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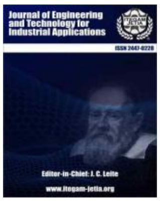

RESEARCH ARTICLE OPEN ACCESS

SWITCHING OF MEDIUM VOLTAGE CAPACITOR BANKS AND THE IMPACT OF OVERVOLTAGES ON THE COMPONENTS OF AN ELECTRICAL SYSTEM

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ABSTRACT

The study aimed to determine the regularities of switching overvoltages during the operation of medium-voltage capacitor banks and to evaluate the effectiveness of methods for their reduction. The methodology was based on a combination of mathematical modelling in specialised environments, laboratory testing of condenser plant models and statistical analysis of operational data. The results showed that the amplitude of overvoltages in capacitor banks increased from 1.6-2.0 to 2.5-3.0 relative units depending on the power, and the duration of transients exceeded 2.8 milliseconds at large capacities, which created a risk of insulation damage. The study determined that more than 90% of capacitor failures were of an insulating nature, with daily switching reducing service life by a third, and overvoltage over 2.5 relative units halving service life. The study showed that in the secondary circuits of transformers during resonant interaction, the amplitude of overvoltages reached 4.0-4.5 relative units, which led to the failure of electronic devices and premature tripping of protections. The effectiveness of the technical equipment confirmed that synchronous circuit breakers reduced the level of overvoltage to 1.2 relative units, while pre-trigger resistors and overvoltage limiters reduced it by 40-50%, but required frequent maintenance.

I. INTRODUCTION

The research relevance of the switching processes of medium-voltage capacitor banks is determined by their significant impact on the reliability and durability of electrical equipment, since switching overvoltages that occur during switching on and off exceed permissible levels and lead to accelerated ageing of insulation, damage to power elements, and disturbance of system stability. The problem is determined by the insufficient efficiency of traditional surge suppressors, such as inductive chokes or pre-actuation resistors, which reduce the amplitude of oscillations but are accompanied by increased heat losses and higher operating costs, and the need for an in-depth analysis of modern solutions, including Metal Oxide Varistor (MOV) surge arresters and synchronous circuit breakers, which demonstrate high technical efficiency but require an assessment of long-term reliability and economic feasibility.

The solution to this problem will reduce the number of emergency failures, extend the service life of capacitors, transformers, induction motors and power electronics, ensure the stability of power grids and increase their energy efficiency, which determines the relevance of an integrated approach to the analysis and optimisation of switching overvoltage reduction methods in the modern power industry.According to [1] demonstrated that the use of time-frequency analysis methods can be used to identify the characteristic signatures of switching overvoltages in medium-voltage networks. This made it possible to detect critical modes with high accuracy and distinguish them from other types of disturbances. According to [2] proved that the choice of the type of switchgear significantly affects the quality of electricity and the level of transient overvoltages.

The study determined that synchronised circuit breakers and specialised devices provide a significant reduction in peak values, which contributes to the stability of the network. In [3] confirmed that the switching of capacitor banks is a source of complex transients that propagate through the power grid and could be amplified in resonant conditions. According to [4] found that the operation of wind power plants creates voltage fluctuations and flicker, which complicates grid stability and increases the risks of capacitor switching. In [5] proved that the integration of vehicle-grid integration technologies changed load profiles and dispatch modes, which indirectly affects the conditions for the formation of overvoltages. According to [6] found that the combination of photovoltaic power plants with hydropower facilities created new scenarios for the distribution of reactive power, which increased the load on capacitor plants. According to [7] demonstrated that the integration of distributed generation based on solar panels changed the characteristics of short-circuit power and contributed to the emergence of unstable switching modes.

According to [8] found that timely detection of overvoltage in high-voltage shunt banks provides early warning of damage, which can improve operational reliability. As a result, the study outlined the significance of diagnosing overvoltages and their connection with new modes of grid operation. Proved that active methods of controlling overcurrents and overvoltages in shunt capacitor banks provide a reduction in peak values and a reduction in the duration of oscillations [9]. According to [10] demonstrated the effectiveness of protection based on resistance-capacitance elements that suppress residual overvoltages during the switching of parallel capacitor banks. The results confirmed the feasibility of using combined methods to reduce the impact of transients. According to [11] found that the use of metal-oxide varistors and spark gaps protects series capacitors in compensated lines from dangerous pulses. In [12] proved that the use of a fuzzy inference system (FIS) can be used to classify switching events at high-voltage substations with a high degree of accuracy.

Thus, both studies confirmed the effectiveness of using both hardware and intelligent methods to control and limit overvoltages. Despite the results obtained, certain gaps were identified in the existing works. The long-term degradation of protective devices under the influence of repeated switching processes and their impact on operational reliability have not been sufficiently investigated. The impact of three-phase asymmetry, grounding configurations and line parameters on the spectrum and amplitudes of overvoltages was considered to a limited extent. There were no large-scale field experiments that would combine technical analysis with economic assessments of different protection methods. There was also a lack of agreed methodologies that could be used to reproduce the results in the practical conditions of modern grids with a high share of renewable sources. The study aimed to establish the patterns of occurrence and development of switching overvoltages in medium-voltage networks with capacitor banks and determine their impact on the reliability of electrical system elements, as well as to assess the effectiveness of technical protection means.

To achieve this goal, several tasks were set that corresponded to the structure of the analysis: conduct empirical research on the switching processes of medium-voltage capacitor banks, taking into account the amplitudes and duration of transient processes; assess the impact of switching overvoltages on the operation and durability of capacitor installations based on the results of experimental and statistical observations; identify the characteristics of the effect of overvoltages on asynchronous motors, transformers and power electronics under conditions of resonant interaction of system elements; conduct an empirical comparison of various methods for reducing switching overvoltages, including inductive chokes, pre-switching resistors, metal-oxide varistor surge arresters and synchronous switches, considering their technical and economic efficiency.

II. MATERIALS AND METHODS

The type of research conducted was defined as comprehensive experimental and theoretical, involving mathematical modelling, laboratory testing and statistical analysis. The chronological framework covered the period 2021-2025, which made it possible to take into account the various stages of process development: from short-term transient phenomena during the switching of medium-voltage capacitor banks to the cumulative effects of degradation of electrical system components. During this period, systematic laboratory tests were conducted on models of capacitor installations with the recording of instantaneous current and voltage values, which made it possible to reproduce the characteristic operating conditions of industrial power grids. The tests were conducted at the Polytechnic University of Tirana, Faculty of Electrical Engineering, where more than 50 series of switching cycles were performed for each type of capacitor. In parallel, statistical data obtained in industrial conditions were analysed, which made it possible to compare the simulation results with real operational observations. This integrated approach within the selected time frame made it possible not only to identify patterns in the formation of switching overvoltages but also to assess their impact on equipment durability and the effectiveness of various protection methods.

The initial data collection was based on the results of laboratory experiments conducted using medium-voltage capacitor bank models of the ABB Capacitor Bank Models MSCDN (Switzerland) type with a rated power of 150 to 300 kVAr. For this purpose, high-speed oscilloscopes with a time resolution of up to microseconds were used to record instantaneous voltage and current values during the equipment switching on and off processes. Tektronix DPO 4104 oscilloscopes (USA, 1 GHz, 5 GS/s) were used, providing a resolution of up to 1 μs. The capacitors belonged to the metallised polypropylene class with a rated breakdown voltage of 10-15 kV. Additionally, the results of bench tests of capacitor installations in industrial conditions were taken into account, where the monitoring of insulation parameters, the response time of protective devices and the failure rate was conducted using the Omicron CPC 100 measuring complex (Austria) and the Fluke 1738 power analyser (USA).

The collected experimental data were supplemented with statistical information from the operational logs of energy companies, which contained records of the number of switching operations, the service life of capacitor elements, and typical types of damage. The analysis also considered data on four groups of industrial manufacturers of capacitor banks. To maintain confidentiality and avoid commercial bias in the work, they were designated with the letters A-D. This approach ensured a fair comparison without disclosing commercially sensitive information. The study used comprehensive methods, including mathematical modelling, laboratory experiments, partial discharge diagnostics and statistical analysis. Each of these approaches ensured the recording of certain characteristics of the switching processes of medium voltage capacitor banks, which made it possible to reproduce a complete picture of their impact on electrical systems. The use of a multi-level methodology made it possible to combine transient simulations in computer modelling environments with field tests, which guaranteed high reliability of the results.

Mathematical modelling was performed in [13-15] environments. The constructed models reproduced the switching processes of capacitor banks in the power range from 150 to 300 kVAr at an operating voltage of 6-35 kV. Various grounding modes, connection configurations, and connection inductance parameters were considered. Particular attention was paid to the formation of voltage at the capacitor terminals after disconnection, which was described by the ratio (1) that determines the possibility of overvoltage three times higher than the nominal value.

$$\mathrm{U_c(t)} \approx +3\mathrm{U}_n \text{if } \mathrm{C} \gg \mathrm{C_s} \tag{1}$$

Where $\mathrm{U_c}$ – instantaneous value of the voltage across the capacitor after disconnection, U_n – the rated voltage, C – capacitance of the capacitor bank, $\mathrm{C_s}$ – system capacitance. This ratio determines the possibility of an overvoltage of three times the rated voltage. The models were used to calculate time diagrams of voltages and currents, determine the conditions for the occurrence of oscillatory processes, and develop scenarios for changing the phase angle at the time of switching. An inverse power model was used to assess the durability of insulating materials:

$$L = \mathrm{L_H}\left(\frac{E}{\mathrm{E_H}}\right)^{-n} \tag{2}$$

where L – predicted service life of the insulation, $\mathrm{L_H}$ – the reference service life at voltage, E – the effective electric field strength, $\mathrm{E_H}$– reference voltage value, n – material endurance factor. The equations were numerically integrated using the fourth-order Runge-Kutta method, which reproduced unsteady-state modes with high accuracy. The modelling variables were the switching moment relative to the phase angle, the capacitance and the inductance of the branches. In addition, the Miner's rule was used to analyse the impact of multiple switching:

$$\sum_{i=0}^{N} \frac{\mathrm{t_{pi}}}{\mathrm{L(V_{pi})}} = 1 \tag{3}$$

Where $\mathrm{t_{pi}}$ – duration of the i-th overvoltage pulse, $\mathrm{LV_{pi}}$ – insulation service life at the amplitude voltage $\mathrm{V_{pi}}$, N – number of switching operations. This ratio determined the cumulative effect of overvoltages and calculate the reliability limit for repeated switching on. For cases with a stochastic distribution of overvoltage amplitudes, the integral form of the rule was used:

$$L = \frac{1}{\int_0^{\infty} \frac{\mathrm{F(V_p)}}{\mathrm{L(V_p)}} \mathrm{dV_p}} \tag{4}$$

Where $\int_0^{\infty} \frac{\mathrm{F(V_p)}}{\mathrm{L(V_p)}} \mathrm{dV_p}$ – probability density function of peak overvoltage values, $\mathrm{V_p}$ – random variable characterising the peak pulse amplitude. The application of this relationship addressed the random nature of the formation of pulses in the network and to quantify the probability of reducing the insulation life in operation. Thus, the mathematical modelling provided the ability to reproduce the actual operating conditions of capacitor banks and quantified the impact of switching modes on both short-term overvoltages and long-term degradation of insulating materials.

Laboratory experiments were conducted using models of medium-voltage capacitor banks assembled under controlled conditions. To record the process parameters, high-speed Tektronix MSO64 digital oscilloscopes (USA) with microsecond resolution were used, which ensured the registration of transient pulses and oscillations. During the tests, the switching conditions, capacitance parameters, load modes and connection schemes were changed, which made it possible to obtain a wide range of experimental data. The research was conducted at a temperature of 20±2°C and a relative humidity of 50-60%. For each mode, at least 30 repeated switching cycles were performed. ABB DS1 (Switzerland) synchronous switches were tested separately to compare their characteristics with traditional switching devices.

Partial discharge diagnostic methods were used to assess the condition of capacitor dielectric materials. Equipment was used to measure the threshold voltage levels of partial discharge occurrence, which identified initial defects and trends in the degradation of insulation systems. Partial discharges in polypropylene dielectrics were recorded using measuring devices capable of determining the amplitude, frequency and time duration of pulses. An Omicron MPD 600 device with a sensitivity range of 2-2000 pC was used for the measurements, which identified the initial stages of insulation degradation.

This assessed the impact of repeated switching on the development of microbreakdowns and local defects. Statistical analysis was used to quantitatively evaluate the obtained data. Methods of multifactorial comparison, correlation analysis, and approximation of dependencies were used, which was used to generalise a large number of experimental and model observations. Additionally, Miner's rule [16] was applied to determine the cumulative effect of transient processes, and methods for constructing inverse dependencies of durability on electric field strength were used to predict the service life of insulating materials.

The statistical significance was verified using Student's t-test, Mann-Whitney test, and Fisher's test, which ensured the correctness of the generalisations. The χ^2 test was also used to assess the conformity of experimental damage distributions with theoretical ones. Data processing was performed in IBM SPSS Statistics 26 (IBM Corporation, USA) and R 4.3.1 (R Foundation for Statistical Computing, Austria). The data obtained were interpreted by combining the results of modelling, laboratory tests and statistical analysis. A systematic approach was used to assess the relationships between switching conditions, equipment characteristics and the effectiveness of protective measures.

This approach ensured consistency between different data sources and provided a holistic view of the mechanisms of switching overvoltages and their impact on the reliability of electrical systems. Thus, the combination of numerical modelling, experimental measurements and statistical verification ensured that the results were representative and reproducible.

III. RESULTS

III.1 EMPIRICAL ANALYSIS OF THE SWITCHING PROCESS OF MEDIUM VOLTAGE CAPACITOR BANKS

Experimental studies of the switching processes of medium voltage capacitor banks have shown that the level of overvoltage and the duration of transients are directly dependent on the capacity of the installed equipment. The study determined that with the increase in the capacity of capacitor banks, the inertia of charging and discharging processes increases, resulting in the formation of longer oscillatory modes with increased amplitudes. This makes it difficult to control the switching conditions and puts an additional strain on the insulation of electrical system components. The accumulation of such processes during the operational period can lead to accelerated ageing of equipment, which emphasises the need for their systematic analysis.

To present the results obtained, a summary Table 1 was compiled, which demonstrates the ranges of overvoltage amplitudes and transient duration in different operating modes. It contains data for capacitor banks with capacities ranging from 150 to 300 kVAr, which traces the pattern of increasing amplitude and duration of oscillations with increasing capacity. This systematisation makes it possible to compare different classes of equipment and provides a quantitative basis for further modelling in software environments and predicting system behaviour under repeated switching conditions.

Table 1: Experimentally recorded ranges of overvoltage amplitudes and duration of transients in capacitor banks of different capacitance.

Bank capacity, kVAr	Amplitude of overvoltages, pu	Transition time, ms	Features of the observations
150	1.6-2.0	0.8-1.2	Short oscillation processes; rare cases of repeated breakdown
200	1.9-2.4	1.1-1.6	Increased peak values; increased likelihood of current recycling
250	2.2-2.7	1.5-2.1	Fixed repeated breakdowns; increased stress on insulation
300	2.5-3.0	2.0-2.8	Long-term oscillating modes; significant risk of damage at isolated neutral

Note: kVAr – reactive power in kilovolt-amperes; pu (per unit) – relative value normalised by the rated voltage determined by formula (1); ms – milliseconds.
Source: Authors, (2026).

With the increase of the capacitor bank capacity, the amplitude of overvoltages increases from the range of 1.6-2.0 pu to the level of 2.5-3.0 pu, which corresponds to an increase of approximately 50-70% compared to the initial values. At the same time, the duration of transient processes more than doubles from 0.8-1.2 ms to 2.0-2.8 ms, which indicates the formation of longer oscillatory modes. The obtained data confirm the direct dependence between the capacitor capacity and the energy stability of oscillations in the system, which directly affects the insulation load. With large capacitances, the probability of repeated breakdown and the occurrence of long-term oscillations that can lead to the degradation of dielectric materials and damage to equipment is significantly increased.

Thus, the results of the experiments highlight the need to incorporate the capacity of capacitor banks when selecting switchgear and applying surge suppression measures. To explain in detail the mechanisms of formation of these phenomena, the study uses simplified electrical models that can be used to reproduce typical switching conditions and trace the interaction of inductive and capacitive elements of the circuit. Figure 1 shows a basic circuit that serves as the basis for modelling transients and quantifying the voltage across system elements. Its use makes it possible to identify the key parameters that determine the amplitude of overvoltages, the duration of oscillatory processes and the overall stability of the power grid, which is critical for developing effective protection methods.

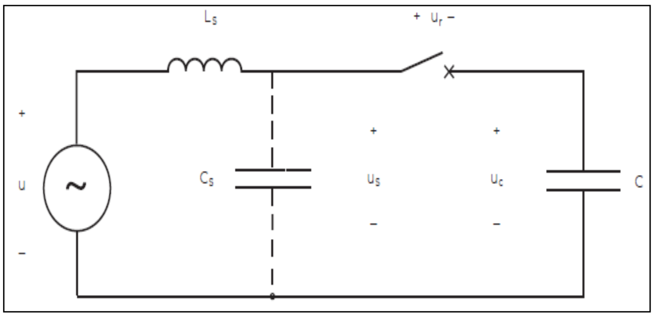

Figure 1: Simplified switching diagram of a medium voltage capacitor bank.
Source: Authors, (2026).

The main elements are an alternating voltage source U, a series inductor Ls, a capacitor Cs, and a switched capacitor C, which is connected by a switch. At the moment of switching, a voltage ur is generated, which is the result of the interaction of voltages us and uc applied to the respective capacitors.

The appearance of this voltage is accompanied by oscillatory processes, the value of which is determined by the parameters of inductance and capacitance, as well as the phase angle of the switching moment relative to the source. Under unfavourable conditions, a repeated breakdown in the circuit breaker and current recirculation can occur, which creates additional electrodynamic loads on the insulating and switching elements of the system. The diagram is the basis for further mathematical description, as it can be used to quantify the impact of circuit parameters on the amplitude of overvoltages, the duration of transients, and to determine the critical operating modes of capacitor plants.

For further analysis of these phenomena, it is necessary to graphically display time dependencies that can be used to trace the dynamics of changes in electrical quantities at the time of switching. Figure 2 shows time diagrams that demonstrate the characteristic oscillatory processes of voltage and current in a circuit with capacitor banks. They make it possible to trace the relationship between the instantaneous values of us, uc and current i, as well as to identify the conditions for the formation of peak overvoltages. Such graphical dependencies are a tool for qualitative assessment of the processes occurring in the first milliseconds after switching and can be used to determine their impact on the electrical strength of insulation and the durability of system elements.

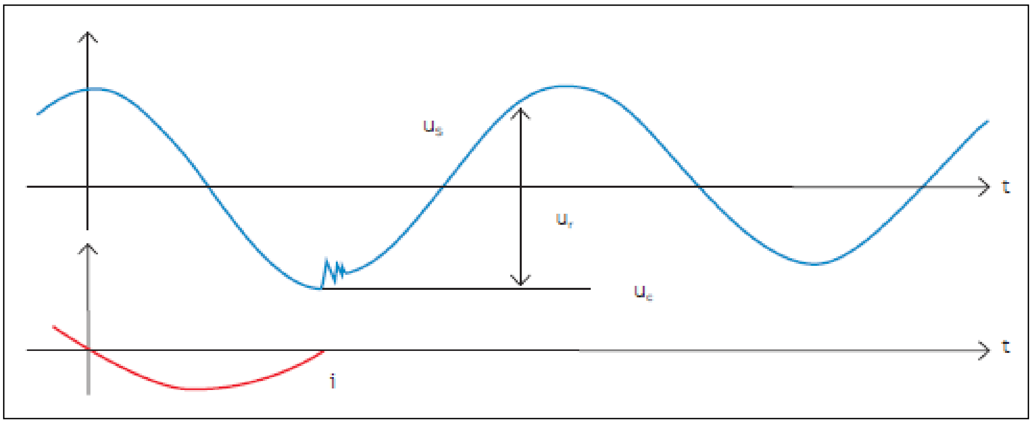

Figure 2: Time diagrams of voltage and current during capacitor bank switching.
Source: Authors, (2026).

At the moment of switching, an instantaneous voltage us is formed, which, together with the voltage uc across the capacitor, determines the resulting value ur. The recorded time diagrams indicate the oscillatory nature of the voltage, the peak values of which significantly exceed the amplitude of the sinusoidal voltage of the source. At the same time, the current i at the initial moment undergoes a sharp decline with the formation of a negative half-wave, after which it gradually stabilises at a new level. The observed oscillatory modes are accompanied by short-term high-frequency pulses, which can create a dangerous electrical load on the insulation of equipment and accelerate the process of its ageing.

The obtained results confirm that the moment of switching is a determining factor in the formation of overvoltage, and therefore requires consideration during the selection of protective devices and the establishment of optimal operating modes of capacitor banks. The phenomenon of arc re-arcing in the circuit breaker deserves special attention in the study, which is one of the most dangerous mechanisms of switching overvoltages. Figure 3 shows the time diagrams illustrating the change in voltage and current during the re-arcing after the circuit break. These processes are characteristic of traditional switchgear, where the moment of switching off is not synchronised with the phase of the source voltage. This creates conditions for the occurrence of repeated oscillatory processes and an increase in the load on the insulation systems, which directly affects the durability and operational reliability of the equipment.

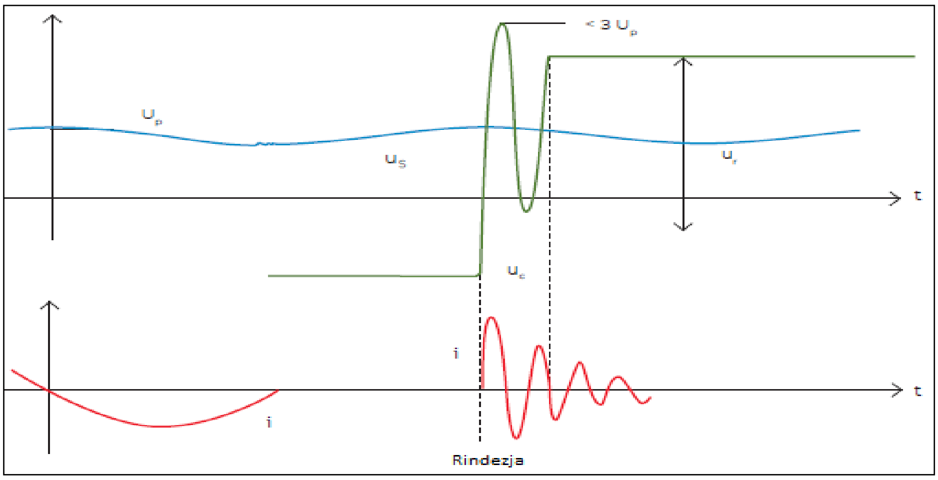

Figure 3: Time diagrams of overvoltage and current during repeated arc faults in a circuit breaker.
Note: “Rindezja” – “tension”.
Source: Authors, (2026).

After the circuit break, the voltage across the capacitor uc increases sharply and can exceed the initial value by almost three times (up to <3Up). Such a voltage jump is accompanied by the formation of high-frequency oscillations, which are manifested in the form of an oscillating current i after a repeated breakdown (rindezja). The results obtained indicate that these processes create significant electrodynamic and thermal loads on the circuit breaker contacts and insulating materials, reducing their durability. In addition, the oscillatory nature of the current can contribute to resonant interaction with other elements of the electrical network, which increases the risk of emergency modes.

The presented time dependencies confirm the critical influence of the moment of re-breakdown on the amplitude of overvoltages and prove the feasibility of using synchronous circuit breakers or specialised limiters to improve system reliability. Analysing transients in three-phase networks, it is necessary to address the connection options for capacitor banks, since it is the connection configuration that determines the nature of voltage distribution and the likelihood of dangerous overvoltages. Figure 4 shows typical schemes for connecting capacitor banks to the grid, which differ in the way they are connected and the organisation of grounding. Such structural models can be used to assess how different connection modes affect phase symmetry, stability of electrical processes and risks of equipment damage, which is key when making recommendations for optimal system configuration.

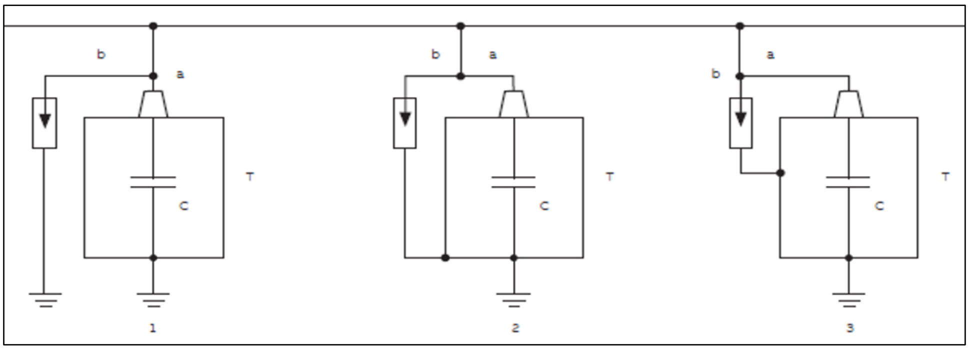

Figure 4: Options for connecting capacitor banks in a three-phase network.
Source: Authors, (2026).

The choice of the capacitor bank connection scheme directly affects both the distribution of potentials between the phases and the conditions for the occurrence of overvoltages in transient modes. Scheme 1 is characterised by a relatively symmetrical load distribution between the phases, but in the case of a mismatch in the switching moment, an increase in the voltage amplitude in the first phase is recorded compared to the others. Scheme 2 partially reduces the level of overvoltage due to the changed grounding mode, but at the same time creates increased current loads on the switchgear during switching. Scheme 3 demonstrates a mixed nature of the processes, in which the amplitude of overvoltages increases, but the duration of oscillations is shorter than in the previous cases.

Thus, the results confirm that the choice of the connection scheme is a determining factor in ensuring optimal operating conditions for capacitor plants and minimising the risk of equipment damage in medium voltage networks. In the course of the study of switching modes, the efficiency of traditional circuit breakers and synchronous devices, which are the most common in the practice of operating electrical networks, was also compared. Experimental results showed that the maximum values of peak overvoltages, the duration of oscillatory processes after switching, and the probability of repeated arc breakdown directly depend on the type of circuit breaker. The systematisation of these data made it possible to summarise the differences between different classes of switching devices and present them in Table 2, which provides a visual comparison of key parameters.

Table 2: Comparison of test results for conventional circuit breakers and synchronous devices.

Type of switching device	**Level of peak overvoltages, pu**	**Oscillation duration, ms**	**Probability of repeated breakdown, %**
Traditional switch	2.2-3.0	2.0-3.5	25-35
Synchronous switch	1.0-1.5	0.5-1.2	<5

Note: pu (per unit) – relative value, normalised by nominal voltage, determined by formula (1); ms – milliseconds.
Source: [13-15].

The use of traditional circuit breakers is accompanied by significantly higher levels of peak overvoltage, which can reach 3.0 pu, while for synchronous devices this figure does not exceed 1.5 pu. The duration of oscillation processes in traditional circuit breakers is, on average, three times longer, which creates an additional thermal and electrodynamic load on the insulating elements and reduces their durability. At the same time, the probability of a repeated breakdown in traditional devices reaches 35%, while in synchronous devices it is practically zero. The summarised data clearly demonstrate the advantages of using synchronous circuit breakers, which ensure reliable switching and contribute to the operational stability of medium-voltage power grids.The obtained results confirm that the nature of switching overvoltages is determined not only by the capacity of capacitor banks and circuit parameters, but also by the choice of the type of switching apparatus and the connection scheme.

The established dependencies demonstrate that even minor differences in switching modes can lead to significant fluctuations in the amplitude and duration of overvoltages, which in some cases exceed the permissible limits for isolation. This highlights the need for a comprehensive consideration of all design and operational factors when designing and upgrading systems with capacitor banks. Thus, the analysis has empirically proved that switching overvoltages are a determining factor in the reliability of medium voltage capacitor banks. The established regularities form the basis for further research aimed to assess their long-term impact on the capacitive elements of the system and determining the mechanisms of gradual ageing of dielectric materials. This provides a logical transition to the next subsection, which is devoted to an empirical analysis of the impact of overvoltages on the operation and durability of capacitors.

III.2 AN EMPIRICAL STUDY OF THE EFFECT OF OVERVOLTAGES ON THE OPERATION AND DURABILITY OF CAPACITORS

In the process of studying the durability and reliability of capacitor banks, it is of particular importance to consider their internal structure, since it is the design features that determine the ability of the equipment to withstand switching overvoltages and thermal overloads. Practical observations and operational statistics confirm that the most vulnerable components are insulating materials, fuses and discharge resistors, which are subject to repeated electrical and thermal effects. Such elements often initiate degradation processes, which eventually lead to a decrease in the electrical strength of the system. Accordingly, a detailed analysis of the structural characteristics of capacitor banks is used not only to identify the main damage mechanisms but also to develop practical recommendations for improving their reliability and extending their service life.

Figure 5 shows a schematic representation of the structure of a capacitor bank, which reflects the spatial arrangement of the main elements and their interaction as part of a single system. This model includes both external components that provide connection and insulation, and internal elements such as working sections, discharge resistors, fuses, and a metal shell. The use of this structural diagram makes it possible to visualise the key components of the equipment, trace their functional role and identify the parts most vulnerable to switching overvoltages and thermal loads. This creates the preconditions for a reasonable development of measures to improve the operational stability of capacitor banks in medium voltage networks.

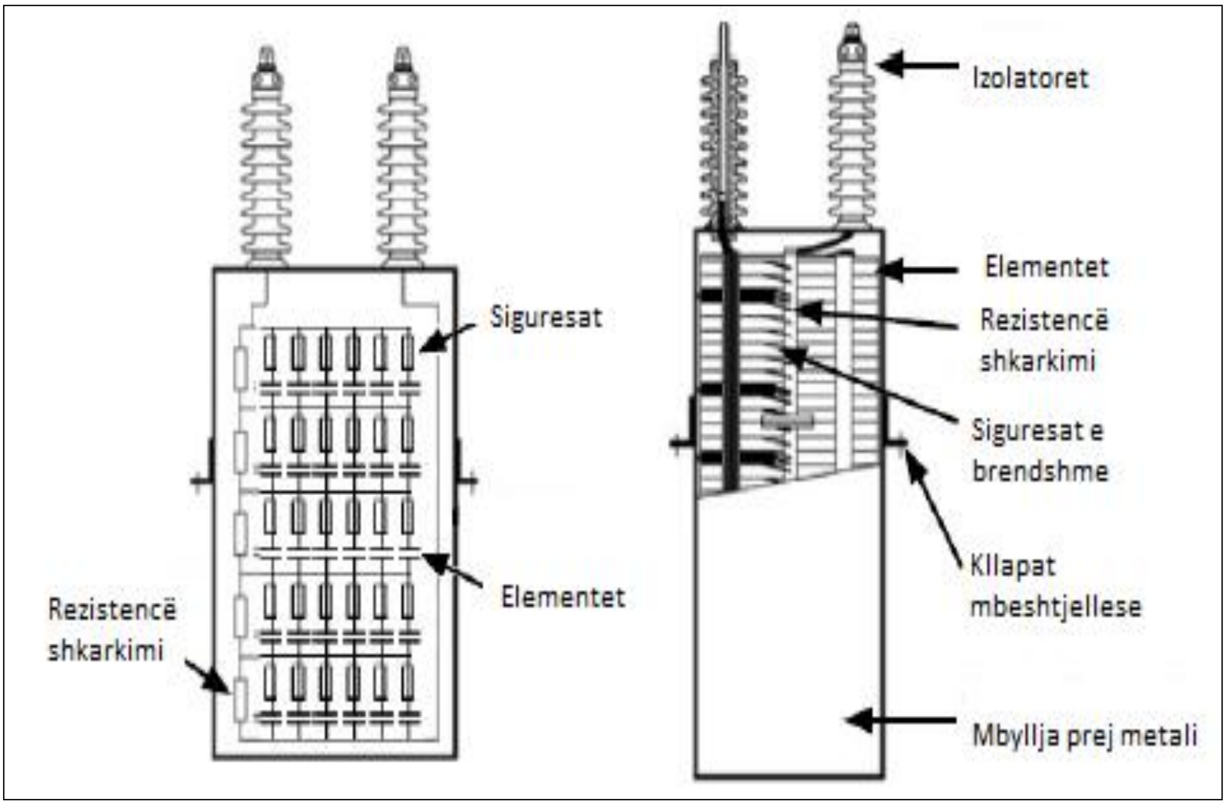

Figure 5: Structural design of the medium voltage capacitor bank.
Note: Elements – individual sections of capacitors that form the bank; Rezistencë shkarkimi – resistors designed to discharge capacitors after shutdown; siguresat – fuses that protect against internal damage; izolatorët – external insulation parts; mbyllja prej metali – metal shell of the case.
Source: Authors, (2026).

The design of the capacitor bank is a multi-level system in which each element performs a specific function to ensure stable and reliable operation of the equipment [17],[18]. The insulators form an electrical barrier and minimise the probability of breakdown between phases, which is critical to maintaining the integrity of the insulation system. The working elements of the bank are connected to discharge resistors that provide a rapid reduction in residual voltage after disconnection, which prevents unwanted charge build-up [19],[20]. The fuses are integrated both externally and internally, which can be used for localised damage and prevents it from spreading to other parts of the plant in the event of a breakdown. The metal shell serves as mechanical protection and electrical shielding, isolating the internal components from external influences [21].

Thus, the reliability of a capacitor bank is determined by a combination of design and protection solutions that must be addressed at the design, production, and operation stages. In the context of studying the impact of switching overvoltages on the durability of capacitor banks, a substantial task is to identify the characteristic damages that most often lead to equipment failures. The results of the statistical analysis of operational data showed that the vast majority of failures are caused by insulation defects, among which partial discharges and local breakdowns dominate. Other damages, such as degradation of impregnating fluids or mechanical defects, are less systematic but also affect the overall reliability of the system. To summarise the results, Table 3 shows the distribution of capacitor failures by the main types of insulation damage with the corresponding percentage.

Table 3: Distribution of capacitor failures by type of insulation damage.

Type of insulation damage	**Failure rate, %**
Partial discharges	48
Localised breakdowns	27
Degradation of impregnating fluids	15
Other defects (mechanical, structural)	10
Total	100

Note: “Partial discharges” denote localised microelectric discharges inside the dielectric; “local breakdowns” – insulation breakdowns in places of field concentration; “degradation of impregnating fluids” includes changes in their electrical and physicochemical properties under the influence of pulse loads. The impact of the identified damage mechanisms on the service life is further quantifiedusing formula (2).

Source: Authors, (2026).

The most common type of damage is partial discharge, which accounts for almost half of all recorded failures and is the main factor in the gradual ageing of dielectric materials. Localised breakdowns account for more than a quarter of the total number of failures and mostly occur in areas with uneven electric field distribution and concentrated stress [22]. Degradation of impregnating fluids is less common, but its impact on equipment durability is significant in the case of long-term operation, as it reduces the dielectric strength and thermal stability of the system. Other defects, such as mechanical damage or design flaws, are less systematic, but their share is significant and indicates the need to accommodate additional factors in the maintenance process [23].

Thus, the results confirm that the priority area of diagnostics should be the detection of early manifestations of partial discharges and local breakdowns as key predictors of capacitor system failures. For a comprehensive research of the nature of capacitor bank failures, it is necessary to break them down by manufacturer, as design features, material quality and manufacturing technology directly affect operational reliability. To this end, a comparative analysis of the frequency of damage to the main insulation, oil leakage and insulator defects in capacitor banks from different manufacturers was carried out. This approach makes it possible to identify the predominant failure mechanisms within each group of equipment and to determine the specific patterns inherent in the products of individual manufacturers. The results of this comparison are summarised in Table 4.

Table 4: Distribution of capacitor failures by types of damage and manufacturers.

Producer	**N_0, unit**	**Basic insulation, units**	**Basic insulation, %**	**Oil leaks, units**	**Oil leakage, %**	**Insulator, unit**	**Insulator, %**
A	325	306	94.15	10	3.08	9	2.77
B	150	137	91.33	11	7.33	2	1.34
C	38	36	94.74	1	2.63	1	2.63
D	23	17	73.91	5	21.74	1	4.35
Total	536	496	92.54	27	5.04	13	2.42

Note: N_0 – total number of capacitor elements examined; indicators are given separately for damage to the main insulation, oil leaks, and insulator defects in natural units and as a percentage of the total number; The expected reduction in service life for each manufacturer group was estimated using formula (2), accomodating the cumulation of damage according to Miner’s rule (3).

Source: Authors, (2026).

The main share of damage is caused by insulation defects, which account for more than 92% of all failures, regardless of the manufacturer. The most reliable in this category are capacitors from manufacturers A and C, where the share of insulation damage exceeds 94%, while the figure for manufacturer D is much lower (73.91%), indicating an increased vulnerability of the equipment. Oil leaks account for about 5% of failures on average, but for manufacturer D, this figure reaches 21.74%, indicating design or process defects. Insulator defects account for a small share of the total (2.42%), but their presence in all manufacturers indicates a systemic problem.

Thus, the results confirm that insulation damage remains the main problem, while oil leaks are also a significant reliability factor for some manufacturers. When assessing the durability of capacitor banks, it is necessary to address their operating conditions, as the frequency of switching has a significant impact on the level of damage. Operational statistics show that equipment subjected to daily switching on and off is subjected to a higher load than installations in constant operation. To quantitatively compare these dependencies, the study analysed the frequency of defects in capacitor banks under different operating conditions. The results are summarised in Table 5.

Table 5: Analysis of damage to capacitor banks depending on switching frequency.

Operating conditions	**Switch on at least once a day**	**Always operational**	**Total**
Total number of banks	2450	462	2912
Banks with defects	293	37	330
Share of damages, %	12	8	11.3

Note: “Defective banks” are defined as installations with recorded insulation damage, oil leaks or mechanical defects; “damage share” – percentage of defective banks to the total number within the respective group; the cumulative effect of daily switching on insulation degradation is determined by the Miner’s rule (3).

Source: Authors, (2026).

Capacitor banks that are subject to regular daily switching are the most vulnerable to damage. In this group, the share of defects is 12%, which is 50% higher than the share of equipment in constant operation (8%). Overall, 11.3% of the banks in the sample had damage, which is significant for equipment with a long service life. The results show that the frequency of switching is one of the key factors in the degradation of insulating materials and the reduction of capacitor life. This emphasises the need to limit the number of switching operations in practical operation or to apply additional protection measures that can reduce the impact of switching overvoltages.

Studies of the durability of capacitor banks have confirmed that both the amplitude of switching overvoltages and the frequency of repeated switching have a significant impact on their service life. Elevated voltage values create conditions for accelerated dielectric ageing and increase the probability of local breakdowns, while regular switching increases the cumulative effect of damage [24]. To quantitatively summarise these patterns, a model has been developed that demonstrates the dependence of the average service life of capacitors on the amplitude of overvoltages (pu) and the number of switching operations per day. The results are summarised in Table 6.

Table 6: Dependence of the average service life of capacitors on the amplitude and frequency of switching overvoltages.

Amplitude of overvoltages, pu	1 switching event/day	5 switching events/day	10 switching events/day
1.5	~22 years	~18 years	~15 years
2.0	~17 years	~13 years	~10 years
2.5	~12 years	~8 years	~6 years

Note: pu (per unit) – relative voltage value normalised to the nominal value; the number of switching operations per day determines the average frequency of switching capacitor banks on and off in real operating conditions.

Source: Authors, (2026).

The service life of capacitors decreases both with the increase in the amplitude of switching overvoltages and with the increase in the switching frequency. At an amplitude of 1.5 pu, even with 10 daily switching operations, the average service life is about 15 years, while at an amplitude of 2.5 pu, this figure is reduced to 6 years. The most critical is the combination of high overvoltages and frequent switching, as it creates conditions for accelerated degradation of dielectric materials and significantly increases the risk of local breakdowns [25]. The results confirm the need to simultaneously control both the amplitude of overvoltage and the number of daily switching operations, as the balance of these parameters determines the durability of capacitor banks. Thus, limiting the level of overvoltage and reducing the frequency of switching should be considered as key measures in the strategy to improve the reliability and economic efficiency of equipment operation.

Studies of operational statistics have also shown that damage in capacitor banks is not always limited to single defects, but often occurs simultaneously in several elements of the same installation. This pattern indicates a systemic nature of failures, caused by both design features and technological factors inherent in the products of individual manufacturers. To quantify this phenomenon, the study analysed the distribution of failures, which determined the frequency of cases with two or three defects within one banking unit. The results are summarised in Table 7.

Table 7: Distribution of damage in capacitor banks by manufacturer and the number of defects in one bank.

Producer	Total number of banks with damage	Total number of damages	2 damages in one bank: banks	2 damages in one bank: units	3 damages in one bank: banks	3 damages in one bank: units
A	215	325	48	96	32	96
B	103	150	41	82	4	12
C	26	38	8	16	2	6
D	21	23	3	6	0	0
Other	2	5	0	0	0	0
Total	365	541	100	200	38	114

Note: “Banks” – number of installations with simultaneous damages; “units” – total number of damaged capacitor elements within these banks; the probability of simultaneous occurrence of two or more damages within one installation was estimated using a stochastic approach using the integral form (4).

Source: Authors, (2026).

The largest number of systemic failures occurred in vendor A, where 325 defects were recorded, many of which occurred simultaneously in several elements of the same banking system. In particular, 48 banks had two defects each, and another 32 had three at once, indicating a high probability of group failures. Vendor B is also characterised by a significant number of systemic defects, but their intensity is lower. Manufacturers C and D show lower absolute numbers, but the presence of repeated failures within the same plant confirms that the problem is typical for different manufacturers. In general, the data obtained indicate that failures in capacitor banks are systemic in nature and often involve several elements at the same time, which should be taken into account when predicting operational reliability and organising preventive maintenance.

To summarise the results of this section, it is possible to state that the durability and reliability of capacitor banks are determined by a combination of design features, manufacturing quality and operating conditions. Insulation defects have the greatest impact on the formation of damage, which is aggravated by switching overvoltages, high switching frequency and specific technological shortcomings of individual manufacturers. Regular statistical observations have confirmed that failures are often grouped and occur simultaneously in several elements of the same installation. The results obtained form the basis for further searching for effective protection methods that can minimise the negative impact of switching overvoltages and ensure increased operational stability of electrical systems.

III.3 THE IMPACT OF SWITCHING OVERVOLTAGES ON OTHER COMPONENTS OF THE ELECTRICAL SYSTEM: EMPIRICAL OBSERVATIONS

During the operation of asynchronous motors, one of the key factors that determines their reliability is the impact of switching overvoltages generated by the interaction with medium voltage capacitor banks. The configuration of the capacitor banks directly determines the level of residual voltage at the motor terminals and the duration of transient oscillations after the motor is switched off. These parameters are critical, as they determine the electrical and thermal loads on the winding insulation, affect the correct operation of relay protection and form the actual service life of electrical machines.

To quantify the impact of different connection modes, the overvoltage amplitude and duration of transients were measured under conditions most typical of industrial electrical installations. In particular, the modes of parallel operation of a motor with a capacitor bank, its long-term connection, and frequent switching scenarios were studied. The data obtained made it possible to trace the dynamics of changes in electrical parameters in each case and identify critical conditions that significantly affect the operational reliability of the equipment. The results of the experimental observations are summarised in Table 8.

Table 8: Results of overvoltage measurements at the terminals of induction motors with different capacitor connection configurations.

Capacitor bank connection configuration	Range of overvoltages, pu	Oscillation duration, ms	Observable effects
Parallel operations	1.6-1.8	1.2-1.6	Impulse overloads in windings
Long-term connection	1.8-2.2	1.8-2.4	Additional heating of the insulation reduces service life
Frequent switching	2.0-2.5	2.5-3.2	Premature tripping of the relay, risk of winding breakdown

Note: pu (per unit) – relative voltage value normalised to the nominal value; the duration of oscillations was determined by the voltage stabilisation time after the motor was switched off.

Source: Authors, (2026).

The lowest overvoltages are observed in the mode of parallel operation of the motor and the capacitor bank, where the values do not exceed 1.8 pu. However, even in this case, impulse overloads in the windings were recorded, which can accelerate the ageing of insulation. Under conditions of prolonged connection, the amplitude of overvoltages increased to 2.2 pu, and the duration of oscillations doubled compared to the previous mode, which caused additional heating of the windings and a decrease in their service life. The most dangerous conditions were those of frequent switching, when the overvoltage reached 2.5 pu and the oscillation duration exceeded 3 ms, which posed a threat to the windings' integrity and provoked premature tripping of the relay protection. Thus, the results obtained confirm the critical dependence of the level of overvoltage and motor reliability on the modes of capacitor connection, which should be addressed when operating and designing power supply systems.

A substantial condition for ensuring the reliability of electrical systems is to address the possibility of resonant interaction between capacitor installations of different voltage levels. A particular danger is posed when medium-voltage capacitors operate simultaneously with low-voltage capacitors, which creates the prerequisites for increasing the amplitude of overvoltages in the secondary circuits of transformers [26]. To illustrate these modes, a block diagram was built to show the characteristic connections between the system elements. Figure 6 shows a generalised diagram of the interaction of medium and low voltage capacitor banks, which can be used to trace the possibility of resonant amplification of oscillations in secondary circuits. It shows the connection of a medium voltage capacitor bank (C_4) and low voltage banks (C_2, C_3) through a transformer supplying an induction motor (M). This approach makes it possible to evaluate the nature of the influence of the connection configuration on the magnitude of overvoltages and the operation of secondary circuits.

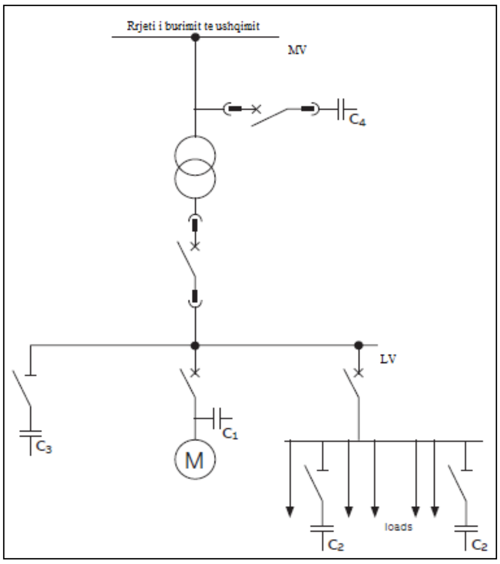

Figure 6: Block diagram of connecting a bank of medium voltage capacitors to the supply network, taking into account loads and an induction motor.

Note: "Rrjeti i burimit te ushqimit" – "power network".

Source: Authors, (2026).

The simultaneous use of capacitor installations of different voltage levels creates prerequisites for the emergence of resonant modes in the system. In such cases, the frequency of the switching oscillations in the medium voltage circuit may coincide with the natural resonant frequency of the low-voltage capacitors, which leads to a significant increase in the amplitude of overvoltages in the secondary windings of the transformer. This results in overloading of protective elements, premature tripping of fuses and relays, and in some cases, failure of sensitive electronic devices. The above diagram confirms that the interaction between capacitors of different voltage levels is one of the critical factors in the stability of the power grid and requires the use of special technical protection measures.

The results of field and experimental studies have shown that it is the resonant interaction between medium and low voltage capacitors that poses the greatest danger to transformer secondary circuits. Under such conditions, the amplitude of overvoltages significantly exceeds the permissible values, which is accompanied by a malfunction of protective devices and damage to electronic equipment. To systematise the results obtained, the measured parameters of overvoltages in relative units (pu), their duration and characteristic consequences for system elements were summarised. The summary data is shown in Table 9.

Table 9: Recorded values of the amplitude of overvoltages in the secondary circuits of transformers under conditions of resonant interaction of capacitors of different voltages and their consequences.

Mode of interaction of capacitors	**Amplitude of overvoltages, pu**	**Oscillation duration, ms**	**Observable effects**
Low level of resonant interaction	2.0-2.5	2.0-2.5	Short-term overloads, single fuse trips
Average level of resonant interaction	3.0-3.5	2.5-3.0	Massive tripping of relay protection, damage to fuses
High level of resonant interaction	4.0-5.0	3.0-4.0	Failure of electronic control devices, disruption of secondary circuits

Note: pu (per unit) – relative voltage value normalised by the nominal value; the duration of oscillations was determined by the stabilisation time after an overvoltage pulse; relay protection – set of devices for automatic shutdown in emergency conditions; the probability of reaching the levels of 3.0-5.0 pu under input parameter fluctuations was estimated using the integral form (4).
Source: Authors, (2026).

Even at low levels of resonant interaction, the amplitude of overvoltages reaches 2.5 pu, which poses a significant danger to the insulation and serviceability of fuses. At an average level of interaction, the amplitude increases to 3.5 pu, which is accompanied by massive failures of protective devices and frequent damage to fuses in secondary circuits. In the case of a high resonance level, the amplitude exceeds 4.0 pu, which leads to the failure of electronic controls and disruption of the stability of secondary systems. The obtained results demonstrate the critical dependence of the reliability of the electrical system on the presence of resonance phenomena, which confirms the need to introduce damping devices and optimise the connection schemes of capacitor plants. Industrial power grids are increasingly using induction motors that are powered by converter devices, including a converter, a DC link and an inverter [27].

This configuration provides speed control and increases energy efficiency, but at the same time makes the system more sensitive to switching overvoltages. The DC link, which accumulates energy, creating conditions for the formation of dangerous voltage pulses, is notable. In these modes, the analysis of the distribution of electrical loads between the components of the converter complex and the identification of the most vulnerable elements are of key importance. Figure 7 shows a block diagram of an induction motor power supply through a converter and an inverter, which is used to study the peculiarities of the impact of switching overvoltages on power electronics.

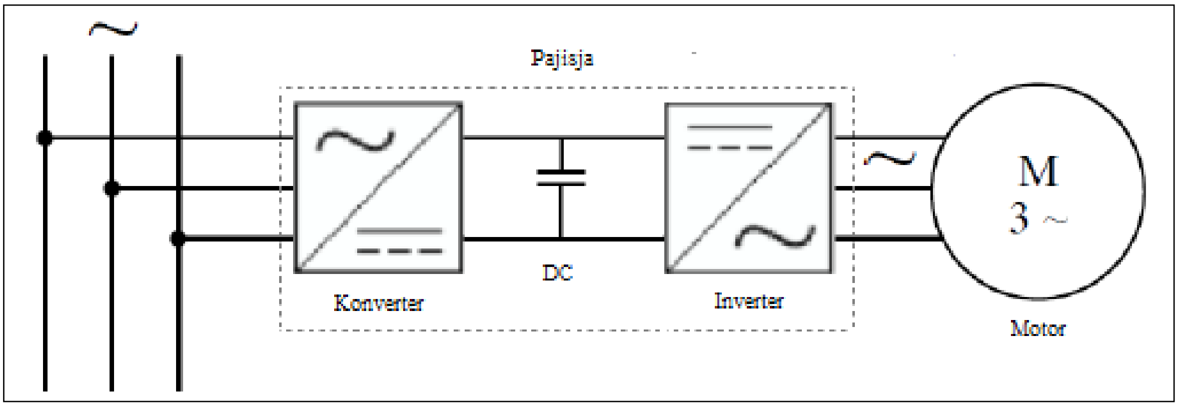

Figure 7: Scheme for powering an induction motor via a converter device (converter-inverter with DC link).
Note: “Pajisja” – “device”.
Source: Authors, (2026).

An induction motor power system consists of a three-phase source, a converter, a direct current link (DC link), an inverter, and an electrical machine. The converter performs the function of rectifying the AC voltage, while the DC link provides energy storage and stability for the inverter. However, it is this element that has proven to be the most sensitive to switching overvoltages, as even short-term fluctuations can lead to an excess of the nominal level by 10-20%. As a result, additional electrical load is placed on the inverter’s power switches, which increases the probability of damage and reduces the service life of electronic components.

Thus, the above diagram confirms the feasibility of using surge arresters and integrated active protection systems that ensure reliable operation of induction motors as part of industrial electric drives. A generalisation of the results obtained shows that switching overvoltages have a complex effect on key components of electrical systems, from the insulation of induction motor windings to the secondary windings of transformers and power electronics. Experimental and field data have confirmed that their effect is manifested both in the form of accelerated ageing of insulating materials and in the form of emergency failures associated with resonant modes and exceeding critical voltage levels. The established patterns emphasise the need for an integrated approach that includes optimisation of connection schemes, the correct choice of protective devices and determination of permissible operating modes of equipment. Thus, this analysis forms the scientific basis for further development and implementation of effective methods to reduce switching overvoltages, which is a prerequisite for improving the reliability and safety of electric power systems.

III.4 EMPIRICAL EVALUATION OF METHODS FOR REDUCING SWITCHING OVERVOLTAGES

In the course of studying methods for reducing switching overvoltages, circuit solutions involving the introduction of inductive chokes and additional elements into the switching circuit were addressed. The use of such approaches makes it possible to partially compensate for the energy of transients by reducing the pulse amplitude and shortening the duration of oscillatory modes. This has a direct impact on the stability of equipment operation and increases the durability of power grids, where regular overvoltage is one of the determining factors of reliability. Figure 8 shows variants of electrical schemes used to limit switching overvoltages in circuits with capacitor banks. The presented structural models show different combinations of series and parallel elements that dissipate excess energy and reduce the likelihood of repeated breakdowns in the circuit breakers. The presented solutions are the basis for comparing the effectiveness of technical measures and determination of the optimal operating conditions of the equipment, taking into account the specifics of switching processes in medium voltage networks.

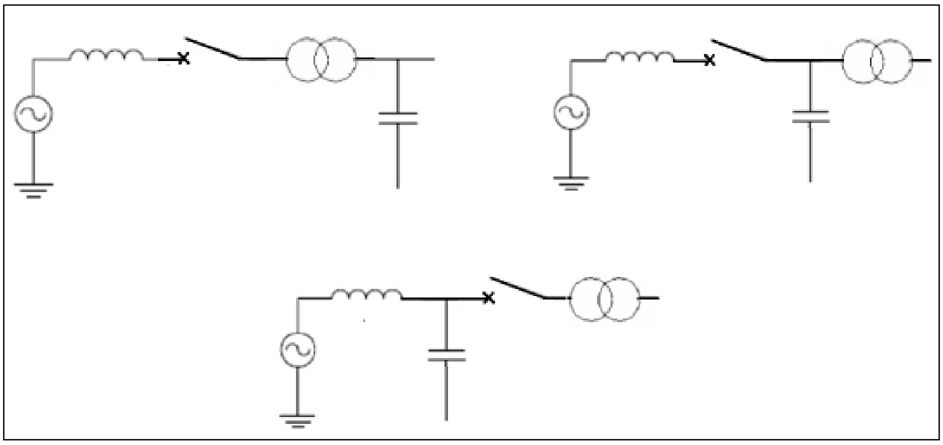

Figure 8: Schemes for reducing switching overvoltages using inductive and resistive elements.
Source: Authors, (2026).

The introduction of inductive elements into the circuit with capacitors provides a significant reduction in the rate of current rise and a decrease in peak voltage values at the moment of commutation. The use of chokes in series connection was found to be most effective for limiting current pulses, while circuits with parallel branches can be used high-frequency oscillations to be effectively damped. Such configurations not only increase the level of electrical insulation but also reduce the thermal load on the equipment, which directly affects its durability. The results obtained confirmed that the optimality of a particular circuit depends on the parameters of the network and the nature of the switching modes. Thus, the presented models can be used as a basis for forming practical recommendations for the implementation of protection against switching overvoltages in industrial electrical systems.

During the experimental tests, the effectiveness of various technical solutions aimed to reduce the level of switching overvoltages in medium-voltage networks was assessed. The comparison was made between the initial values of overvoltages occurring in the absence of protective measures and the residual levels recorded after the use of inductive chokes, pre-commutation resistors, overvoltage limiters and synchronous switches. The summarised results made it possible to assess the effectiveness of each method both in terms of reducing peak amplitudes and in terms of reducing the duration of oscillatory processes. The systematic data are shown in Table 10.

Table 10: Initial and residual values of overvoltages with different protection methods.

Method of protection	Initial overvoltage, pu	Residual overvoltage, pu
Without protection	3.0	3.0
Inductive choke	3.0	2.0
Pre-enabling resistor	3.0	1.7
Surge arrester	3.0	1.5
Synchronous switch	3.0	1.2

Note: pu (per unit) – relative units used for normalisation of electrical values; MOV (Metal Oxide Varistor) – surge arrester based on metal oxide varistors.
Source: Authors, (2026).

The absence of any protection means leads to the preservation of the maximum overvoltage amplitude at the level of 3.0 pu, which poses a danger to the insulation of equipment and increases the likelihood of emergency modes. The use of inductive chokes reduces the amplitude by about a third, but does not eliminate the risk of resonant oscillations. The pre-trigger resistors and surge arresters demonstrated significantly higher efficiency, reducing the amplitude to 1.7 and 1.5 pu, respectively. The best results were achieved by synchronous circuit breakers, which limited the overvoltage to 1.2 pu and actually reduced the risk of a second breakdown to a minimum level.

The generalised results confirm the prospects of introducing synchronous switching technologies in modern power grids as one of the most effective methods of improving their reliability.In the process of further evaluation of methods for reducing switching overvoltages, special attention was paid to pre-tapering schemes using resistive-inductive elements. Such solutions provide controlled capacitor charging, reduce the amplitude of impulse overvoltages, and significantly reduce the likelihood of repeated arc breakdown in the circuit breakers. Figure 9 shows a wiring diagram showing the operation of a switching device with a resistor and a choke in the circuit of one of the phases. This model is used to study the mechanisms of damping oscillatory processes and determine the optimal parameters of elements that ensure the reliability of electrical equipment under conditions of frequent switching.

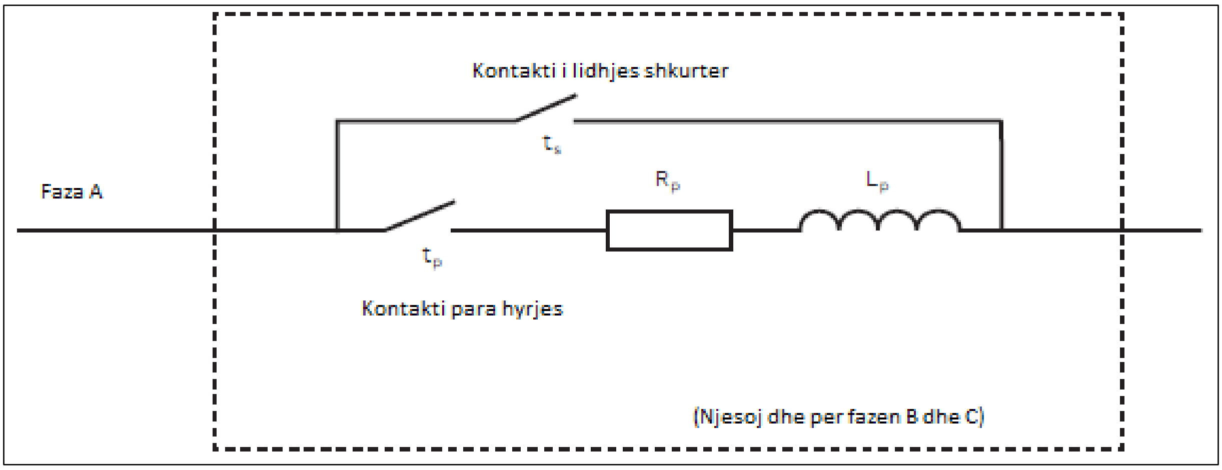

Figure 9: Pre-enabling circuit with a resistor (Rp) and an inductor (Lp) in the phase circuit of the capacitor bank.
Note: Rp – pre-commutation resistor that provides partial energy dissipation during switching; Lp – choke that limits the rate of current rise; tp – closing time of the preliminary contact; tc – closing time of the main contact; “Kontakti i lidhjes shkurtër” – “short-circuit contact”; “Kontakti para hyrjes” – “preliminary contact”; “Njesoj dhe per fazen B dhe C” – “same for phase B and C”.
Source: Authors, (2026).

The use of a preliminary contact with a resistive-inductive circuit can significantly reduce the level of overvoltage in the switching transients. At the initial stage of switching on, the resistor Rp dissipates part of the energy, reducing the peak voltage values, while the inductance Lp limits the rate of current growth. After the main contact closes, the system switches to nominal operation, which minimises shock loads on the circuit elements and ensures smoother switching. Such technical solutions reduced the probability of repeated breakdowns, increased the durability of capacitors and switchgear, and improved the overall stability of the electrical system. The use of resistive-inductive circuits can be considered one of the most promising ways to improve the operational reliability of industrial electrical installations.

In the practice of designing and operating electrical systems, the assessment of the technical effectiveness of switching overvoltage reduction methods should be combined with economic analysis. Initial implementation costs, regular maintenance costs, and the projected service life of the equipment determine the total life-cycle operating costs, which are a key criterion for engineering decision-making [28-30]. Comparison of different protection methods helps to establish an optimal balance between the level of technical reliability and economic feasibility, especially in conditions of limited resources and high requirements for the stability of power grids. Table 11 summarises the economic assessment of the main switching overvoltage protection equipment, which can be used for a comprehensive assessment of their feasibility in practical operation.

Table 11: Economic assessment of methods for reducing switching overvoltages.

Method of protection	**Implementation cost (unit)**	**Maintenance costs (% of implementation/year)**	**Average service life (years)**	**Total life cycle operating costs (unit)**
Without protection	0	0	-	High indirect losses (accidents, repairs)
Throttle	3000	5%	12	~4800
Pre-enabling resistor	1500	8%	8	~4000
MOV (surge arrester)	2000	10%	6	~5200
Synchronous switch	5000	3%	15	~6950

Note: MOV (Metal-Oxide Varistor) – nonlinear surge arrester; “unit” – conventional units used for cost comparisons; total operating costs are calculated as the product of the service life and maintenance costs, including initial investment.
Source: Authors, (2026).

The most cost-effective solution is the use of pre-commutation resistors, as they combine relatively low implementation costs with acceptable operating costs. Chokes provide lower costs in the long term due to their long service life, but their high initial cost limits their economic viability in large-scale applications. MOV surge arresters are characterised by moderate capital costs, but the need for frequent replacement significantly increases the total operating costs. Despite their higher initial cost, synchronous circuit breakers offer maximum technical efficiency and durability, which justifies investment in critical power supply facilities. Thus, the optimal solution depends on a combination of technical parameters, service life and long-term economic viability.

The study confirmed that switching overvoltages have a multilevel impact on the operation of electrical systems. The study determined that they accelerate the ageing of capacitor insulation, cause additional thermal and electrodynamic loads on the windings of induction motors, lead to resonance phenomena in the secondary circuits of transformers and adversely affect the operation of power electronics. The use of technical protection equipment has made it possible to significantly reduce the amplitudes of overvoltages and minimise the probability of damage, which confirms the feasibility of implementing combined measures to improve the operational stability of the systems [31].

The economic assessment proved that, despite the relatively high capital costs, synchronous switches and MOV limiters have lower total life-cycle costs due to reduced failures and extended system life. Traditional methods, such as chokes or resistors, have lower implementation costs but require significant maintenance and are less effective in preventing critical damage. Thus, the choice of the optimal protection should be based on a combination of technical efficiency and economic aspects, which is particularly relevant for industrial plants.

Summarising the results, it is possible to conclude that an integrated approach to the analysis of switching overvoltages, which combines experimental measurements, mathematical modelling and economic evaluation, provided a holistic view of their impact on the elements of the electrical system. The established patterns confirmed that effective overvoltage limitation is a key factor in improving the reliability, durability and economic efficiency of capacitor banks and related equipment. The results obtained form the scientific basis for further research aimed to optimise protection schemes, develop new technological solutions and improve energy security in medium-voltage power supply systems.

IV. DISCUSSION

The results of the study confirmed the close relationship between the switching modes of capacitor banks and the parameters of overvoltages in industrial electrical systems. It was found that in the absence of protection, the peak voltage values reached 3.0 pu, while the use of synchronous switches and MOV limiters reduced them to 1.2-1.5 pu, which significantly reduced the load on insulating materials. The detected effect of resonant amplification in the secondary circuits of transformers, which reached 4-5 pu, demonstrated the criticality of matching the parameters of capacitor banks of different voltage levels and the need to correct the frequency characteristics of the system.

The application of the inverse power model and Miner's rule [16] made it possible to quantify the effect of repeated pulses on the durability of insulating materials, which confirmed the expediency of limiting the number of switching operations in modes with increased pulses. These results formed the basis for optimising wiring diagrams and technical solutions aimed to improve the stability and reliability of electrical equipment.

The analysis of the data obtained was consistent with the findings by [32], proving the effectiveness of modern arresters in medium voltage systems. Similarly to the study, the authors noted that the combined use of protective devices reduced the risk of breakdowns and ensured insulation stability during short-term impulses. At the same time, modelling and test results confirmed the accelerated degradation of insulating materials at pulse amplitudes above 2.5 pu. This was consistent with the study by [33], demonstrating that increased voltage pulses in inverter modes caused local dielectric ageing and reduced the service life of insulation systems.

The dependence of the degradation of polypropylene dielectrics on the amplitude of switching overvoltages established in this study confirmed the general patterns identified by other authors. The study of the development of partial discharges showed that at an amplitude of more than 2.5 pu, the probability of local breakdowns increased exponentially, which indicated a limited life of insulating systems in high-frequency switching modes. Similar conclusions are presented in [34], noting that the rate of insulation degradation was influenced not only by the peak value of the pulse, but also by its duration.

This correlated with the results obtained in the study, which indicated the decisive role of the duration of the oscillatory process in the progression of partial discharges. Additionally, the study determined that the geometry and location of the insulating units directly affected the level of permissible overvoltages and the service life of the equipment. This conclusion was consistent with the study by [35], proving that optimisation of the insulating structure of medium-voltage transformers could reduce peak field strengths and increase equipment durability. In the present study, a similar effect was confirmed by the reduction of shock loads on insulating elements when using resistive-inductive circuits in switching circuits.

The results of the study showed that the durability of capacitor installations was determined not only by the properties of insulating materials, but also by the conditions of their operation, in particular, the frequency of switching processes. Similar conclusions were confirmed by [36] in an analysis of the prospects for the use of new dielectric materials in aviation electrical equipment. The authors proved that even advanced insulation systems underwent accelerated degradation under cyclic loads, which was consistent with the critical effect of repeated switching on polymeric dielectrics of capacitor banks identified in the study.

Further analysis showed that the use of synchronous circuit breakers in combination with surge arresters reduced the number of repeated breakdowns and increased equipment reliability. A similar approach to improving the resilience of medium voltage systems was reflected by. According to [37] in an analysis of the possibility of using deep learning algorithms for automated monitoring of switchgear. The study determined that the timely detection of abnormal modes made it possible to reduce the probability of failures, which was consistent with the emphasis on diagnostic control made in the study. The experimental data obtained confirmed that repeated voltage pulses with an amplitude of more than 2.5 pu led to accelerated dielectric ageing.

Similar patterns were described in the work of [38], demonstrating that even in low-voltage machines, cyclic loads caused the formation of partial discharges that limited the service life of the insulation. The results of the study confirmed these findings, demonstrating the crucial importance of pulse repeatability in predicting equipment life. The tests also showed that traditional protection schemes did not always provide sufficient efficiency in cases of high-frequency switching overvoltages, which necessitated the combined use of modern devices. This thesis correlated with the conclusions of analysis by [39] on the vulnerability of industrial power systems to various external and internal influences and emphasised the need for multi-level technical solutions. The study confirmed this position, showing the effectiveness of an integrated approach to limiting overvoltages.

The analysis of operational data showed that the effectiveness of protective devices largely depended on the regularity of maintenance. A similar conclusion was presented by [40], developing a system of technical support for surge protective devices. The study proved that timely preventive maintenance ensured the stability of protection parameters and extended the service life of the equipment. The study confirmed this relationship through the identified link between the frequency of failures and the quality of maintenance. Additionally, the study determined that the random nature of the distribution of switching pulse amplitudes significantly affected the forecasting of the service life of insulation systems, which required the use of probabilistic models.

A similar approach was traced in the study by [41], proposing a two-level system of protection against coordinated impacts in electric vehicle charging networks. The study emphasised that the effectiveness of protection was determined not only by the technical characteristics of the equipment, but also by its adaptability to stochastic processes. This was consistent with the study, which showed that adequate durability forecasting is possible only if the probabilistic nature of switching overvoltages is addressed. The results of the study showed that the stochastic nature of switching overvoltages significantly affected the prediction of equipment durability and required the use of intelligent analysis methods for the timely detection of deviations. A similar approach was presented by [42], proposing a hybrid deep learning model to separate physical disturbances from cyber threats in smart grids. The study proved that the combination of machine learning algorithms increased the accuracy of diagnostics under conditions of uncertainty, which was consistent with the conclusions about the need to address the probabilistic nature of overvoltage in diagnostic models.

The study determined that repeated overvoltage pulses formed a cumulative effect of insulation material degradation, which reduced the service life of the equipment. The results also confirmed that the development of partial discharges was closely related to the progressive ageing of insulating materials. Similar points were made by [43], which emphasised the need for comprehensive protection of infrastructure from stochastic disruptions that combined physical and information risks. This correlated with the study, which found that timely diagnosis of partial discharges is crucial for preventing unforeseen failures. The assessment of the degree of insulation degradation using partial discharges was a substantial part of the study, which correlated with the approach of [44], who described practical methods for measuring discharges in high-voltage equipment. The study proved that the determination of identification thresholds was crucial for predicting the service life of equipment, which was consistent with the results obtained in this study on the assessment of the performance characteristics of capacitor plants.

The problem of early detection of partial discharges was also reflected in the thesis of [45], which proposed a multisensor method for diagnosing medium voltage cable connections. The study proved that the integration of data from several sensor systems made it possible to identify even minimal defects that could eventually lead to critical damage. This conclusion was consistent with the results of previous work, which also emphasised the importance of identifying critical voltage levels to prevent the development of microbreakdowns. According to [46] systematised standards and methods for assessing the condition of switching devices, in particular considering partial discharges as one of the key diagnostic parameters. The study showed that taking into account failure statistics and diagnostic test results is crucial for effective maintenance planning and extending equipment service life. The results of the study were consistent with this approach, as combining statistical analysis data with test results improved objectivity of predictions of capacitor bank reliability.

The significance of the impact of repeated impulse loads on the reliability of power electronics was highlighted by 3[47] in an analysis of the failures of power converter modules. The authors found that cyclic overvoltages caused specific modes of degradation of semiconductor elements, which shortened their service life. Similar patterns were confirmed in the study, where repeated switching overvoltages determined the rate of ageing of insulating materials in capacitor installations. According to [48] summarised modern strategies for managing the assets of switchgear in power systems, including methods of condition monitoring, residual life assessment, and maintenance planning. The study proved that a comprehensive assessment of the technical condition of equipment increased the level of its reliability and ensured economic efficiency of operation.

This approach was consistent with the results of a study in which statistical analysis of the degradation of insulating materials was used to make reasonable predictions about the service life of condensing units. The development of methods for predicting the residual life of electronic components was presented by [49], where a combination of the fractional Weibull distribution and the Poisson random load model was used. The study demonstrated that this approach increased the accuracy of modelling degradation processes under stochastic influences. This was directly related to the study, which also incorporated the randomness of switching overvoltages to assess the durability of insulating materials. According to [50] developed multi-criteria methods for optimising the reliability of electrical machines, taking into account the thermal ageing of insulating materials.

It was found that the accuracy of predictions increased when temperature conditions were taken into account, which minimised the risk of premature failures. This correlated with the study, which also showed that repetitive impulse loads and overvoltages are the determining factors in the degradation of insulation systems. In [51] applied the physics of failure approach to predict the durability of power electronics at the PCB level. The study showed that the analysis of physical failure mechanisms provided more realistic estimates of the service life under multifactorial loads. This approach was consistent with the study conducted, where a combination of mathematical modelling, laboratory tests and statistical methods can be used to reproduce the complex impact of switching modes on equipment durability.

The generalisation of the results confirmed that the application of a multi-level approach combining mathematical modelling, experimental testing and statistical analysis made it possible to quantify the impact of switching overvoltages on the life of insulating materials and equipment reliability. The established regularities highlighted the importance of the choice of switching equipment and protection methods, and proved the critical role of repetitive impulse loads in the degradation of insulation systems.

V. CONCLUSIONS

The study revealed several key regularities that determine the impact of switching overvoltages on elements of medium-voltage power systems. For the first time, experimental data, mathematical modelling results and statistical analysis were comprehensively combined, which made it possible to quantify the effects of both short-term pulses and long-term degradation of insulating materials. It was found that more than 92% of failures in capacitor plants are related to insulation damage, while oil leaks and insulator defects account for only 5% and 2.4%, respectively.

The study noted that the frequency of daily switching increased the number of failures by 50% compared to equipment operating in a constant mode, and an increase in the amplitude of the overvoltage from 1.5 to 2.5 pu reduced the service life of capacitors from 15 to 6 years. The study showed that the failures were not isolated but systemic. In particular, at manufacturer A, more than 80 banks demonstrated group failures, with two or three defects occurring within the same installation. The resonant interaction of capacitors of different voltage levels posed an additional threat to the transformers' secondary circuits: at low resonance levels, overvoltages reached 2.5 pu, at an average of 3.5 pu, and at high resonance levels, they exceeded 4.0 pu, causing massive damage to fuses and failure of electronic control devices.

The analysis of the power electronics confirmed that the DC link was a particularly vulnerable element, where switching pulses caused a voltage surge of 10-20%, increasing the risk of damage to the inverter keys. The results confirmed the critical role of switching modes in the formation of emergency failures in all elements of the system. An assessment of the effectiveness of protection methods showed that the absence of measures led to maximum overvoltages of 3.0 pu. The use of chokes reduced the amplitude by about 30%, pre-tap resistors by up to 1.7 pu, and surge arresters by up to 1.5 pu. The highest efficiency was demonstrated by synchronous circuit breakers, which limited overvoltages to 1.2 pu, effectively minimising the risk of a second breakdown. An economic assessment showed that pre-commutation resistors were the most balanced solution in terms of cost-effectiveness, while synchronous circuit breakers had a higher initial cost but provided maximum durability and were appropriate for critical facilities.

Thus, the study formed the scientific basis for developing recommendations for choosing the optimal protection methods in industrial operations. The main limitations of the study were the use of mock-up laboratory installations that did not always accurately reproduce the conditions of industrial operation, as well as the dependence of the results obtained on the characteristics of specific equipment samples. Another limitation was the use of idealised models that simplified the reproduction of stochastic oscillatory processes in real power grids. Further research should be directed to the development of combined protection systems using MOV limiters and synchronous switches, improvement of damping methods based on adaptive control algorithms, as well as expansion of the experimental base with tests in industrial conditions to confirm the long-term effectiveness of the proposed solutions.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Aldi Mucka, Elio Voshtina and Denis Qirollari.
Methodology: Aldi Mucka and Elio Voshtina.
Investigation: Aldi Mucka and Elio Voshtina.
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