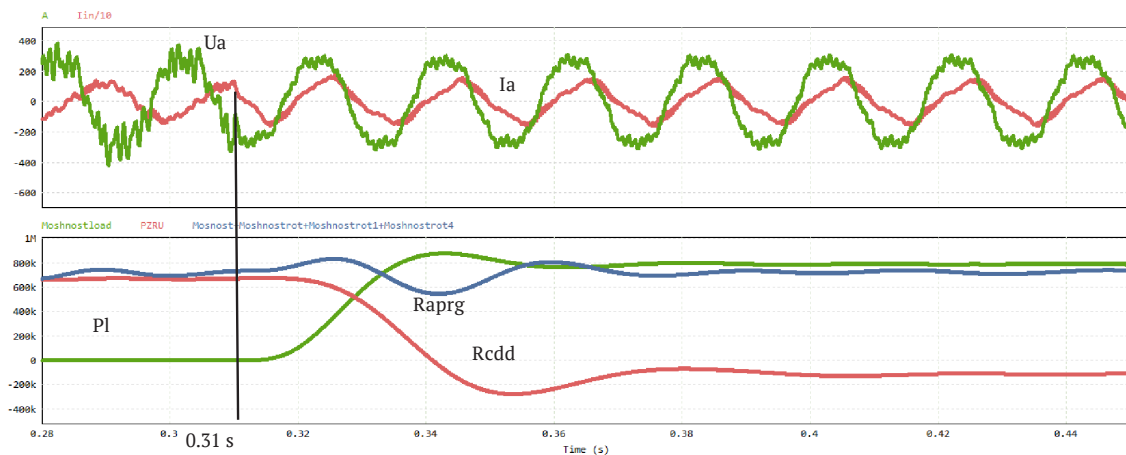


Figure 11. Results of load surge simulation

Note: U_a , I_a – voltage and phase current of the inverter; R_{aprg} , R_{cdd} , Z_l – power, respectively, of the asynchronous generator, charging and discharging device, and load

Source: developed by the author

It was possible to see that the process of the surge was more favourable for the generator, almost without overloads. Additionally, full idling in an autonomous wind turbine cannot be conditioned by the fact that the circuits of the own needs of the installation itself (power supplies of the control system, fans, alarm) are powered from the output voltage of the installation, and this gives a minimum consumption of 1 kW or more.

A significant number of studies are devoted to modelling the operation of autonomous wind turbines. P.K. Goel *et al.* (2010) started considering autonomous wind power plants based on APRG, which also uses an inverter with a zero wire, but with a vector algorithm for generating the output voltage. Their research was subsequently continued by a group of researchers led by J. Monroy-Morales *et al.* (2024), who combined the wind power plant in question with a diesel generator to increase battery life. The paper also analysed the battery life in an autonomous wind power plant. The study by M.S. Chabani *et al.* (2017) proposed a new system for direct torque control of the generator, which developed the well-known vector algorithms for controlling APRG.

The team of researchers led by S.K. Tiwari *et al.* (2018) built a model of a hybrid solar-wind power plant, which in the forecast allowed abandoning the use of a diesel generator for long periods of time without the presence of wind.

A.R. Kumhar (2018) also performed modelling of vector algorithms for regulating the generator power, but using the so-called “Transparent converter” in the APRG rotor circuit, which, on the one hand, expanded the control range, and, on the other hand, complicated the converter and reduced its efficiency.

A group of researchers led by T. Jangid *et al.* (2018) modelled a system for finding the maximum power of a wind turbine based on scanning logic, which excluded the presence of a wind flow speed sensor. A similar problem was solved by S. Puchalapalli & B. Singh (2020), who considered the use of generator power control systems based on fuzzy logic algorithms also without installing a wind speed sensor.

I.E. Atawi *et al.* (2019), V. Golovko *et al.* (2020) considered modelling of autonomous wind turbines based on synchronous permanent magnet generators and with a frequency converter at full power of a wind power plant. However, the need for complete conversion of the generated energy reduces the overall efficiency of wind turbines. M. Kovalenko *et al.* (2024) covered modelling of an autonomous wind turbine based on a synchronous generator without a frequency converter. In this case, the generator power is regulated using a magnetic gearbox, the efficiency of which remains a debatable topic.

In the proposed paper, in contrast to the ones considered, modelling covers a segment of a new type of autonomous wind turbines – with a wind turbine with aerodynamic multiplication. Simulations of these types of installations were also carried out, for example, by D.G. Alekseevskiy *et al.* (2019), but this only applied to system wind turbines. In addition, the visual-block modelling proposed by the

researcher currently allowed analysing only the smooth component of voltage and currents, and the electromagnetic processes associated with the presence of switching in semiconductor wind turbine converters were ignored by the study. Without a doubt, this method of modelling has accelerated the analysis of electromechanical processes in a wind power plant, but when switching to considering electromagnetic processes in an inverter and describing its behaviour along a smooth component, a significant error will arise. The development of visual-block models that will analyse the behaviour of the inverter with its switching frequency negates the advantages of this method of analysis due to slowing down the speed of modelling, and spending time on additional development and description of models. Thus, the model in the specialised PSIM software used in this paper helped to analyse the processes in the AI with available tools with little time spent on developing a simulation model. The disadvantage of simultaneous modelling of electromechanical and electromagnetic wind turbine processes is the considerable time required for each calculation.

Conclusions

To confirm the theoretical foundations of using the developed method for calculating inverter filters for an autonomous WPP with an ADM based on an asynchronous generator with a phase rotor, a simulation model was developed using the tools of the PSIM software suite. When using the specified method of calculating the output filter of the AVI, it was possible to obtain the harmonic coefficient of the output voltage of 4.9%, which meets the requirements of the standard in force in Ukraine, which regulates the maximum value of the harmonic coefficient of the output voltage not higher than 5%. This value was included in the input data for the calculation.

The method of calculating the input filter of the inverter provided the specified requirements for the output voltage asymmetry (10%) under uneven load, when the load of one of the phases is reduced by 15% relative to the others. According to the simulation results, when setting up the regulators of the AVI control system according to the specified method, it is possible to obtain the desired quality of transients (input data for calculation: 40 ms – duration and 30% – overvoltage when the load is reset; according to the simulation results, the duration was 38 ms, and the overvoltage – 30%).

In comparison with the visual-block modelling proposed for the modelling of WPP with ADM, the simulation time of the created simulation model is higher, but the model allowed combining modelling of both electromechanical and electromagnetic processes in a wind power plant without using specially designed tools. Thus, in accordance with this goal, a full compliance of the modelling results with the input data used in the calculations can be noted.

The topic of subsequent publications will focus on modelling the energy modes of an autonomous wind power plant with an aerodynamic multiplier and analysing its

behaviour at variable primary wind flow rates. When modelling changes in the primary wind flow, it is possible to exclude internal parameters of semiconductor devices from the model, for example, the dynamic resistance of IGBT and diodes, to reduce the calculation time.

None.

None.

Acknowledgements

Conflict of Interest

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Моделювання роботи інвертора напруги у складі автономної вітроенергетичної установки з аеродинамічним мультиплікуванням на базі асинхронного генератора з фазним ротором

Гліб Стрункін

Магістр

Інженерний навчально-науковий інститут Запорізького національного університету
69006, просп. Соборний, 226, м. Запоріжжя, Україна
<https://orcid.org/0009-0009-1719-4132>

Анотація. В умовах енергодефіциту, спричиненого знищенням енергетичної інфраструктури, нестабільністю постачання електроенергії та зростанням попиту на автономні джерела енергії, виникає потреба у розробці незалежних і ефективних систем енергозабезпечення. Особливе значення мають вітроенергетичні установки, які здатні функціонувати автономно, забезпечуючи стабільність енергопостачання навіть у кризових умовах. У зв'язку з цим актуальним є вивчення перспективних рішень, які відповідають сучасним стандартам якості та здатні інтегруватися в автономні енергетичні системи. Метою роботи було підтвердження ефективності розрахунку фільтрів інвертора у статичних та динамічних режимах, а також за умов несиметричного навантаження. Це було досягнуто на основі імітаційного моделювання автономної вітроенергетичної установки з аеродинамічним мультиплікуванням, що працює на базі асинхронного генератора з фазним ротором і збудженням від інвертора напруги. Описано імітаційну модель автономної вітроенергетичної установки, параметри інвертора, яку розраховано за авторськими методиками, у середовищі PSIM. Програмно виконано Фур'є-аналіз гармонічного складу вихідної напруги інвертора, розраховано його коефіцієнт гармонік, який не перевищує 5 %, відповідно до діючого стандарту. Доведено, що збудження від інвертора напруги поліпшує її роботу при несиметричному навантаженні та скиданні-накиданні навантаження. Виконано порівняння результатів моделювання вихідної напруги інвертора з вимогами стандартів на безперервні джерела енергоживлення. На основі результатів імітаційного моделювання автономної вітроенергетичної установки з аеродинамічним мультиплікуванням підтверджено ефективність розрахунку фільтрів інвертора напруги для асинхронного генератора з фазним ротором. Методики показали свою результативність як у статичних і динамічних режимах, так і за умов несиметричного навантаження

Ключові слова: автономний інвертор напруги; скидання та накидання навантаження; несиметричне навантаження; коефіцієнт гармонік; імітаційне моделювання

ТЕХНОЛОГІЇ ТА ІНЖИНІРИНГ

Науковий журнал

Том 25, № 6, 2024

Оригінал-макет видання виготовлено
у редакційно-видавничому відділі Київського національного університету технологій та дизайну

Відповідальний редактор:

О. Кривонос

Редагування англomовних текстів:

С. Вороський, К. Касьянов

Комп'ютерна верстка:

О. Глінченко

Підписано до друку 18.12.2024 р. Формат 60*84/8

Умовн. друк. арк. 9,5

Наклад 100 примірників

Адреса видавництва:

Київський національний університет технологій та дизайну

01011, вул. Мала Шияновська, 2, м. Київ, Україна

тел/факс: +38 (044) 256-84-27

E-mail: info@technologies-engineering.com.ua

<https://technologies-engineering.com.ua/uk>

TECHNOLOGIES AND ENGINEERING

Scientific Journal

Vol. 25, No. 6, 2024

The original layout of the publication is made
in the publishing department of Kyiv National University of Technologies and Design

Managing editor:

O. Kryvonos

Editing English-language texts:

S. Vorovsky, K. Kasianov

Desktop publishing:

O. Glinchenko

Signed for print 18.12.2024. Format 60*84/8

Conventional printed pages 9.5

Circulation 100 copies

Publishing Address:

Kyiv National University of Technologies and Design

01011, 2 Mala Shyianovska Str., Kyiv, Ukraine

tel/fax: +38 (044) 256-84-27

E-mail: info@technologies-engineering.com.ua

<https://technologies-engineering.com.ua/en>