The main aspects of building cyber-physical systems for optimal regulation of reactive power flows in main step-down substations of mining and processing plants

Andrey Kupin, Yurii Sherstnov, Yuriy Osadchuk and Olexander Savytskyi

Kryvyi Rih National University, Vitaly Matusevich 11, Kryvyi Rih, 50027, Ukraine

Abstract

The substation of the mining and processing plant is presented as a cyber-physical system (CPS). The use of the main principles of CPS construction for the rational regulation of reactive power flows in the main step-down substations of the mining and processing complex is substantiated. The results of modeling the reactive power compensation process are presented based on real electricity consumption data from the powerful substations of the mining and processing plant. An analysis of the effectiveness of using CPS aspects for managing compensating devices is conducted. For testing, the authors used experimental data from January and June 2019 for one of the plant's main substations. An algorithm for the operation of compensating devices to regulate reactive power in substations, taking into account CPS aspects, was developed.

Keywords

Mining and beneficiation plants, cyber-physical system, power grids, energy efficiency, filter-compensating devices, synchronous motors

1. Introduction

Electric networks of industrial enterprises, such as in our case, substations of mining and beneficiation complexes, are complex systems with a large number of consumers characterized by rapidly changing load patterns. This feature of the operating process makes it almost impossible to predict disturbances in electricity consumption. However, the high level of development of automatic control systems for technological processes allows for the relatively inexpensive implementation of these systems in each technological cycle of the enterprises. Control of compensating devices (synchronous motors (SM) and capacitor batteries (CB)) in such cases should take into account all possible factors to minimize cases of overcompensation. In this regard, it is expedient to consider substations as a unified CPS for controlling SM and CB according to a specific algorithm.

For CB, the main tasks include complete compensation of reactive power, and equally important issues are the problem of overvoltage and the reliability of operation that may arise during their switching, which is addressed through a series of measures. To create an effective control system, an important practical issue remains the need to determine the significance of certain parameters (number of SMs, their load, temperature, etc.). The impact and importance of such parameters on the compensating capabilities of the system have been discussed in the authors' previous works [1,2].

The assessment of the performance indicators of such an energy system is important in terms of the reliability of the technical equipment, stable quality of energy indicators, etc. The use of information and communication technologies (ICT) allows for more accurate control and tracking of rapid changes in the energy system [3]. At the same time, providing an optimal solution to the

ICST-2024: Information Control Systems & Technologies, September 23-25, 2023, Odesa, Ukraine.
kupin.andrew@gmail.com (A. Kupin); yurasw1@gmail.com (Y. Sherstnov); u.osadchuk@knu.edu.ua (Y. Osadchuk); savytskiy@knu.edu.ua (O. Savytskyi)
0000-0001-7569-1721 (A. Kupin); 0009-0003-3210-5552 (Y. Sherstnov); 0000-0001-6110-9534 (Y. Osadchuk); 0000-0002-8904-1807 (O. Savytskyi)

control problem can be achieved using mathematical optimization methods [4] to minimize the likelihood of incidents and failures related to computational and communication infrastructure [5].

This study focuses on the substations of the mining and beneficiation complex. The subject of the research is the reactive power compensator control system as a CPS. The main features of this work are as follows:

1. Representation of the powerful substation of the mining and beneficiation industry as a CPS. An algorithm for controlling compensating devices taking into account the CPS features is proposed.
2. Evaluation of the reliability and effectiveness of the proposed reactive power compensator control system (synchronous motors and capacitor installations) of substations as a CPS.

Thus, the article addresses the main aspects of constructing a CPS for rational regulation of reactive power flows in substations with synchronous motors.

2. Presentation of the cyber-physical system of reactive power flows at the substations of the mining and beneficiation complex.

To ensure high performance and energy efficiency at industrial substations, computational capabilities of automated process control systems (APCS) are integrated with physical processes of energy management [6]. Such an approach to structuring power supply is crucial for the effective and safe operation of industrial facilities. CPS are characterized by the interaction of computer algorithms and physical processes [5]. In the case of substations, computer systems provide monitoring, control, analysis, and optimization of electrical equipment operation, allowing for the detection and prevention of possible failures, as well as equipment condition forecasting [6].

Modern substations utilize various sensors and data collection devices that gather information about the state of electrical equipment, such as transformers, circuit breakers, converters, soft starters, etc. [7]. This data is transmitted to the central control system, where commands are formulated to regulate equipment operation parameters, thereby optimizing power supply and increasing overall system efficiency [8,9].

Furthermore, integration with information technologies enables remote control of substations, significantly enhancing safety, reducing risks, and increasing responsiveness to emergency situations [10]. Such use of technologies makes substations part of broader cyber-physical systems that interact with other elements of industrial infrastructure [11].

Powerful substations of mining and beneficiation complexes are large and complex systems, comprising multiple stages of electrical energy transmission and conversion. In turn, the substations themselves are components of even larger energy systems. Analyzing and managing components in such a case would be very complex and inefficient in terms of computational resources expended. Therefore, it is advisable to consider a limited structure of the energy system, namely substations as an example, as depicted in Fig. 1.

For example, the mining and beneficiation complex in Fig. 1 includes 10 distribution substations (DS), 7 of which have from 2 to 6 synchronous motors with a power of 1250 kVA each. DS without synchronous motors perform compensation using capacitor installations at 2 levels: on the 0.38 kV buses of 6/0.4 kV transformer substations and on the 6 kV buses of DS. DS with minimal synchronous motor quantity perform compensation either on the 0.38 kV buses of 6/0.4 kV transformer substations or on the 6 kV buses of DS.

As a typical example, Fig. 2 shows the main reactive power flows at substations. Using CPS principles, where sensors, equipment, and information systems are integrated into a unified structure using internet protocols, allows us to accurately predict, adjust, and adapt the reactive power compensation system to changes.

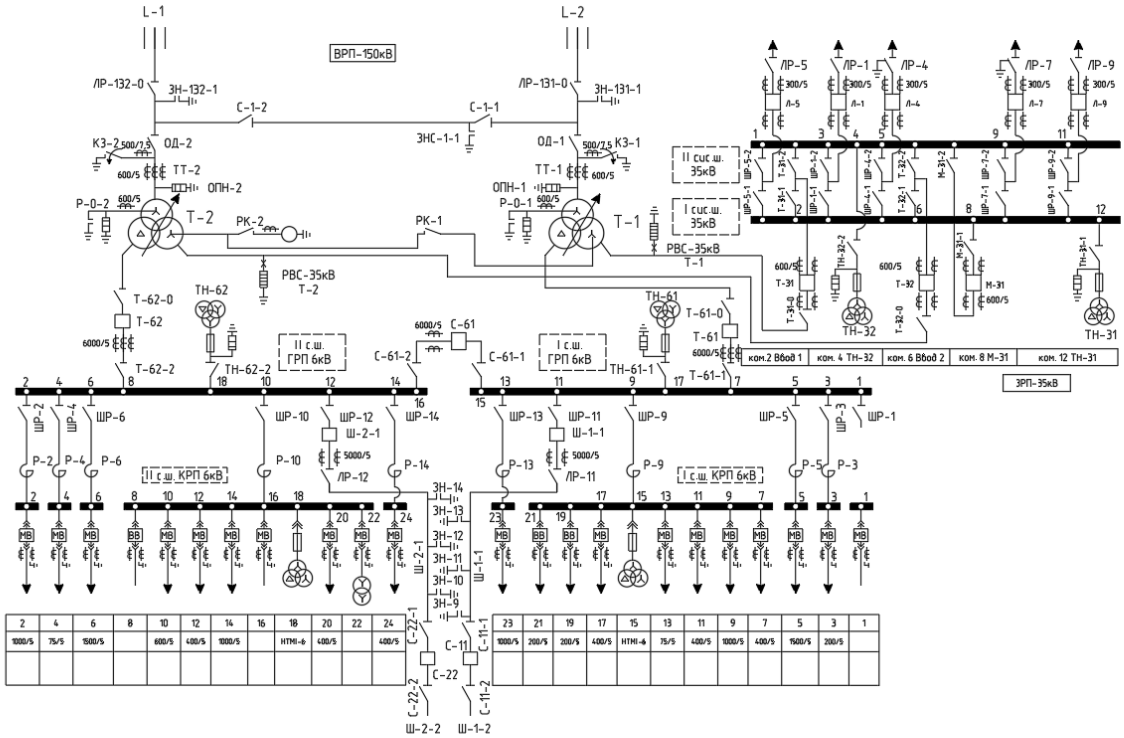

Figure 1: One-line scheme of the main step-down substation.

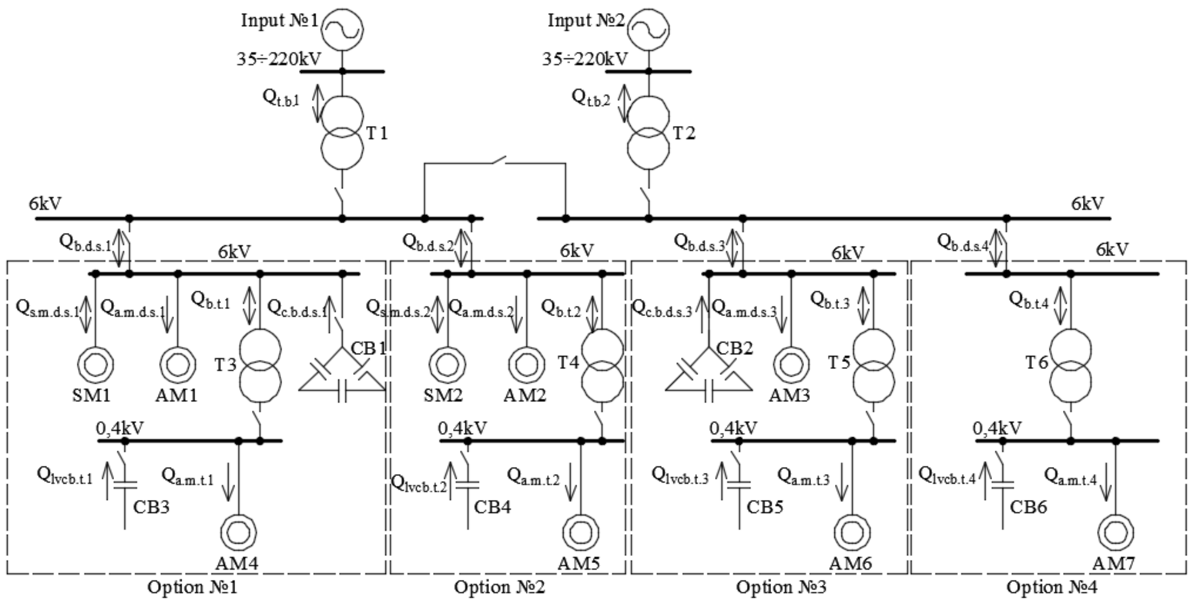

Figure 2: Reactive energy flows at substations. T1 (T2, T3, T4, T5, T6) - transformers; SM1 (SM2) - synchronous motors; AM1 (AM2, AM3, AM4, AM5, AM6, AM7) - asynchronous motors; CB1 (CB2, CB3, CB4, CB5, CB6) - capacitor batteries.

The schematic representation of reactive power flows at the substation in Fig. 2 comprises 4 Options:

1. Consumption of active and reactive power by 6kV AM ($Q_{a.m.d.s.1}$) and 0.4kV AM ($Q_{a.m.t.1}$). Generation by 6kV CB ($Q_{c.b.d.s.1}$) and 0.4kV CB ($Q_{lvcb.t.1}$). Consumption and generation by 6kV SM ($Q_{s.m.d.s.1}$);

2. Consumption of active and reactive power by 6kV AM ($Q_{a.m.d.s.2}$) and 0.4kV AM ($Q_{a.m.t.2}$). Generation by 0.4kV CB ($Q_{lvcb.t.2}$). Consumption and generation by 6kV synchronous motors ($Q_{s.m.d.s.2}$);
3. Consumption of active and reactive power by 6kV AM ($Q_{a.m.d.s.3}$) and 0.4kV AM ($Q_{a.m.t.3}$). Generation by 6kV CB ($Q_{c.b.d.s.3}$) and 0.4kV CB ($Q_{lvcb.t.3}$);
4. Consumption of active and reactive power by 0.4kV AM ($Q_{a.m.t.4}$). Generation by 0.4kV CB ($Q_{lvcb.t.4}$).

The desired level of values for $Q_{t.b.1}$ and $Q_{t.b.2}$ (MVAR·h) should be zero, meaning that the system neither generates nor consumes reactive power from the grid. This can significantly reduce the charges incurred by the enterprise for electric power [1, 2]. It is also desirable for the values of $Q_{b.d.s.1}$, $Q_{b.d.s.2}$, $Q_{b.d.s.3}$, $Q_{b.d.s.4}$ for 6kV and $Q_{b.t.1}$, $Q_{b.t.2}$, $Q_{b.t.3}$, $Q_{b.t.4}$ for 0,4кV to also be zero. Such a setting will help avoid a range of negative phenomena, including conductor overheating, overvoltage occurrence, and failure of switching and technical equipment. Moreover, electric power meters are installed on the secondary side of each transformer. This monitoring allows for the prompt identification of the power supply line with excessive reactive power consumption or generation into the grid for controlling the available compensating powers on it.

Considering the conditions and features mentioned, a graph can be constructed based on Fig. 2, as shown in Fig. 3, which illustrates the reactive power flows and its control system.

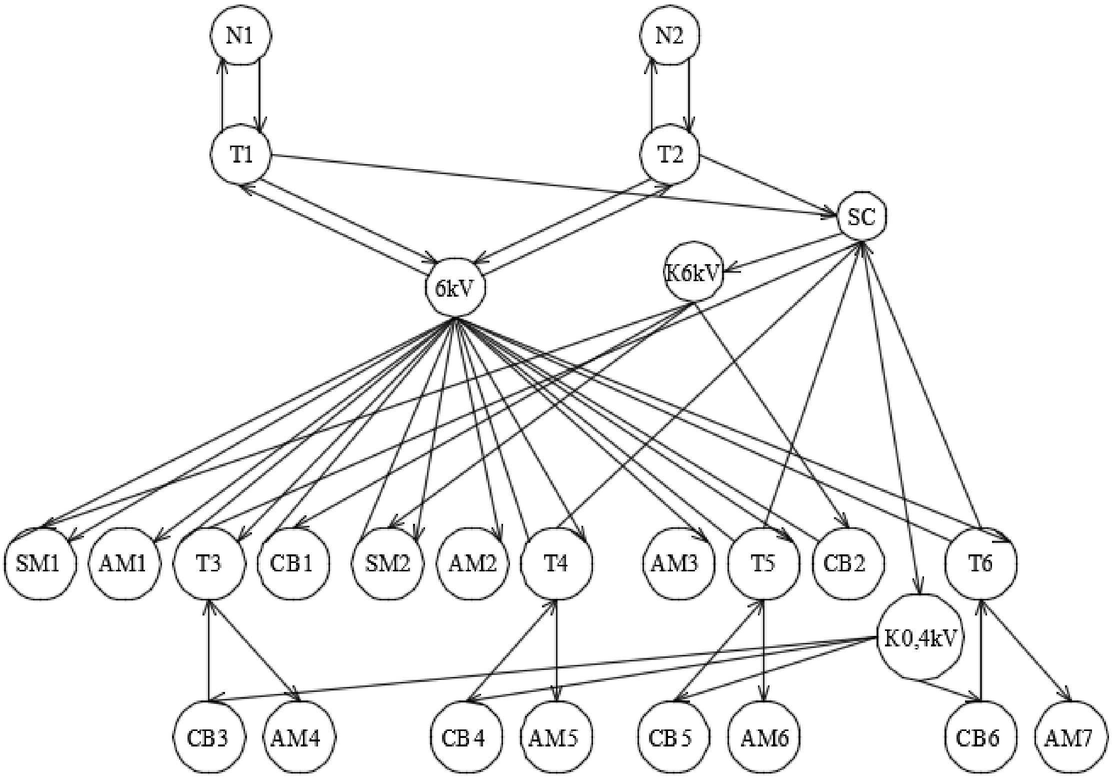

Figure 3: Reactive energy flows at substations. T1 (T2, T3, T4, T5, T6) - transformers; SM1 (SM2) - synchronous motors; AM1 (AM2, AM3, AM4, AM5, AM6, AM7) - asynchronous motors; CB1 (CB2, CB3, CB4, CB5, CB6) - capacitor batteries; N1 (N2) - network input; SC - control system; K6kV – equipment control 6kV; K0,4kV - equipment control 0,4kV.

Fig. 3 depicts the main connections between network components necessary for monitoring and controlling the consumption and generation of reactive power. It is worth noting that this Fig. 3 can be modified according to the existing system. Fig. 4 presents the adjacency matrix of such a graph.

And, correspondingly, the components of the incidence matrices (1) and (2). Thus, the list of vertices (1):

$$V = \{M1, M2, T1, T2, 6kV, K6, SC, SM1, AM1, T3, CB1, SM2, AM2, T4, AM3, T5, CB2, T6, K0{,}4, CB3, AM4, CB4, AM5, CB5, AM6, CB6, AM7\}. \quad (1)$$

And the set of edges (2):

$$E = [(M1, T1), (M2, T2), (T1, SC), (T2, SC), (6kV, T1), (6kV, T2), (6kV, SM1), (6kV, AM1), (6kV, T3), (6kV, CB1), (6kV, SM2), (6kV, AM2), (6kV, T4), (6kV, AM3), (6kV, T5), (6kV, CB2), (6kV, T6), (SC, K6), (K6, SM1), (K6, CB1), (K6, SM2), (K6, CB2), (SC, K0{,}4), (CB3, T3), (T3, AM4), (CB4, T4), (T4, AM5), (CB5, T3), (T5, AM6), (CB6, T6), (T6, AM7), (K0{,}4, CB3), (K0{,}4, CB4), (K0{,}4, CB5), (K0{,}4, CB6)] \quad (2)$$

	M1	M2	T1	T2	6kV	K6	SC	SM1	AM1	T3	CB1	SM2	AM2	T4	AM3	T5	CB2	T6	K0,4	CB3	AM4	CB4	AM5	CB5	AM6	CB6	AM7
M1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M2	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T1	1	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T2	0	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6kV	0	0	1	1	0	0	0	1	1	1	0	1	1	1	1	1	0	1	0	0	0	0	0	0	0	0	0
K6	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
SC	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
SM1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AM1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T3	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CB1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SM2	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AM2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T4	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AM3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T5	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CB2	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T6	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
K0,4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	1	0
CB3	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AM4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CB4	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
AM5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CB5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
AM6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CB6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0

Figure 4: Substation graph adjacency matrix.

Therefore, the resulting incidence matrix $\Lambda=\|\lambda_{ij}\|$ (where $i,j=1,\dots,26$ – block numbers; $\lambda_{ij}=1$, if i-th block is the start of an edge, the end of which is another block j; $\lambda_{ij}=0$, if $i=j$ or i-th block is not the start of an edge, the end of which is another block j; row numbers correspond to the designation of simplices) for this case are presented analytically in Fig. 5.

The obtained adjacency matrix (Fig. 4) and incidence matrix (Fig. 5) are part of the topological analysis of the substation structure. Simplicial analysis utilizes both these matrices to construct simplicial complexes, which are sets of simplices organized according to certain rules. Simplicial complexes can be analyzed to study the topological properties of the network, observing how its structure changes with variations in node or link parameters.

To assess the hierarchical control structure and analyze dependencies of potential information and control flows and relationships within the conditions of an industrial enterprise substation, we will apply the algorithm of structural *q*-connectivity, which is one of the most widely used and well-researched qualitative characteristics of systems.

	M1	M2	T1	T2	6kV	K6	SC	SM1	AM1	T3	CB1	SM2	AM2	T4	AM3	T5	CB2	T6	K0,4	CB3	AM4	CB4	AM5	CB5	AM6	CB6	AM7
(M1,T1)	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(M2,T2)	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(T1,SC)	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(T2,SC)	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(6kV,T1)	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(6kV,T2)	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(6kV,SM1)	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(6kV,AM1)	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(6kV,T3)	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(6kV,CB1)	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(6kV,SM2)	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(6kV,AM2)	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(6kV,T4)	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
(6kV,AM3)	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
(6kV,T5)	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
(6kV,CB2)	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
(6kV,T6)	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
(SC,K6)	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(K6,SM1)	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(K6,CB1)	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(K6,SM2)	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(K6,CB2)	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
(SC,K0,4)	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
(CB3,T3)	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
(T3,AM4)	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
(CB4,T4)	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0
(T4,AM5)	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0
(CB5,T3)	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
(T5,AM6)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0
(CB6,T6)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
(T6,AM7)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
(K0,4,CB3)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0
(K0,4,CB4)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0
(K0,4,CB5)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0
(K0,4,CB6)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0

Figure 5: Substation graph incidence matrix.

3. Simplicial analysis of information and control flows and connections in the conditions of the mining and beneficiation plant substation

For systematic investigation and identification of shared control tasks between individual CB and FCD, we will base our analysis on the electrical scheme of the substation and apply a decomposition methodology. Issues related to the reliability of the obtained results and identification of interconnected system concepts and essential relationships between them remain relevant. Therefore, attention should be paid to simplicial analysis, which helps address these crucial issues. We will conduct simplicial analysis of the structure of the developed model of the mining and beneficiation plant substation.

The structural deficiency of the matrix Λ is assessed based on the indicator $R_\kappa \in \mathfrak{R}$:

$$R_к = \left[\sum_{i=1}^{27}\sum_{j=1}^{35}\lambda_{ij}\right]\frac{1}{26} - 1 = \frac{70}{26} - 1 \approx 1{,}69 \quad (3)$$

Since $R_к$=1,69>0, the system is connected (without breaks) and has deficiency (i.e., potentially reliable).

Performing q-analysis of the matrix Λ, by summing rows and subsequent grouping, we obtain the following equivalence classes Q_{qc} (Q_{qc} – the number of simplices of dimension $q_c \in \Im$, q_c=0,…,20; {the numbers of q-connected simplices are indicated in curly brackets}):

$$\begin{gathered}
Q_0 = 7: \{AM1\}, \{AM2\}, \{AM3\}, \{AM4\}, \{AM5\}, \{AM6\}, \{AM7\};\\
Q_1 = 8: \{M1\}, \{M2\}, \{CB1\}, \{CB2\}, \{CB3\}, \{CB4\}, \{CB5\}, \{CB6\};\\
Q_2 = 3: \{SM1\}, \{SM2\}, \{SM3\};\\
Q_3 = 0;\\
Q_4 = 8: \{T1\}, \{T2\}, \{T3\}, \{T4\}, \{T5\}, \{T6\}, \{K0{,}4kV\}, \{K6kV\};\\
Q_5 = Q_6 = 0;\\
Q_7 = 1: \{SC\};\\
Q_8 \dots Q_{19} = 0;\\
Q_{20} = 1: \{6kV\}.
\end{gathered} \quad (4)$$

The structural vector of the complex takes the following form:

$$Q_k = (7; 8; 3; 0; 8; 0; 0; 1; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 1). \quad (5)$$

Analysis of the vector $Q_к$ shows that it is connected for large (Q_{20}), medium (Q_2, Q_4) and small (Q_0, Q_1) values of q_c. In particular, when q_c=0, 1, 2 the complex breaks down into several disconnected components, which is interpreted as the presence of two geometric obstacles in the system or three levels of q-connected simplices.

The hierarchical organization of the typical equipment control structure of the substation in the conditions of the mining and beneficiation plant (provided in Fig. 1, Fig. 2) is also confirmed by the uniform functional characteristics of the maximum dimension simplex values (where the simplex number is indicated in curly brackets followed by a set of blocks that belong to it; ∅ - empty set), grouped as follows:

$$\begin{gathered}
q_c = -1: \{\emptyset(\emptyset)\};\\
q_c = 17: \{M1(T1)\}, \{M2(T2)\}, \{k6kV(SC)\}, \{k0{,}4kV(SC)\}, \{AM1(6kV)\},\\
\{AM2(6kV)\}, \{AM3(6kV)\}, \{CB1(k6kV)\}, \{CB2(k6kV)\}, \{CB3(k0{,}4kV)\},\\
\{CB4(k0{,}4kV)\}, \{CB5(k0{,}4kV)\}, \{CB6(k0{,}4kV)\}, \{AM7(T6)\},\\
\{AM4(T3)\}, \{AM5(T4)\}, \{AM6(T5)\},\\
q_c = 9: \{SM1(6kV, k6kV)\}, \{SM2(6kV, k6kV)\}, \{6kV(T1, T2)\}, \{T1(M1{,}6kV)\},\\
\{T2(M2{,}6kV)\}, \{T3(CB3{,}6kV)\}, \{T4(CB4{,}6kV)\}, \{T5(CB5{,}6kV)\}, \{T6(CB6{,}6kV)\};\\
q_c = 1: \{SC(T1, T2, T3, T4, T5, T6)\},
\end{gathered} \quad (6)$$

Analysis of the groups of small q_c (-1, 0) shows that their content can be interpreted as simplices characterizing the input and output parameters of consumption and control of reactive power flows.

Different values of maximum simplex dimensions are formally reflected in the parameter $\varepsilon \in \Re$ of a uniform distribution of links in a directed graph, which has $m_1 \in \Im$ edges and $m_2 \in \Im$ vertices:

$$\varepsilon^2 = \sum_{i=1}^{m_2} (\rho_i - \rho_{aver})^2 = \sum_{i=1}^{m_2} \left(\rho_i - \frac{m_1}{m_2}\right)^2 \quad (7)$$

where $\rho_{aver} \in \Re$ – average vertex degree; $\rho_i \in \Im$ - actual degree of the i-th vertex.

For the model of consumption and control of reactive power flows under consideration, taking into account the dependency $\rho_{aver} = m_1/m_2 = 70/26 \approx 2,69$ we obtain:

$$\varepsilon^2 = 16,66. \quad (8)$$

Therefore, finally, we obtain:

$$\varepsilon = \sqrt{\varepsilon^2} \approx 4,08. \quad (9)$$

The result $R_\kappa > 0$ indicates that the topological structure of the substation section in mining and processing plants approaches a complete graph, but when $\varepsilon \neq 0$ this is not explicitly expressed. A comparative analysis of different topologies (sequential, ring, radial, tree-like, complete graph, disjoint) based on R_κ and ε, as well as simplicial and visual analysis of the structure provided in Fig. 3, indicate that it corresponds to a hierarchical structure.

During the work, expressions (1, 2) may change when certain components of matrices are excluded [12].

Based on these matrices, matrices with weighting coefficients are formed, which reflect the variable parameters of reactive power that are promptly measured by the controller with corresponding converters at certain intervals. Based on these matrices, the feasibility of reactive power compensation is calculated for each decision-making period at the substation and at each level of power supply (0.4 kV and 6 kV) [13].

Further, this process will be considered in more detail in the developed algorithm.

Thus, in the hierarchical structure of the mining and processing plant substation, three interacting levels of compensation device control are clearly distinguished:

- 0,4 kV compensators (first level of control);
- 6 kV compensators (second level of control);
- Synchronous motors capable of compensating reactive power (third level of control).

This structure fully complies with the currently accepted concept of industrial automation and well-known relevant standards for the construction of ACS, ACSP, ACSTP, as well as international ones: IEC-1131; ISA S88, S95, ISO/IEC 14908) [14].

4. Control algorithm for compensation devices

Taking into account the required level of reliability and the designated control levels of compensation devices, an algorithm for control can be constructed. Fig. 6 presents this algorithm. The input data include the compensation capability of capacitor banks 0,4kV ($Q_{c.d.1(0.4)}$, $Q_{c.d.1+n(0.4)}$) and 6 kV ($Q_{c.d.1(6)}$, $Q_{c.d.1+n(6)}$). Parameters $Q_{u.c.0.4}$ та $Q_{u.c.6}$ correspond to the setpoint values of undercompensation of reactive power. These values serve as an additional safeguard in the system against overcompensation. Subsequently, the algorithm manages the compensation devices, starting with the 0.4 kV capacitor banks, followed by the 6 kV ones.

The algorithm prioritizes the involvement of capacitor banks in the compensation process because, on average, losses in terms of kW/kVAR for capacitor banks range from 0.002 to 0.0045 kW/kVAR [2]. In contrast, for synchronous motors, this figure is approximately 0.013 kW/kVAR under the existing conditions and parameters, aligning with general trend estimates. Hence, capacitor units are preferred for initial engagement in the compensation process.

The switching of 0.4 kV capacitor banks occurs by selecting one or several stages, depending on the consumption meter $Q_{c0.4}$ readings. Similarly, the switching of 6 kV capacitor banks happens by choosing one or several stages, depending on the consumption meter Q_{c6} readings. In the subsequent process, when the maximum CB of the capacitor banks are reached, SM are engaged.

In the subsequent process, when the maximum compensation capabilities of the capacitor banks are reached, synchronous motors are engaged. Synchronous motors, operating with a leading power factor, can act as reactive power generators necessary for ensuring the normal operation of transformers, asynchronous motors, DC motors, and other station equipment. This possibility arises because, according to the examination of the operating modes of powerful synchronous motors in the mining-metallurgical complex of Kryvyi Rih, their average utilization regarding active power is 67-72% [1].

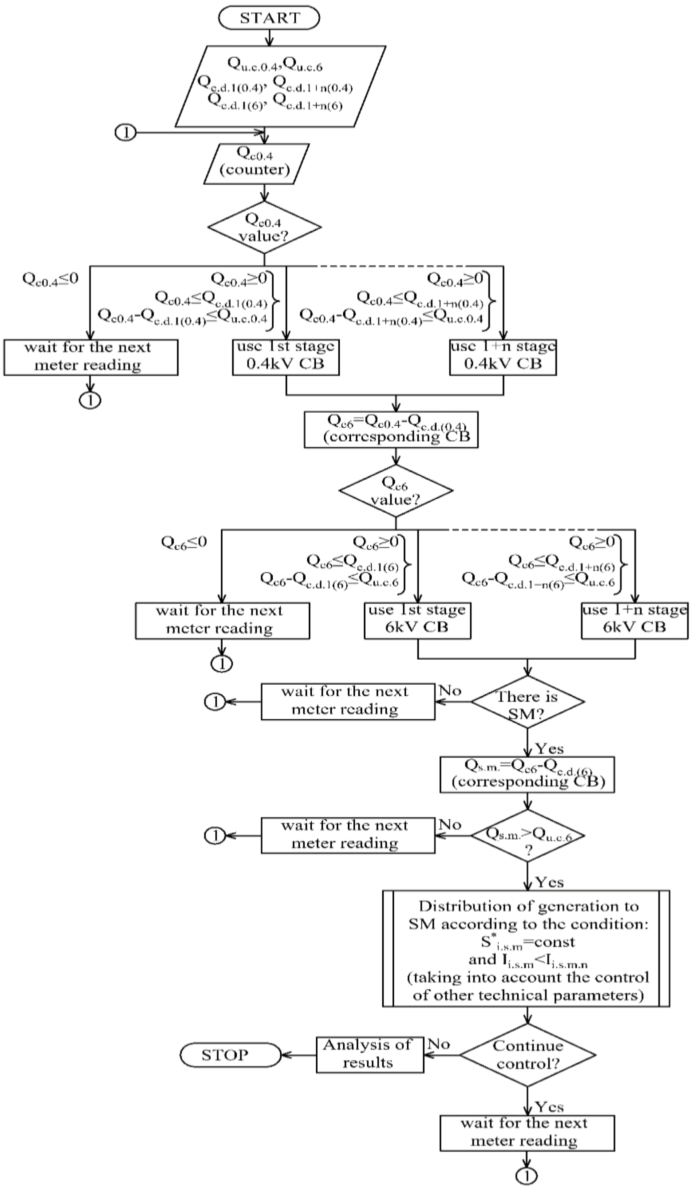

Figure 6: Operation algorithm of compensating devices of 0,4kV and 6kV on substations.

The primary goal of the system's construction is to ensure equal relative loading values in terms of the total power – S^*_i of the synchronous motors engaged in the compensation process. For this purpose, the system determines the relative threshold value $S^*_{mar.i}$ for each motor, the exceeding of which is undesirable. The value of $S^*_{mar.i}$ can be the same for all SM engaged in compensation. Depending on the specific loading of the SM – β_i and the value of $S^*_{mar.i}$ the compensation capability of each motor is determined – Q_i. The required compensation value – Q_n is obtained from the reactive power sensor at the substation's input or set manually [15]. Subsequently, the compensation feasibility is determined by the condition: $\sum Q_i > Q_n$. If this inequality holds true, the value of Q_n is distributed among all SM engaged in compensation while maintaining the equality S^*_i=const. Conversely, $\sum Q_i < Q_n$, indicating the need for additional compensation resources, and considering that $S^*_{mar.i}$ is determined without potential power excess, it is recommended to partially exceed the generation of reactive power by synchronous motors with the lowest loading β_i until the condition: $\sum Q_i = Q_n$ is met. In this case, the nominal excitation current of the motor should not exceed the nominal value $I_g \leq I_{g.n.}$, and the maximum possible value of overcompensation is: $\Delta Q_{i\ max} \leq (8 \div 10)\% Q_i$. It is important to note that in the event that substations have additional compensation devices (FCD, SM, etc.) they should also be utilized.

When SMs operate in reactive power compensation mode, it is desirable to additionally monitor their operational technological parameters, namely: the temperature of the cooling air, the temperature of the stator and rotor windings, the supply voltage, and not exceed the permissible values of these parameters. Thus, the proposed system for regulating reactive power flows at substations through the control of SMs provides the necessary level of reactive power compensation in the power grid of industrial enterprises [16].

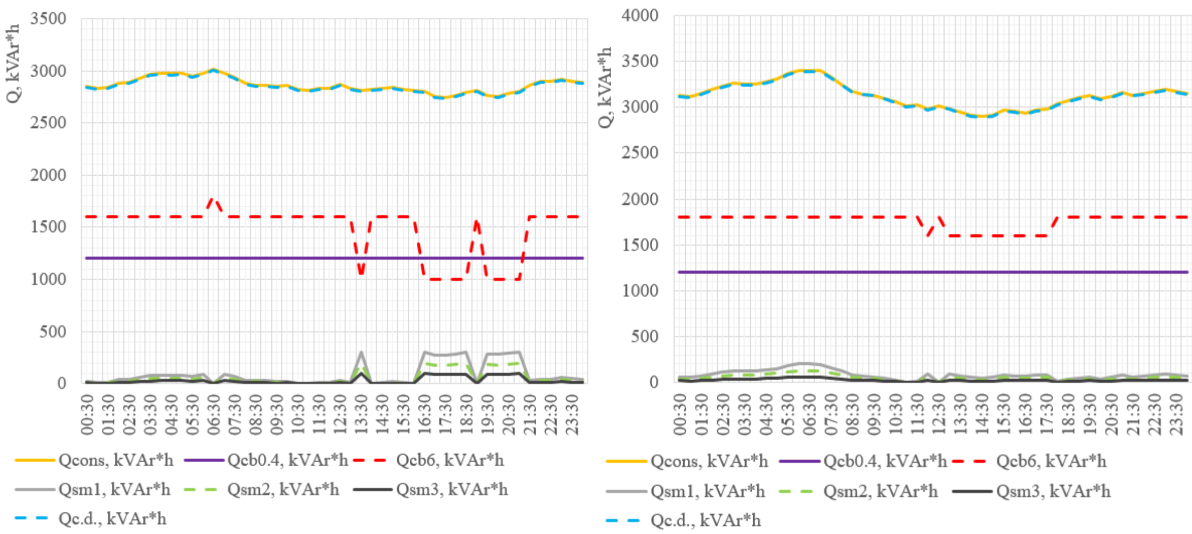

Figure 7: The result of the algorithm for *a)* – January; *b)* – June.

Fig. 7 (*a*, *b*) depict the results of the reactive power compensation algorithm process using 0.4 kV and 6 kV CB and SM for the day in January and June, respectively. The Q_{cons} values in Fig. 7 – represent the actual statistical consumption of reactive power by the enterprise substation (Fig. 1). As observed from the plotted graphs, according to the algorithm, the generated power by compensating devices never exceeds the consumption power (due to the set value of undercompensation threshold) [17]. Throughout the day, all levels of 0.4 kV CBs are consistently engaged for each month, while the 6 kV CBs are connected as needed [18]. Any remaining uncompensated reactive power is distributed among the synchronous motors based on their load and current capabilities.

Thus, the obtained results demonstrate the utilization of cyber-physical system principles for the substations of mining and processing enterprises to control reactive power flows [19].

5. Conclusion

Based on statistical data on reactive power consumption by the substation of the mining and processing enterprise, the key aspects of constructing cyber-physical systems for rational regulation of reactive power flows in powerful substations with synchronous motors were examined. The proposed algorithm for automatic control of compensation devices (switching of capacitor banks at 0.4kV and 6kV) and regulation of synchronous motor excitation for reactive power compensation considers the peculiarities of monitoring and control links of reactive power flows in the developed substation graph. The developed algorithm is implemented taking into account the reliability and stability of cyber-physical system indicators [20]. According to the results of graphical representations, the required level of compensation ensures high energy efficiency.

References

[1] V. Verbynets, Yu. Sherstnov, S. Silchenko, A. Kupin, Yu. Osadchuk, O. Savytskyi, Control algorithm of filter-compensating devices under the conditions of the presence of synchronous motors, Scientific Notes of Tavria National University named by V.I. Vernadsky 34 73 1 (2023) 173-179. doi: 10.32782/2663-5941/2023.1/26.

[2] Yu. Osadchuk, Yu. Sherstnov, The method of increasing the energy efficiency of technical systems of technological units with synchronous drives by adjusting their reactive power, 2020. Patent No. 141771, Filed November 17th., 2019, Issued April 27th., 2020.

[3] Y. Xiang, L. Wang, Y. Zhang, Adequacy evaluation of electric power grids considering substation cyber vulnerabilities, International Journal of Electrical Power & Energy Systems 96 (2018) 368-379. doi:10.1016/j.ijepes.2017.10.004 .

[4] L. Li, J. Qin, H. Hu, Q. Zhang, L. Luo , Optimized operational approach for multi-type reactive power compensation to enhance the grid integration strength of newenergy clusters, Front, Energy Res 11 (2024) 11:1342770. doi: 10.3389/fenrg.2023.1342770.

[5] R. Monteiro L.F., Y.R. Rodrigues, A.C. Zambroni de Souza, Cybersecurity in Cyber–Physical Power Systems, Energies 16 12 (2023) 4556. doi:10.3390/en16124556.

[6] R. Yohanandhan, R. M. Elavarasan, P. Manoharan, L. Mihet-Popa, Cyber-Physical Power System (CPPS): A Review on Modeling, Simulation, and Analysis with Cyber Security Applications, IEEE Access 8 (2020) 151019–151064. doi:10.1109/ACCESS.2020.3016826.

[7] E. Spiliotis, F. Petropoulos, N. Kourentzes, V. Assimakopoulos, Cross-temporal aggregation: Improving the forecast accuracy of hierarchical electricity consumption, Applied Energy 261 (2019) 114339. doi: 10.1016/j.apenergy.2019.114339.

[8] N. Wei, Ch. Li, X. Peng, F. Zeng, X. Lu, Conventional models and artificial intelligence-based models for energy consumption forecasting: A review, Journal of Petroleum Science and Engineering 181 (2019) 106187. doi:10.1016/j.petrol.2019.106187.

[9] Y. He, Y. Zheng, Q. Xu, Forecasting energy consumption in Anhui province of China through two Box-Cox transformation quantile regression probability density methods, Measurement 136 (2019) 579–593. doi:10.1016/j.measurement.2019.01.008.

[10] R. Wang, Sh. Lu, W. Feng, A novel improved model for building energy consumption prediction based on model integration, Applied Energy 262 (2020) 114561. doi:10.1016/j.apenergy.2020.114561.

[11] A. Rehman, M.A. Koondhar, Z. Ali, M. Jamali, R.A. El-Sehiemy, Critical Issues of Optimal Reactive Power Compensation Based on an HVAC Transmission System for an Offshore Wind Farm, Sustainability 15 19 (2023) 14175. doi:10.3390/su151914175.

[12] J. Xiao, Y. Li, L. Xie, D. Liu, J. Huang, A hybrid model based on selective ensemble for energy consumption forecasting in China, Energy 159 (2018) 534–546. doi:10.1016/j.energy.2018.06.161.

[13] S. Karamdel, X. Liang, S.O. Faried, M. Mitolo, Optimization Models in Cyber-Physical Power Systems: A Review, IEEE Access 10 (2022) 130469–130486. doi: 10.1109/ACCESS.2022.3229626.

[14] X. Wang, S. McArthur, S. Strachan, J.D. Kirkwood, A Data Analytic Approach to Automatic Fault Diagnosis and Prognosis for Distribution Automation, IEEE Transactions on Smart Grid 9 9 (2017) 6265-6273. doi:10.1109/TSG.2017.2707107.

[15] C. Zhang, M. Liu, Y. Gao, Y. Li, Modeling and fault diagnosis of distribution networks cyber physical system based on IEC61850, sustainable Energy Technologies and Assessments 53 (2022) 102609. doi:10.1016/j.seta.2022.102609 .
[16] F. Viawan, D. Karlsson, Voltage and Reactive Power Control in Systems With Synchronous Machine-Based Distributed Generation, Power Delivery, IEEE Transactions 23 (2008) 1079-1087. doi:10.1109/TPWRD.2007.915870.
[17] M. Gholami, A.Gholami, M. Mohammadtaheri, Cyber-physical power system reliability assessment considering multi-state independent components, Electric Power Systems Research 217 (2023) 109141. doi:10.1016/j.epsr.2023.109141.
[18] H. Dirik, C. Gezegin, H. S. Dirik, Reactive power compensation with hybrid compensator combining a synchronous motor and switched capacitors, Electric Power Systems Research 216 (2023) 109010. doi:10.1016/j.epsr.2022.109010.
[19] J. Q. Wang, Y. Du, J. Wang, LSTM based long-term energy consumption prediction with periodicity, Energy 197 (2020) 117197. doi:10.1016/j.energy.2020.117197.
[20] J. P. Carvallo, P. Larsen, A. H. Sanstad, Ch. A. Goldman, Long term load forecasting accuracy in electric utility integrated resource planning, Energy Policy 119 (2018) 410–422. doi:10.1016/j.enpol.2018.04.060.