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Compensation of Reactive Power of AC Catenary System

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Abstract

The article analyses the theoretic and practical solutions of appearance of reactive power and compensation of it in the 25 kV, 50 Hz supply system of a contact network. The article proposes the theoretic (by using formulas, equivalent, structural schemes, phasor diagrams) and practical research (by providing the schemes of connecting capacitor banks, calculating the parameters of capacitor banks) for the compensation of reactive power. The main purpose of this article is to introduce and illustrate a new method of reactive power compensation.

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Keywords: reactive power, AC catenary, distribution, shunt compensation, capacitor bank

1. Introduction

The impedance of the overhead catenary feeding system and the train loading cause imperfections in the AC railway power supply, e.g. voltage drop along the feeder length, severe harmonic currents caused by powerful trains operating in poor power-factor conditions (0.5–0.85 typically), etc. Although most electric locomotives can operate under a wide range of pantograph voltage (19–29 kV) the traction performances and the power supply conditions are better at nominal voltage 25 kV. For rational use of electric energy, economic generation, transmission and distribution systems with minimum losses have to be used [1]. This means that all the factors which may cause losses in the electric power supply networks have to be restricted. One of such factors is reactive power. It is only

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lately that modern solutions in the area of reactive power compensation to not only reduce the costs for the use of reactive power but also to improve the quality of the energy system has been applied. The compensation of reactive power by installing external reactive power sources has become one possible solution to power supply. Harmonic filtering implies mitigating harmonic currents generated by the non-linear loads like rectifiers, converters, HF lamps, electronic equipment etc. in the network [2, 3]. The aim of load compensation is to boost the power factor of the system, to support the real power drawn from the system, to compensate the voltage regulation and to remove current harmonics [1, 3].

2. Compensation of reactive power in the traction system of 25 kV, 50 Hz

A simplified scheme of alternating current 25 kV, 50 Hz electrified railway is depicted in Fig. 1.

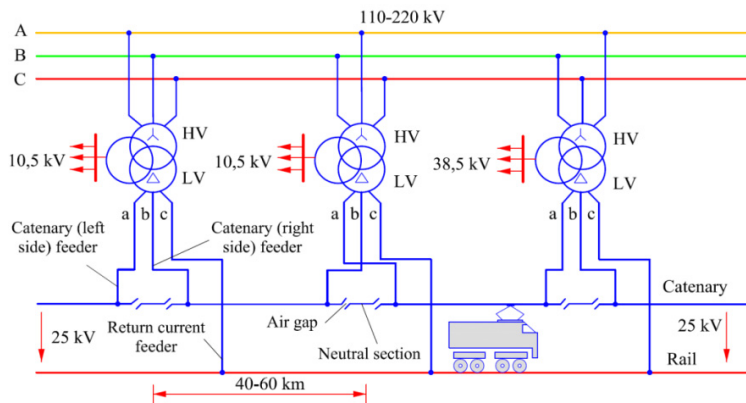


Fig. 1. A simplified scheme of a 25 kV, 50 Hz alternating current electrified railway.

To increase the power factor $\cos \varphi$ (in the point of traction substation buses) static non-regulated and regulated reactive power compensator installations are used. To improve the quantitative indicators of alternating current of 25 kV, 50 Hz of the traction system, one needs to take into consideration the fact that the power factor of the system is low (as a result of high consumption of reactive power), there is asymmetry of current between phases, which supply current for electric traction system consumers, the transformers of traction substations are not fully loaded (only 68% of their nominal value). In addition to this, in the AC/DC structures of the electric traction vehicles (ETV) electric power AC/DC, static semiconductor converters-rectifiers are used, as well as inverters which cause appearance of currents, voltage harmony constituents in the supply system. As a result of this, by applying reactive power compensation, it is essential to use the systems of filtration of harmonious currents and voltage constituents. For the improvement of energy indicators of 25 kV, 50 Hz alternating current of electrified railways, it is essential to use the compensation systems of reactive power. To increase the power factor $\cos \varphi$ of 25 kV, 50 Hz alternating current traction system, one can adjust the Standard reactive power compensation equipment that is used in other systems. Synchronous compensators, synchronous motors and capacitor banks may serve as reactive power sources [4, 5]. Synchronous compensators and synchronous electric machines are usually used in symmetric three-phase power supply systems. It is useful to use synchronous compensators where the capacity of reactive power sources is over 7500 kVar. In the course of newly designed electrified railway section networks with the help of reactive power compensation the number of project traction substation transformers and their capacity may be reduced, and the cross-section of the catenary wires may be reduced.

2.1. The influence of low capacity factor $\cos \varphi$

Contrary to the situation in the industrial energy sector, the load in the railway power sector, and especially in railway power traction lines may change significantly (see Fig. 2). Therefore, it is essential to ensure reliable, stable

electric power supply for electric traction vehicles (electric trains, electric locomotives). Electric traction vehicles (ETV) consume a significant share of reactive power from the 25 kV, 50 Hz catenary hence the power factor $\cos \varphi$ in the point of traction substation bus is relatively low (0.75–0.85) [6]. The value of average power factor $\cos \varphi$ is 0.8 [3]. A low power factor has a negative influence. Reactive power is needed for electric traction vehicles (ETV) which consume it from the energy system and load the power transmission lines, transformers, increase the active power and losses. In a single supply system of alternating current electric traction, the active power is expressed as: $P = UI \cos \varphi$. The losses of active power ΔP , with active circuit resistance are calculated as follows: $\Delta P = I^2 R$. By expressing the current as $I = P/U \cos \varphi$, the losses of active power ΔP are calculated as follows:

$$\Delta P = \frac{P^2}{U^2 \cos^2 \varphi} R. \quad (1)$$

From the formula (1), we can see that the smaller $\cos \varphi$, the greater are the losses of active power. In addition to this, with low $\cos \varphi$, with reactive current I_p in the power supply circuit, the resistance of which is of reactive type, additional voltage losses are produced ΔU (with the same value of the constituent I_a active current) [8].

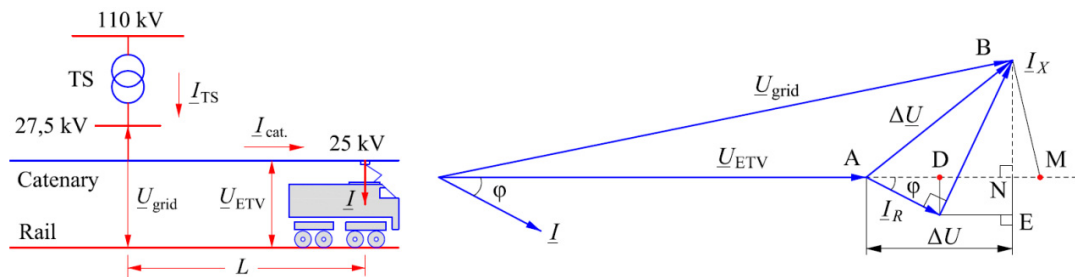


Fig. 2. The scheme of the section of 25 kV, 50 Hz catenary single supply (left) and phasor currents, voltages diagram.

The scheme of a single supply catenary of 25 kV, 50 Hz and phasor currents, voltages diagram is provided in Fig. 2. In a phasor diagram of voltages it is considered that $AN \equiv AM$. In this case, the projection of the vector of decrease of voltage ΔU is decrease of voltage ΔU .

2.2. Load of 25 kV, 50 Hz catenary JSC “Lithuanian Railways”

The 25 kV/50 Hz AC single-phase traction power supply system is a widespread railway supply solution in Lithuania. The main function of AC railway power supply systems is to deliver electric energy to the electric locomotives that are connected to the system, and to do this effectively and economically. For calculations related to the AC railway power supply systems, basic tools such as power flow algorithms for obtaining voltage, current or power flows through each feeder section are needed. The calculations of the decrease of voltage (losses) and power losses in the line of catenary have been completed, where in the section between the traction substations: N. Vilnia–Lentvaris three electric trains EJ-575 are moving, whose active power $P_{\text{ETV1}} = 2$ MW, $P_{\text{ETV2}} = 2$ MW, $P_{\text{ETV3}} = 2$ MW, catenary voltage $U = 25$ kV, apparent power of the traction substation is $S = 25$ MVA, power factor $\cos \varphi = 0.85$. Traction substations, the scheme of calculation of the parameters of the catenary, the current diagram and the diagram of voltage decrease (losses) have been provided in Fig. 3.

The losses of voltage in active resistance (Fig. 3) catenary R_{cat} and rails R_{rail} are calculated as follows:

$$\begin{cases} \Delta U_{A-1} = (I_1 + I_2 + I_3 + \dots + I_m) \cdot R \cdot L_1, \\ \Delta U_{1-2} = (I_2 + I_3 + \dots + I_m) \cdot R \cdot (L_2 - L_1), \\ \Delta U_{2-3} = (I_3 + \dots + I_m) \cdot R \cdot (L_3 - L_2). \end{cases} \quad (2)$$

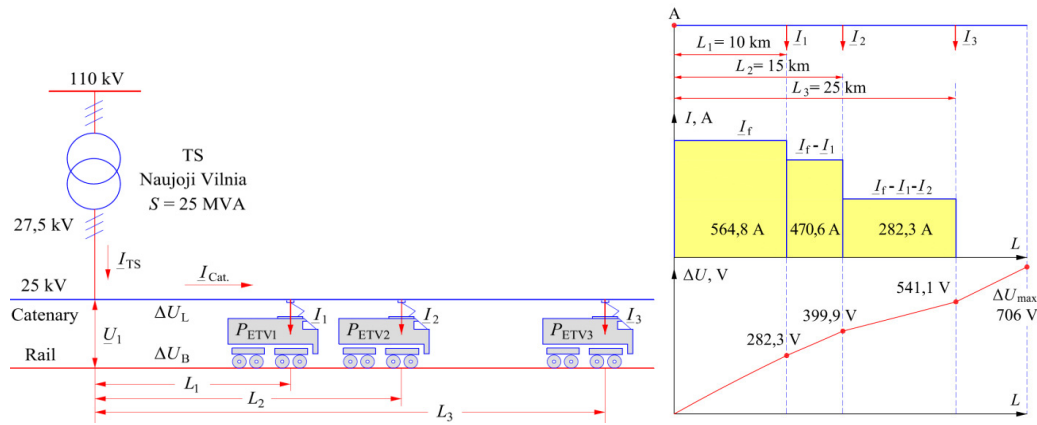


Fig. 3. The scheme of calculation of traction substations, catenary parameters (a), currents and voltage decrease (losses) diagram (b): I_f – current flowing by feeder; I_{cat} – catenary current; L_1 – distance 10 km; L_2 – distance 15 km; L_3 – distance 25 km.

Maximum losses of voltage ΔU_{max} in the entire section of the catenary with single catenary supply are calculated as follows (Fig. 3):

$$\Delta U_{max} = R \cdot (\underline{I}_1 \cdot L_1 + \underline{I}_2 \cdot L_2 + \underline{I}_3 \cdot L_3 + \dots + \underline{I}_m \cdot L_m). \quad (3)$$

Active resistance of catenary R_{cat} and rails R_{rail} of a 1 km line is calculated as follows:

$$R = R_{cat} + R_{rail} = 0.04 \, \Omega / \text{km} + 0.01 \, \Omega / \text{km} = 0.05 \, \Omega / \text{km}.$$

The feeder current is calculated in a complex form:

$$\underline{I}_j = \underline{I}_{Rj} - j \underline{I}_{Xj}, \quad (4)$$

here: I_j – current; i – load in a complex form; I_{jr} – constituent of active current; I_{jx} – constituent of inductive current.

The feeder current is calculated in a complex form as follows:

$$\underline{I}_f = \sum_{j=1}^m \underline{I}_{Rj} - j \sum_{j=1}^m \underline{I}_{Xj}. \quad (5)$$

Losses of voltage in traction substation TS buses U_{grid} and in the traction rolling stock U_{ETV} are calculated as follows:

$$\Delta U = |U_{grid}| - |U_{ETV}|. \quad (6)$$

Voltage losses by using vectors are calculated as follows:

$$\Delta U = U_{grid} - U_{ETV}. \quad (7)$$

With a nonsinusoidal form of U and I , the losses of voltage are calculated by considering that full resistance is calculated as follows:

$$z=0.8r+0.69x. \quad (8)$$

The results calculation provided in Table 1.

Table 1. The calculation results.

Title	Value
Average electric traction vehicle ETV1 current I_1	94.18 A
Voltage losses ΔU_{L1}	47.06 V
Power losses ΔP_{L1}	13.3 kW
Average ETV2 current I_2	188.24 A
Voltage losses ΔU_{L2}	211.8 V
Power losses ΔP_{L2}	79.6 kW
Average ETV3 current I_3	282.35 A
Power losses ΔP_{L3}	298.9 kW
The current of traction substation feeder load (calculated according to 4)	564.8 A

The consumption of active P , apparent S , reactive Q powers of JSC “Lithuanian Railways” for electric traction in the period between 2010–2015 are provided in Fig. 4.

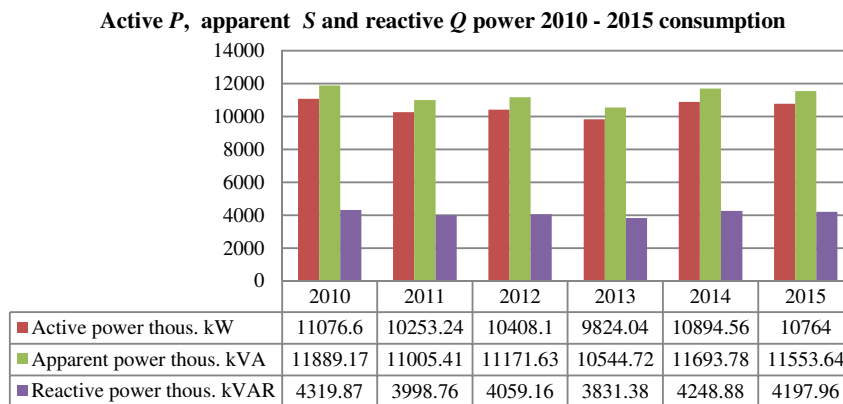


Fig. 4. Power consumption of JSC “Lietuvos geležinkeliai” active P , apparent S , reactive Q for electric traction in the period between 2010–2015.

The consumption of active P , apparent S , reactive Q powers of JSC “Lithuanian Railways” for electric traction in the period between 2010–2015 are provided in Fig. 4.

3. Compensation of reactive power by using capacitors

3.1. Technical solutions for 25 kV, 50 Hz catenary power system using shunt compensation

Shunt compensation – here the device (capacitor bank) is connected in parallel with the 25 kV, 50 Hz catenary line. Shunt compensation of reactive power can be employed either at the load level, substation level or at transmission level. Compensation should be provided as close as possible to the consumption point to avoid having to distribute this power in the other part of network. A shunt compensator is always connected in the middle of the transmission line along with either a current source, voltage source or a capacitor. It supplies reactive power to the system. An equivalent scheme of compensation of reactive power equivalent circuit, where the capacitor bank (PCB

device) connected in parallel to the load (electric locomotives) is located in the traction substation as provided in Fig. 5. A capacitor bank (PCB device) connected in parallel is located in point «a». The phasor diagrams where the shunt of reactive power compensation equipment PCB is connected and disconnected is provided in Fig. 6. In the, to improve the visibility, a different scale is used, a phasor diagram, where the shunt capacitor bank PCB is disconnected showing solid lines. At the beginning, the phasor diagram voltage vector is taken $\underline{U}_2$ (see Fig. 6), the location of the current $\underline{I}_2$ vector is established according to the active-inductive load character (the angle is $\varphi_1 = 36.9^\circ$). Subsequently, the components of active $\underline{I}_{2a}$ and reactive $\underline{I}_{2p}$ currents are drawn, the vectors of the decrease of voltage $\underline{I}_{2p}R_s$ and $j\underline{I}_{2p}X_s$ is illustrated, the location of the vector of the voltage source $\underline{U}_1$ is established. Angle φ_1 defines the factor of the supply system capacity. The losses of voltage to level «a» are marked as ΔU_2 . For the compensation of reactive power in point «a», capacitor C is connected. The vector diagram is depicted in dotted lines. Upon connection of a reactive power compensation device in point «a», on the circuit of the capacitor current $\underline{I}'_c$ is flowing, the vector outstrips by 90° vector $\underline{U}_2$ of load voltage (see Fig. 6). In this case, current $\underline{I} = \underline{I}_2 + \underline{I}'_c$ (see Fig. 6) is flowing on the circuit up to point «a». Vector $\underline{I}'_{2p}$ of the reactive component current becomes smaller in the system than reactive component current vector $\underline{I}_{2p}$ until the connection of the compensation device, whereas the vector of the active component current $\underline{I}_{2a}$ remains unchanged (see Fig. 6). We continue with the vector diagram from the end of the vector $\underline{U}_1$ of the voltage source due to the fact that the value of its module and the position do not depend on the fact if the compensation equipment is connected to the circuit or not. From the end of this vector, a vector of voltage decrease $j\underline{I}X_s$ is drawn, and subsequently a voltage decrease vector $\underline{I}R_s$ by taking into consideration the fact the vector of current $\underline{I}$ is smaller than the vector of current $\underline{I}_2$. As a result of this, the module of voltage decrease of vector $j\underline{I}X_s$ is smaller than the module of voltage decrease vector $j\underline{I}_2X_s$, and the module of voltage decrease vector $\underline{I}R_s$ is lower than the module of voltage decrease vector $\underline{I}_2R_s$. Upon connection of the starting point of the vector diagram with the start of the voltage decrease vector $\underline{I}R_s$, vector module of voltage $\underline{U}'_c$ in point «a» after connecting the compensation equipment is determined. The module of voltage $\underline{U}'_c$ of the vector is greater than that of vector $\underline{U}_2$ voltage in point «a» (until the connection of the compensation equipment). This difference was a result of the decrease of voltage value of vector $j\underline{I}'_cX_s$. The angle of the phase between voltage $\underline{U}_2$ and current $\underline{I}$ is φ' (see Fig. 6). The voltage losses up to point «a» in the phasor diagram are marked as $\Delta U'_2$. Upon completion of a vectorial analysis, it was established that angle $\varphi' < \varphi$, that is the power factor in the supply system increases ($\cos' \varphi_1 > \cos \varphi_1$), and $\Delta U'_2 < \Delta U_2$, means that the voltage in the connection point of capacitor device PCB «a» increases (see Fig. 6). The voltage losses to point «a» $\Delta U'_2$ are calculated as follows:

$$\Delta U'_2 = \Delta U_2 - \underline{I}'_c X_s. \quad (9)$$

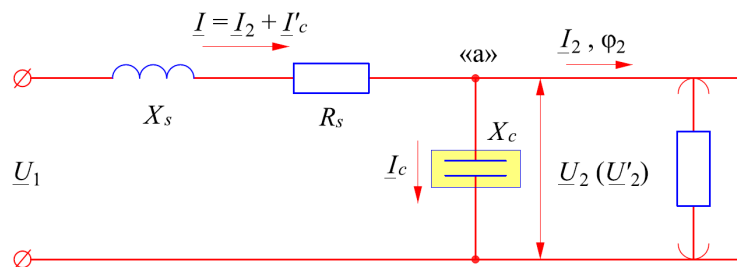


Fig. 5. Equivalent power compensation of equivalent circuit, where a capacitor bank (PCB device) parallel connected of electric locomotive and is located in the traction substation: $\underline{U}_1$ – voltage of power supply; $\underline{I}$ – current in the ETV supply system; $\underline{U}_2(\underline{U}'_2)$ – voltage in installation point of PCB; $\underline{I}_2$ – current of loading circuit; $\underline{I}'_c$ – PCB capacitor current; $R_s X_s$ – active and inductive circuit voltage up to the point of connecting PCB; X_c – (PCB device) capacity resistance; φ_2 – the angle between the voltage and current phases at the point of PCB device installation.

Knowing that $\Delta U = I_e R \cos \varphi_e + I_e X_e \sin \varphi_e$, formula (9), we will rewrite as:

$$\Delta U'_2 = I_2 R_2 \cos \varphi_2 + I_2 X_s \sin \varphi_2 - \underline{I}'_c X_s. \quad (10)$$

The voltage losses up to point «a» in the phasor diagram are marked as $\Delta U'_2$. Upon completion of a vectoral analysis, it was established that angle $\varphi' < \varphi$, that is the power factor in the supply system increases ($\cos' \varphi_1 > \cos \varphi_1$), and $\Delta U'_2 < \Delta U_2$, means that the voltage in the connection point of capacitor device PCB «a» increases (see Fig. 6). The voltage losses to point «a» $\Delta U'_2$ are calculated as follows:

$$\Delta U'_2 = \Delta U_2 - I'_c X_s. \quad (11)$$

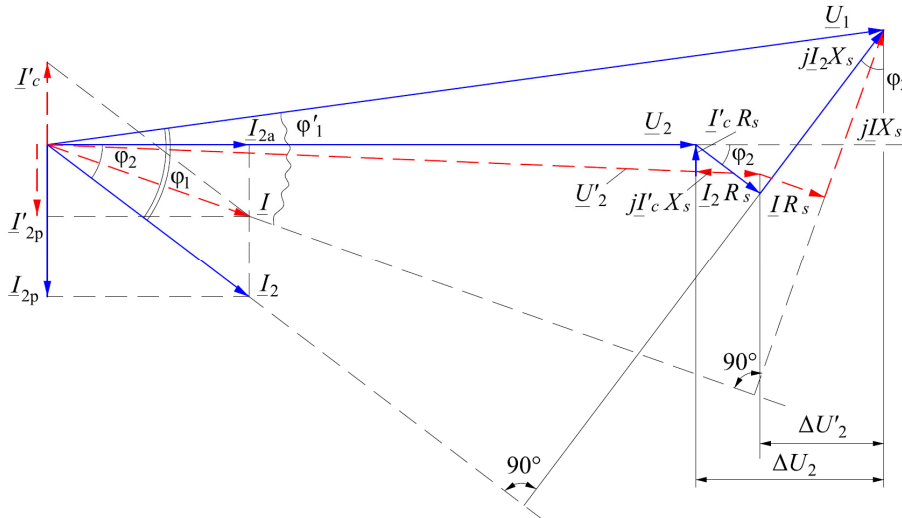


Fig. 6. Phasor diagrams where the shunt reactive power compensation device PCB is connected (dotted lines) and disconnected (solid lines).

Knowing that $\Delta U = I_e R \cos \varphi_e + I_e X_e \sin \varphi_e$, formula (11), we will rewrite as:

$$\Delta U'_2 = I_2 R_s \cos \varphi_2 + I_2 X_s \sin \varphi_2 - I'_c X_s. \quad (12)$$

Having evaluated the components of active I_{2a} and reactive I_{2p} load current $\Delta U = I_{ea} R + I_{ep} X$, the losses of voltage U'_2 shall be calculated as follows:

$$\Delta U'_2 = I_{2a} R_s + I_{2p} X_s - I'_c X_s, \text{ or } \Delta U'_2 = I_{2a} R_s + (I_{2p} - I'_c) X_s. \quad (13)$$

The author propose to locate the shunt reactive power compensation device (capacitor bank PCB) on the side of A and B traction substations of 27.5 kV voltage in two points and in a sectioning position (see Fig. 7). By locating the reactive power compensation device (capacitor bank PCB) in the arm of the traction substation 25 kV (left) and 25 kV (right), they are connected to parallel load of electric locomotives. The capacitor of the reactive power compensation device (capacitor bank PCB) is conditionally depicted as a capacitor C connected between the catenary wire and the rails. The schemes of the 25 kV, 50 Hz catenary of 110/27.5/10 kV traction substations by using a shunt reactive power compensation device (capacitor bank PCB) connecting method is provided in Fig. 7.

Reactive power compensation device (capacitor banks PCB) connected in parallel reduce the losses of voltage in both arms of the catenary 25 kV (left) and 25 kV (right). PCB connected in the catenary sectioning post. In this case, the capacitor banks of reactive power compensation PCB empower the reduction of the losses of voltage in the traction network and to increase the voltage in the sectioning post [9]. To remove the resonance of voltage consistently, a reactor is connected with capacitors C. With the voltage of 50 Hz of the catenary (according to the calculations completed by the author), to remove the voltage resonance, the inductive resistance of the reactor has to be 1/9 of the capacitor resistance: $X_1 = 1/9 X_c$. The simplified and automatic control of PCB capacitor parameters

schemes, a phasor diagram of the reactive power compensation is provided, where the capacitor bank and the reactor are connected consistently have been provided in Fig. 8 [10, 11].

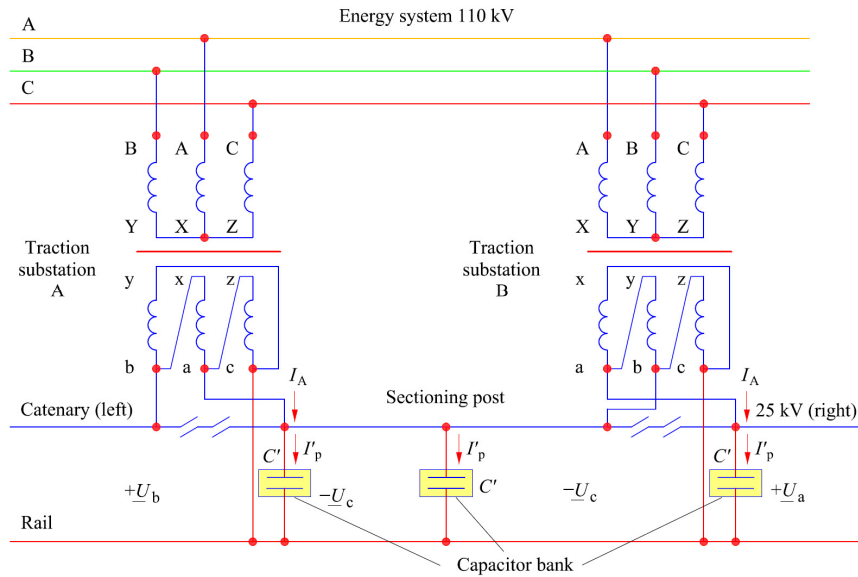


Fig. 7. 25 kV, 50 Hz catenary 110/27.5/10 kV traction substation schemes with connected shunt reactive power compensation device – capacitor banks PCB.

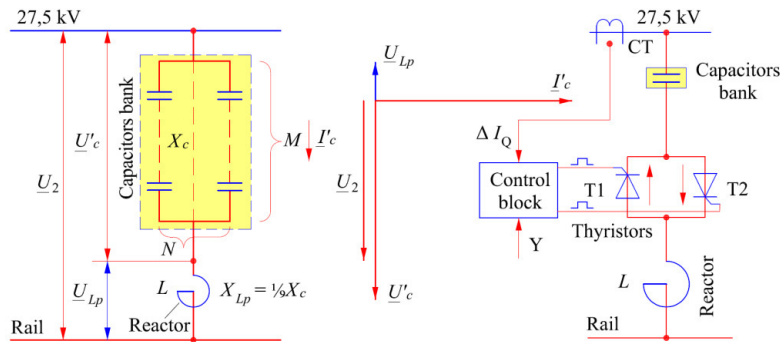


Fig. 8. The simplified and automatic control of PCB capacitor parameters schemes, a phasor diagram of the reactive power compensation: CT – current transformer; ΔI_Q – reactive component current deviations signal; T1–T2 – thyristors; Y – control signal.

In the middle part of the schemes (see Fig. 8), a phasor diagram of the reactive power compensation is provided, where the capacitor bank and the reactor are connected consistently.

3.2. Calculation of the shunt compensation device (capacitor bank PCB) parameters

In the case of capacity of parallel (shunt) connected capacitor banks PCB, the reactive power is transferred to the traction network. The total capacity of the reactive power necessary for compensation of the PCB capacitors C depends on the number of series consistently connected capacitors in arm M and the number of parallel groups N (see Fig. 8) and the inductivity of the reactor L. The capacity of the parallel capacity compensation banks PCB

needed Q_n'' is calculated as a difference between the reactive power consumed from the system without the compensation equipment and with them.

$$Q_n' = \frac{A(\operatorname{tg}\varphi_1 - \operatorname{tg}\varphi_2)}{24}, \quad (14)$$

here: A – active electric energy consumed for traction of the substation; φ_1 – the angle of the phase between the traction substation supply arm current and voltage; φ_2 – the angle of the phase between the current of the traction substation supply arm current and voltage (with a capacitor device switched on). Having in mind that the voltage in the arm with the capacitors U'_c and reactor U_{Lp} is in the opposite phase, it can be written that voltage in the arm of the traction transformer is $U_2 = (U'_c - U_{Lp})$. Considering that $U_{Lp} = 1/9 U'_c$, hence:

$$U_2 = U_c - \frac{1}{9} U'_c. \quad (15)$$

From here: $U'_c = 1.125 U_2$. In this way, by connecting the reactor with voltage in them consistently, the capacity increases by 12.5%. This means that the number of capacitors must be increased by 12.5%, the reactive power of the compensation device used Q_n' will be 1.125 Q_n'' . To increase the reliability, the reactive power of the compensation device Q_n'' has to be increased not by 12.5%, but by 20% [12]. The reactive power of the compensation device capacitors shall be calculated as follows:

$$Q_c = \frac{U_c^2}{x_c}, \quad (16)$$

here: U_c – the voltage of the capacitor; x_c – the capacitive reactance. The number of capacitors M connected consistently in one arm shall be calculated according to the maximum value of voltage U'_c and the allowed voltage of one capacitor. Considering that the maximum voltage of the catenary U_2 is equal to 29 kV, the value of voltage U'_c will be 33 kV. To calculate the total number of the compensating capacitor K , one needs to know the factual reactance $Q_{c \text{ fact.}}$, of one capacitor, which is calculated as follows:

$$Q_{c \text{ fact.}} = \frac{U_{c \text{ fact.}}^2}{x_c}, \quad (17)$$

here: $U_{c \text{ fact.}}$ – factual voltage of a single capacitor terminals. The factual voltage of the PCB capacitors $U_{c \text{ fact.}}$ may be calculated as follows:

$$U_{c \text{ fact.}} = \frac{1.125 U_{c \text{ calc.}}^2}{M}. \quad (18)$$

For establishing the inductive reactance X_{Lp} , the capacity resistance X_c of the compensation device needs to be calculated as:

$$X_c = \frac{x_c M}{N}. \quad (19)$$

According to the inductive resistance of the reactor X_{Lp} , which amounts to $1/9$ of X_c , the inductivity of the reactor L_p is established, where the total reactance of the compensation device is $X_{ycm} = (X_c - X_{Lp})$. Knowing these parameters, one may calculate Q_{Fact} , the factual $\text{tg}\varphi_2$ and $\cos\varphi_2$. The number of capacitors connected consistently M and the number of parallel groups N are established on the basis of the technical characteristics of the capacitors used. M , as a rule, it is from 6 to 32, whereas N – from 2 to 4. In the system, a reactor may be used (of ΦPOM type), the inductivity of which is from 75 to 107 mH, with separate terminals at 8 mH interval [13]. For the catenary sections of 25 kV (НИИЭФА- ЭНЕРГО Russia institution), equipment for reactance compensation and 27.5 kV voltage filtration has been installed, the reactive power of which is 2800 kVAr.

4. Automatic control of the compensation devices parameters

The most important technologies covered include: detuned reactive power compensation (capacitive), thyristor switched reactive power compensation (capacitive and inductive), passive filter circuits (capacitive), active electronic filters (capacitive and inductive as 4 or 3 conductor versions).

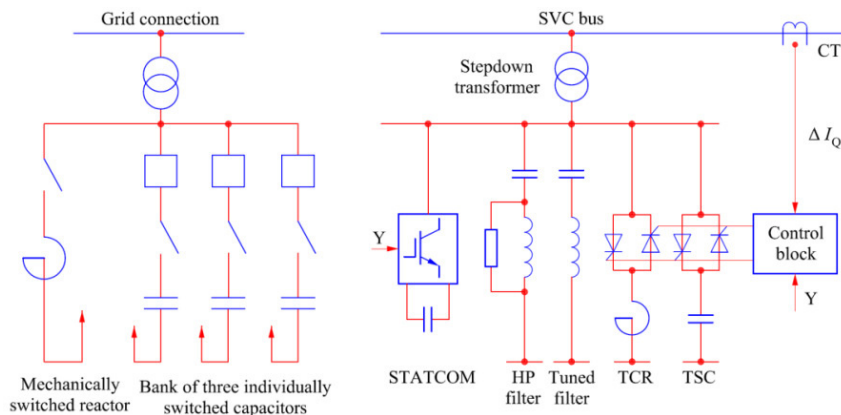


Fig. 9. Examples of FACTS for shunt compensation (schematic): CT – current transformer; Y – automatic control signal; ΔI_Q – reactive current deviation signal.

In practical systems, manual and automatic control systems of reactive power Q are applied in capacity device parameters. The schemes of compensation of reactive power equipment connection and control are provided in Fig. 9. It is crucial to measure the value consumed in the dynamic mode from the feeder and to only connect to the circuit for compensation the necessary number of capacitors (respectively Q_c). It is crucial to measure the value consumed in the dynamic mode from the feeder and to only connect to the circuit for compensation the necessary number of capacitors (respectively Q_c). It is not allowed to supply to the feeder the reactive power of capacitors greater than instantaneous consumed from the feeder. For the control of the compensation equipment parameter (C value of the capacity bank) it is proposed to connect an electronic device made of thyristors connected in series and inverse-parallel thyristor valves [13]. By sending respective opening signals to the thyristor gates, the value of the reactive power consumed (in the straightforward direction) and the value of the compensatory reactive power (in the inverse direction) may be controlled.

4.1. Static synchronous compensator (STATCOM)

Static VAR compensator (SVC). Most common SVCs are: Thyristor-controlled reactor (TCR): reactor is connected in series with a bidirectional thyristor valve. The thyristor valve is phase-controlled. Equivalent reactance varies continuously. Thyristor-switched reactor (TSR): Same as TCR but thyristor is either in zero- or full-conduction. Equivalent reactance is varied in stepwise manner. Thyristor-switched capacitor (TSC): capacitor is connected in series with a bidirectional thyristor valve. Thyristor is either in zero or full-conduction. Equivalent

reactance is varied in stepwise manner. Mechanically-switched capacitor (MSC): capacitor is switched by circuit-breaker. It aims at compensating steady state reactive power. It is switched only a few times a day.

4.2. Static reactive power compensators

Prior to the invention of the static reactive power compensators, power factor compensation was to preserve large rotating machines such as synchronous condensers or switched capacitor banks [14]. The thyristor-controlled reactor (TCR) and thyristor-controlled capacitor (TSC) are a set of electrical devices for providing fast-operating reactive power on high-voltage electricity transmission networks [15]. Using of phase control thyristors (see. Fig. 8, 9), the thyristor controlled reactor TCR may be variably switched into the circuit and so provide a continuously variable MVar injection (or absorption) to the electrical network [16]. In this electrical scheme configuration, coarse voltage control is provided by the capacitors; the thyristor-controlled reactor (TCR) and thyristor-controlled capacitor (TSC) are to provide smooth control [16]. Reactive power compensators should regulate the voltage, power factor, harmonics and stabilize the system [17, 18]. By using alternating current 25 kV, 50 Hz catenary 110/27.5/10 kV in traction substations the reactive power compensation equipment, on the side of PCB high voltage 110 kV the power factor is increased to 0.91–0.93 [19, 20].

5. Research results

Research results is provided when the author proposed to locate the shunt reactive power compensation device (capacitor bank PCB) on the side of traction substations of 27.5 kV voltage (see Fig. 7) and offered automatic control of PCB capacitor parameters schemes (see Fig. 8) [22].

The calculated 25 kV, 50 Hz alternating current catenary feeder system parameters before compensation and after compensation are provided in Table 1.

Table 1. The calculated 25 kV, 50 Hz alternating current catenary system parameters before compensation and after compensation.

Before compensation			After compensation		
Cos $\varphi_1 = 0.85$			Cos $\varphi_2 = 0.97$		
$P = 20 \text{ MW}$					
$S_1 = \frac{P}{\cos\varphi_1} = \frac{20}{0.85} = 23.53 \text{ MVA}$		$\varphi_1 = 31.76^\circ$	$S_1 = \frac{P}{\cos\varphi_2} = \frac{20}{0.97} = 20.6 \text{ MVA}$		$\varphi_2 = 14.07^\circ$
$Q_1 = P \cdot \text{tg}\varphi_1 = 20 \cdot 0.62 = 12.4 \text{ MVar}$			$Q_2 = P \cdot \text{tg}\varphi_2 = 20 \cdot 0.25 = 5 \text{ MVar}$		
Capacitor bank reactive power: $\Delta Q_c = S_1 - S_2 = 12.4 - 5 = 7.4 \text{ MVar}$					

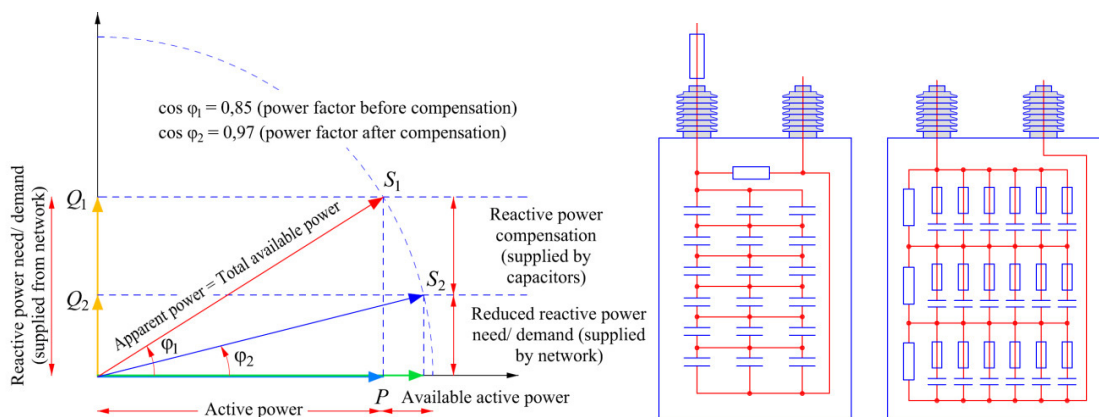


Fig. 10. A diagram illustrating compensation of reactive power (a) and the schemes of capacitor bank (b).

Table 1. Definitions: P – active traction substation power; S_1 – apparent power, when the power factor $\cos \varphi_1 = 0.85$; Q_1 – reactive power from network, when the power factor $\cos \varphi_1 = 0.85$; S_2 – apparent power, when the power factor $\cos \varphi_2 = 0.97$; ΔQ_c – reactive power compensation (supplied by capacitors).

The diagram illustrating the compensation of the reactive power and capacitor bank schemes are provided in Fig. 10. The diagram illustrates 25 kV, 50 Hz the parameters of alternating current in the catenary feeder before compensation and after compensation that were produced after the implementation of the authors solutions, that is after installing in the 110/27.5/10 kV traction substation 7.4 MVar reactive power capacitor banks PCB. For the creation of 7.4 MVar reactive power capacitor bank, fuseless units of company ABB (12–25 kV) may be used. Unit voltage range is 300–1200 kVar (50 Hz). For compensation of reactive power, high voltage capacitors are used [21].

6. Conclusions

1. From the calculations it was established that to increase the power factor $\cos \varphi$ from 0.85 to 0.97 of 25 kV, 50 Hz contact network feeder system power $\cos \varphi$ in the traction substation, 7.4 MVar reactive power capacitors have to be equipped.
2. Where the PCB are connected in the traction substation, the voltage increases by 2–5%.
3. By connecting the PCB into the catenary sectioning post, the voltage may be increased by 6–12%.
4. To increase 25 kV, 50 Hz contact network feeder capacity factor $\cos \varphi$, synchronous capacitors or capacitor banks may be used.
5. A 25 kV, 50 Hz contact network supply system is asymmetric, that is the load of the phases is not equal, hence it is difficult to use synchronous capacitors in a contact network of 25 kV, 50 Hz for the compensation of reactive power.
6. Upon installation in a 110/27.5/10 kV traction substation 7.4 MVar reactive power capacitor banks, $\cos \varphi_1 = 0.85$ increased to $\cos \varphi_2 = 0.97$.
7. Static reactive power compensators are more expensive than mechanically switched capacitors.
8. Static reactive power compensators are used to provide support for fast changes and the mechanically switched capacitors to provide steady-state VARs.
9. Optimally designed compensation systems that take into account the requirements of the equipment and systems to be compensated: reduce energy costs by complying with the contractually agreed power factor, enable the planned connection of consumers with a high level of load fluctuation, reduce losses in equipment in customer systems such as transformers and cables as well as in the transmission and distribution network of the network operator, stabilize public and industrial networks by reducing total harmonic distortion, and sustainably reduce CO₂ emissions.

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