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A unique method for detection, registration and two-stage elimination of the ferroresonance phenomenon

The ferroresonance phenomenon is regarded as one of the primary causes of damage to voltage transformers installed in power systems. Ferroresonance increases current in the primary winding of the transformer due to significant core saturation, causing thermal damage to the insulation system. Although the ferroresonance phenomenon has been known for over a hundred years, there are no unambiguous criteria for when it appears, and there are no effective methods of eliminating this phenomenon. Due to the risks it poses, ferroresonance is still a subject of interest to research facilities and operating personnel. Disruptions caused by ferroresonance can also cause the malfunctioning of automatic protection systems.

Quick detection and effective elimination of the ferroresonance phenomenon is particularly important in power systems due to the possible damage to voltage transformers and cables, which may cause arc faults and much more severe losses. Integrating ferroresonance protection in the bay controller improves the control of this protective feature and enables its logical interconnection with other protection devices. The ability to register the detected ferroresonance phenomena, including the recording of current and voltage, enables a more accurate analysis of this phenomenon to adapt the functioning of the protection device to the characteristics of the system affected by the phenomenon.

Ferroresonance phenomenon

Ferroresonant oscillations in power systems appear as a result of the series or parallel connection of linear capacitance with non-linear inductance. Voltage ferroresonance may occur if these reactances are connected in a series, and current ferroresonance may appear if they are connected in parallel. From the practical perspective, non-linear inductance in power systems usually represents core magnetisation in the power transformer and voltage transformers. The non-linear nature of these circuits makes this phenomenon difficult to analyse because it distorts current and voltage waveforms.

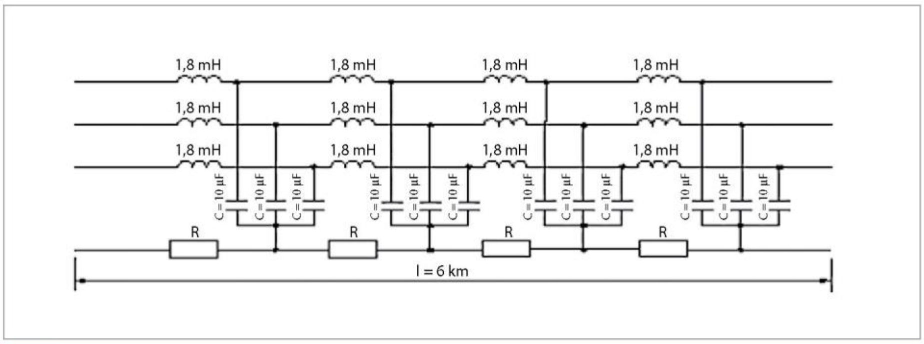

Fig. 1. Line model, dwg. by W. Chmielak, D. Sajewicz

Instrument transformer core overfluxing causes overheating and damage to the insulation and – sometimes – explosion. It also causes surges in the form of ferroresonant voltage oscillations, which may adversely affect other power system components. The presence of short-time overvoltages in the form of ferroresonant oscillations depends on the configuration of the power system and the parameters of its individual components. Another important factor is the connection of the system neutral to earth. Two cases should be considered in the context of this phenomenon in high-voltage power systems:

- a directly earthed neutral network,
- an isolated neutral network.

In high-voltage directly earthed neutral networks, ferroresonant oscillations occur mainly when certain switching operations generate a series or series-parallel resonant system. In medium-voltage isolated neutral networks, ferroresonance may occur following sudden changes in network voltage caused by an earth fault..

SUMMARY

Power infrastructure management is increasingly supported by intelligent decision-making systems, with the participation of measurement and data acquisition systems. To meet these expectations, Elektrometal Energetyka S.A. introduces a number of new functionalities of e^{2}TANGO bay controllers, which not only helps users in the control and management of power facilities, but also thanks to being equipped with proprietary decision-making algorithms, they allow for damage predictions and elimination of disruptions.

Keywords: predictive algorithms, asset management, ferroresonance.

Such changes produce a parallel or series-parallel resonant system. The immediate cause of ferroresonance in the network can be any change in its configuration or disruptions – such as energisation or the appearance and tripping of a phase-to-earth fault.

The ferroresonance phenomenon is also referred to as ferroresonant oscillations, non-linear oscillations or relaxation oscillations. With high instrument transformer core saturation, the voltage waveform of the network star point is significantly distorted and has properties of relaxation oscillations. Ferroresonant oscillations often occur in a complex structure, e.g., medium-voltage power networks of mines. The cause of star point voltage oscillations in mine networks, which are isolated star point networks, is the higher number of inductive voltage transformers which act as zero-sequence filters. The instrument transformers functioning as the filter have primary windings connected into a star, and the star point of this connection is directly earthed. Thus, the non-linear inductance of transformer magnetisation with the line-to-ground capacitance form a circuit where relaxation oscillations may appear and persist. A characteristic feature of the protection devices used in that system is the fact that every relay has an individual zero-sequence filter. The filter is formed by three single-phase voltage transformers with two secondary windings. The primary windings of the transformers are connected into a star with an earthed star point. This introduces additional transverse parameters of an inductive-resonant nature.

Ferroresonance is often confused with resonance. However, unlike linear resonance, where the resonance frequency is specifically defined, ferroresonance may occur for a frequency depending on the operating conditions of the system. The primary difference between these phenomena is that resonance may occur at a specific frequency, which means that in order to produce it, it is necessary to change the frequency of the source of the system, and in the case of ferroresonance, ferroresonant oscillations can be initiated by changing the RMS value of supply voltage without changing the frequency of the source.

Ferroresonance, although it only manifests in the waveforms of earth fault voltage and respective currents, is a dangerous disruption to the operation of the network. The overvoltages and overcurrents accompanying this phenomenon may damage components of the network, e.g., voltage transformers or buried lines. Ferroresonance also increases the potential of the neutral of the system, causing the appearance of the zero-sequence voltage component, which may falsify the operation of earth fault protection systems.

Laboratory tests

Laboratory tests have been conducted on a physical model of an HV/MV substation with three outgoing MV lines and an isolated neutral. The model was supplied with line-to-line voltage reduced to 100 V.

The test setup was provided with a voltage measurement bay consisting of three three-winding voltage transformers. Registration was performed using a recorder integrated into the bay controller and an independently connected autonomous recorder. The laboratory test setup contains models of the medium-voltage line and enables the selection of network neutral operating mode.

Ferroresonant oscillations occurred at the test setup during earth fault elimination.

The tests examined two methods of eliminating such faults: introducing an open delta resistance into the circuit until the achievement of the highest power of the voltage transformers and interrupting the connection of the star point of the voltage transformer with the ground.

Simulation tests

A significant progress in the analysis of ferroresonance phenomena was made possible thanks to special computational software that enables computer simulations of non-linear circuits. This article presents selected results of computer simulations of medium-voltage power systems with ferroresonance using the ATP-EMTP program.

A fragment of the power system of a 6-kV mine network was used to conduct a multi-variant analysis of the impact of changes in network configuration on the possible initiation of relaxation oscillations. Power is supplied by a 630-kVA transformer. The substation has 5 outgoing bays with buried lines with the following parameters: K1 – HKFtA 3x35 mm^2 with a length of 1 km, K2 – HKFtA 3x35 mm^2 with a length of 1 km, K3 – HKFtA 3x35 mm^2 with a length of 1 km, K4 – HKFtA 3x35 mm^2 with a length of 0.56 km, K5 – HKFtA 3xmm^2 with a length of 0.35 km; two measurement bays P6 and P7 and the capacitor bank bay simulating the line-to-earth capacitance of the network.

In the first case, the change in network configuration consisted of the energisation of buried line K1 and measurement bays P6 and P7 before the energisation of the voltage source. Buried lines K2 and K3 remain open. The voltage source was energised in time t = 0, initiating relaxation oscillations in the system. After t = 1 s, two remaining buried lines, K2 and K3, were energised. **Figure 2** shows the waveforms of current flowing in the primary winding of the

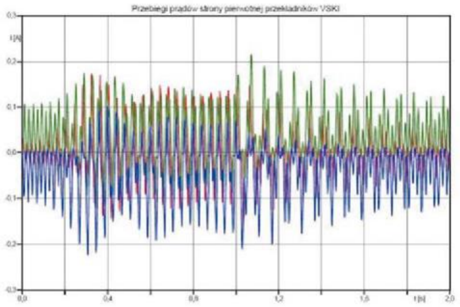

Fig. 2. Waveforms of current on the primary side of the voltage transformers functioning as zero-sequence filters in bay P6, variant 1, dwg. by W. Chmielak, D. Saiewicz

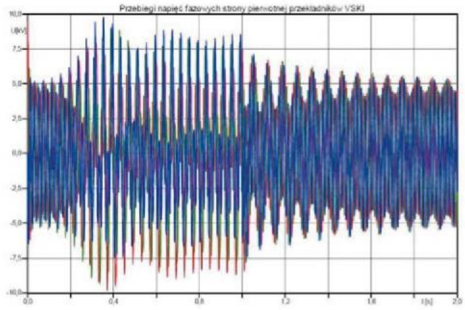

Fig. 3. Waveforms of phase voltages on the primary side of the voltage transformers functioning as zero-sequence filters in bay P6, variant 1, dwg. by W. Chmielak, D. Saiewicz

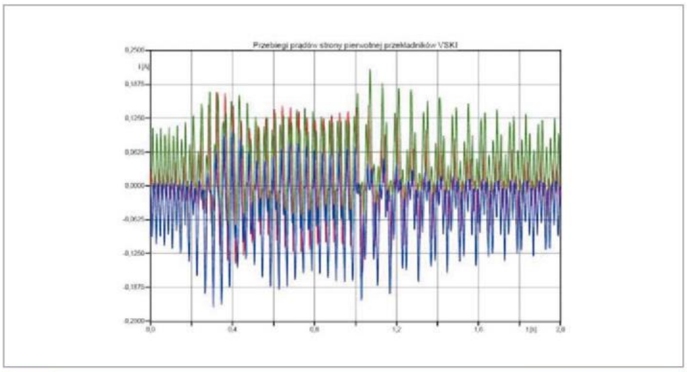

Fig. 4. Waveforms of current on the primary side of the voltage transformers functioning as zero-sequence filters in bay P6, variant 2, dwg. by W. Chmielak, D. Sajewicz

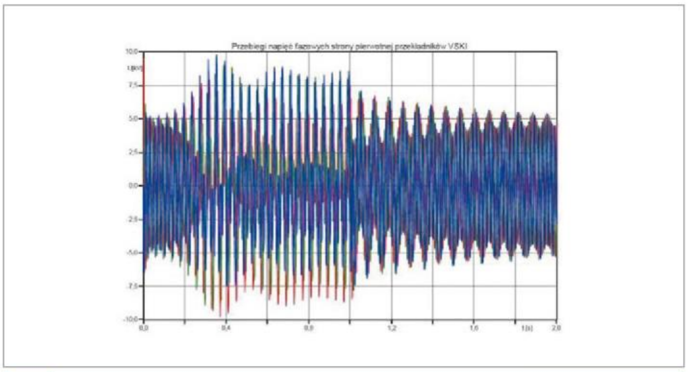

Fig. 5. Waveforms of phase voltages on the primary side of the voltage transformers functioning as zero-sequence filters in bay P6, variant 2, dwg. by W. Chmielak, D. Sajewicz

voltage transformers functioning as zero-sequence filters in bays P6 and P7. **Figure 3**, in turn, shows the waveforms of phase voltages in the busbars of the substation. The voltage and current waveforms shown in **figures 2** and **3** clearly show the instability of relaxation oscillations.

The voltages and currents observed during the simulation upon the appearance of ferroresonance present a significant risk to the instrument transformers and may cause them to suffer thermal and mechanical damage. Following the energisation of the buried lines K2 and K3 after t = 1 s, ferroresonance turns into transient chaotic oscillations.

In the second case selected for the analysis, buried lines K1, K2 and K3 and measurement bays P6 and P7 were energised in t = 0 s. After 1 s from the energisation of the power source, buried lines K2 and K3 are tripped. The results of the analysis given in **figures 4** and **5** confirm the significant impact of the change in network topology on the possible appearance of relaxation oscillations in mine power systems.

Tests at a real facility

The tests were conducted at a 6 kV auxiliary substation of a combined heat and power plant. The substation consists of 30 bays, and it is a double-busbar substation, where each system can be divided into two sections. The substation is supplied via two auxiliary transformers, with a power of 20 MVA each. In the normal configuration, the systems are not divided into sections, and each of them is supplied by a dedicated auxiliary transformer. Ferroresonance most often appeared during switching operations involving a change in substation configuration, with a short voltage interruption (operation of the automatic source-changeover system). The symptoms of ferroresonant oscillations included the activation of earth current relays and unstable indications of instruments that measured substation busbar voltage.

In such situations, the operating personnel switched off voltage measurement bays to eliminate ferroresonance. After the measurement bays were restarted, resonant oscillations usually did not re-appear.

The appearance of this undesirable phenomenon at the substation always required an intervention of the operating personnel, which – if the personnel did not react quickly enough – could lead to damage to the instrument transformers due to the thermal overload of primary windings and damage to the insulation of the operating apparatus and devices. Consequently, it was necessary to implement a solution at the substation to remove dangerous ferroresonant oscillations automatically, without involving the operating personnel.

One of the substation systems (system II) was sectioned off for the duration of the experiment and connected to two voltage measurement bays and an unloaded buried line with a length of 3 km. With such a substation configuration and no loads to receive active power, ferroresonance occurred during almost every energisation of substation busbars via the incoming bay.

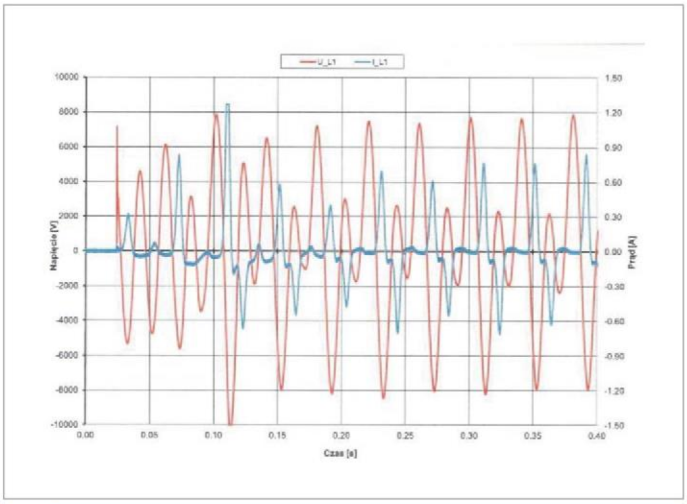

Fig. 6. Waveforms of voltage and current on the primary side of the voltage transformers in phase L1 after energisation of the busbars of the 6 kV RG substation – initiation of ferroresonant oscillations, dwg. by W. Chmielak, D. Sajewicz

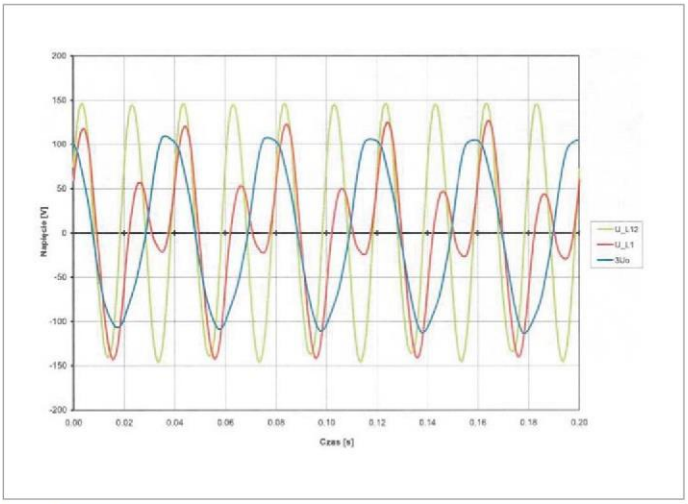

Fig. 7. Voltage waveforms recorded on the secondary side of the voltage transformers during the ferroresonance phenomenon: U_L12 – line-to-line voltage, U_L1 – phase voltage, 3Uo – in the open delta circuit, dwg. by W. Chmielak, D. Sajewicz

A measurement system was installed in the voltage measurement bay to record the waveforms of current and voltage during ferroresonance. The measurement system also included high-voltage probes connected to substation busbars, clamp-on current probes to measure the current flowing through the primary side of the instrument transformers and a digital recorder. The recorder was also connected to measurement signals from the secondary side of the instrument transformers in the form of phase voltage, line-to-line voltage and the zero-sequence component of the open delta.

After the initiation of resonant oscillations by energising the substation busbars (closing the circuit breaker in the incoming bay), resistors with the following values were "manually" connected in the measurement bay into the open delta circuit of the instrument transformers: 100 Ω, 47 Ω, 30 Ω and 15 Ω. In all tests, 100-Ω and 47-Ω resistors did not suppress the resonant oscillations, while 30-Ω and 15-Ω resistors successfully eliminated the oscillations.

Further drawings show the waveforms of voltages and currents recorded on the primary and secondary sides of the voltage transformers. The waveforms show the initiation of ferroresonance after the closing of the circuit breaker in the incoming bay (**fig. 6**), the oscillations during ferroresonance (**fig. 7**) and the suppression of ferroresonant oscillations after the connection of resistor R = 30 Ω (**figs. 8** and **9**).

During ferroresonant oscillations, phase voltages are very strongly distorted, and their amplitudes can exceed 10 kV on the primary side, whereas in the nominal conditions, the amplitude should not exceed 5 kV. The increase of voltage by more than two times presents a big risk to the strength of the insulation of the substation and the connected loads. The distortions are practically unnoticeable in the waveforms of line-to-line voltage, which indicates that the phase voltages are distorted by a zero-sequence component with a frequency different from 50 Hz. The analysis of the $3U_O$ voltage waveforms in the open delta circuit indicates that this component has a sinusoidal form with a frequency of 25 Hz.

Ferroresonance protection (U_{fr})

The industrial research conducted by Elektrometal Energetyka S.A. resulted in the development of a fast adaptive algorithm to detect the ferroresonance phenomenon using any phase voltage (L_1, L_2, L_3) and the zero-sequence component voltage U_0. The algorithm was implemented in the e^{2}TANGO-800 bay controller, with individual phase voltages used to detect the ferroresonance phenomenon. The developed ferroresonance elimination system consists of two stages: the first is used to close the open delta winding of voltage transformers (signal U_O), the resistance was determined based on calculations and experimentally as $R_\triangle$ = 10 Ω – constant value for each instrument transformer type; the second is used to close individual secondary windings of voltage transformers and can be connected both to the open delta windings and other cores. The resistance was determined based on calculations and experimentally depending on the rated voltage of the instrument transformers as R = 10–20 Ω. The schematic diagram of the outgoing bay with the connected ferroresonance suppression system is shown in **figure 10.**

The commercial version of ferroresonance protection can be implemented in the new e^{2}TANGO controller using a special output card.

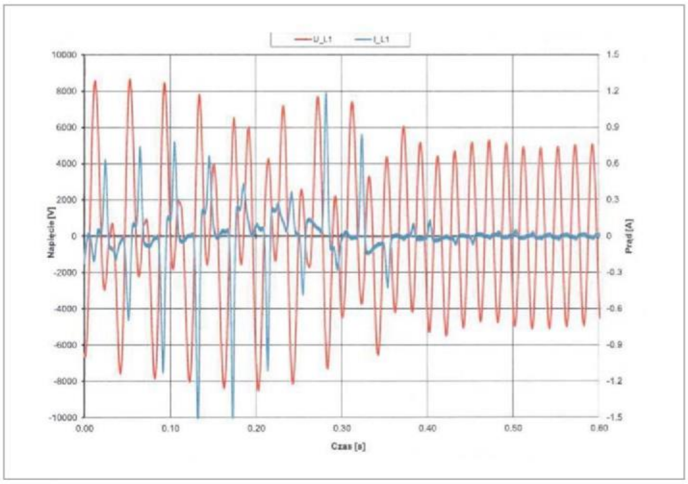

Fig. 8. Waveforms of voltage and current on the primary side of the voltage transformers in phase L1 after the connection of resistor R = 30 Ω in the open delta circuit – ferroresonance suppression, dwg. by W. Chmielak, D. Sajewicz

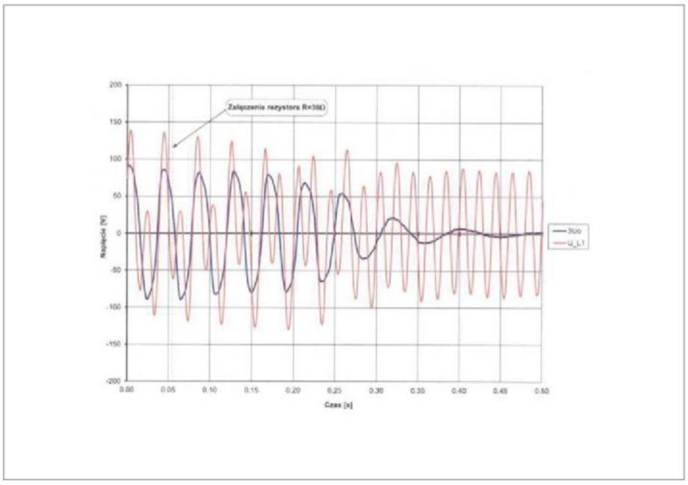

Fig. 9. Waveforms of voltage and current on the secondary side of the voltage transformers in phase L1 and in the open delta circuit after the connection of resistor R = 30 Ω – ferroresonance suppression, dwg. by W. Chmielak, D. Sajewicz

For older versions of the device, the new functions can be implemented by purchasing an output card and a set for ferroresonance suppression and updating the software. Also, to ensure the correct operation of the remaining bay controllers in the substation, it is necessary to extend two additional circuits from the voltage measurement bay: one to lock the protection devices using the zero-sequence component, before the activation of the first-stage ferroresonance protection; one to lock the protection devices using phase voltages, before the activation of the second-stage ferroresonance protection.

Summary

The new protection functions implemented using e^2TANGO bay controllers will enable contemporary automatic protection systems to even better diagnose and analyse the protected devices and facilities and improve the reliability of power supply to the consumers.

Tests conducted at a laboratory test setup indicate that the best way of eliminating ferroresonance is to temporarily interrupt the connection of the star point of voltage transformers to the earth electrode, which is not always possible. Introducing open delta resistance was insufficient to eliminate all instances of ferroresonance due to the limiting power of the voltage transformers. Studies of relevant literature and information from persons who operate MV networks indicate that only 30% of ferroresonance phenomena can be eliminated using this method. The proposed second stage of ferroresonance elimination, which may be effective for cores other than the cores dedicated to the open delta, seems to be an effective way of significantly improving the effectiveness of ferroresonance suppression. However, it requires further development work at physical facilities and verification of the developed actuation system.

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The article presents the results of industrial research and development work implemented by Elektrometal Energetyka S.A. as part of the following project: “Construction of integrated systems supporting and optimising work and safety of the MV switchgear”. The Project is co-funded by the European Union from the European Regional Development Fund under the Priority Axis I, “The use of R&D in the economy” of the Regional Operational Programme of Mazovia Province for 2014–2020.

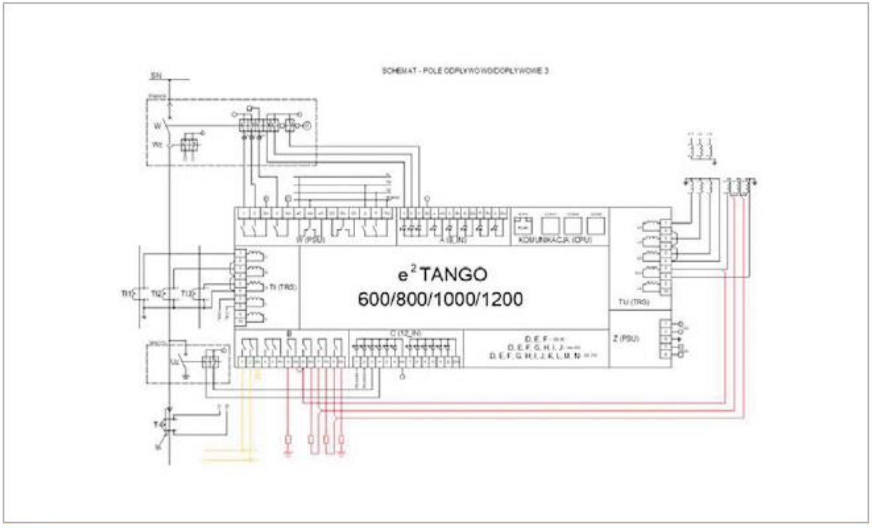

Fig. 10. Schematic diagram of the electrical connections of the e^2TANGO controller in the version with ferroresonance protection, dwg. by W. Chmielak, D. Sajewicz

ABSTRACT

A unique method for detection, registration and two-stage elimination of the ferroresonance phenomenon

Power infrastructure management is increasingly supported by intelligent decision-making systems, with the participation of measurement and data acquisition systems. To meet these expectations, Elektrometal Energetyka S.A. introduces a number of new functionalities of e^2TANGO bay controllers, which not only helps users in the control and management of power facilities, but also thanks to being equipped with proprietary decision-making algorithms, they allow for damage predictions and elimination of disruptions.

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