Active Filters for Standard-Compliant Power Quality in Electrical Networks

G.M. Mustafa, S.I. Gusev*

LLC NPP LM Invertor, Moscow, Russia

***Abstract* — The focus of this paper is on three circuits of Modular Multilevel Converters (MMC) with series connected single-phase full-bridge and half-bridge voltage source inverters, each of which operates in the pulse-width modulation (PWM) mode. The key defining feature of MMC-based active filters (AF) is their capability to perform selective fast filtering of voltage harmonics in real time. AFs suppress any given set of voltage harmonics, including the negative harmonic (fundamental frequency negative sequence voltage) with a given degree of suppression down to zero or a standardized value. This is achieved by enabling an appropriate setting in the control program. The study proposes a DSB-algorithm (D – damping, S – selective harmonic suppression, B – balancing) of MMC control to make power quality indices standard-compliant. The algorithm rests on the classical theory of automatic control and the theory of three-phase circuits. A comparative assessment of the use of various MMC circuits is made for voltage balancing adjustment and reactive power compensation. The findings suggest that the problem of voltage balancing adjustment by means of MMCs is unique because it requires the application of dedicated algorithms to ensure the reactive nature of the branches of MMC circuits in order to solve it.**

* Corresponding author.
E-mail: Gusev-si@lm-inverter.ru

http://dx.doi.org/10.25729/esr.2024.01.0006

Received February 28, 2024. Revised March 25, 2024. Accepted April 19, 2024. Available online April 30, 2024.

***Index Terms* — modular multilevel voltage source converter, fast harmonic filtering, balancing adjustment, DSB control algorithm.**

I. Introduction

The issue of power quality has become more acute in recent years due to the appearance of a large number of nonlinear loads that compromise the power quality in electrical networks. Conventional solutions based on static thyristor-controlled compensators (STC) with passive resonant filters or transistor-clamped three-level voltage source converters (STATCOM) fail to address the quality issues in a truly comprehensive way. The emergence of the MMC concept was instrumental in yielding robust technology for the design of active filtering, compensating, and balancing devices (AFCD), which could provide a comprehensive solution to the problems of making power quality parameters standard-compliant in power systems and electrical networks of industrial enterprises in accordance with State Standard (GOST) 32144-2013 [1]. The recent years have seen the development of theoretical, procedural, and regulatory frameworks of MMC-based AFCD design worldwide with the start of adoption of prototype AFCDs in AC networks [2–11]. There are several MMC circuits suitable for the design of AFCDs [12–14], and hence there is a need to make reasonable choices with respect to AFCD design schemes to solve specific problems [15].

Ensuring compliance of power quality parameters in electrical networks with the requirements, as stated in GOST 32144-2013 [1], requires addressing the following issues:

1) reactive power regulation (voltage stabilization);
2) balancing adjustment;
3) harmonic filtering;
4) transient response damping;

5) flicker reduction;
6) voltage dips elimination.

The advent of STATCOM devices based on MMC (modular multilevel voltage source converter) has provided a comprehensive and efficient solution to these issues. The appearance of such devices is a result of higher values of parameters of high-capacity power semiconductor devices such as fast-acting Insulated Gate Bipolar Transistors (IGBT) and Integrated Gate-Commutated Thyristors (IGCT) [18]. Another contributing factor is the advances in the development of digital signal microprocessors (higher speed, higher capacity), which enabled the implementation of the most complex control algorithms. MMC-based STATCOMs are capable of forming the output AC voltage of a given waveform in a wide range of frequencies and making use of the accomplishments of the theory of automatic regulation to create tracking regulation systems. PWM-controlled MMCs enabled the use of active power filter (APF), which is a versatile tool to make power quality standard-compliant. In terms of its integral action in an electrical network, MMC is a broadband controlled voltage source that amplifies the reference signal with high accuracy. Furthermore, the reference signal may vary at a high rate, in particular, it may contain significant harmonics. The output impedance of MMCs is negligible over a wide frequency range. Even highly distorted fast-changing currents do not cause malfunction of the MMC. Representing MMC as an ideal controlled voltage source allows us to claim that high-frequency tracking pulse-width modulation converters based on IGBT transistors form a new class of broadband power amplifiers whose action is not accompanied by power losses [7]. From the theoretical standpoint, the action of an active filter is treated as the algebraic transformation of sinusoidal variables into the sum of complex exponents of the positive and negative sequences, which yields

$$U(\theta)^k = \vec{A}_{pk} e^{jk\theta} + \vec{A}_{mk} e^{-jk\theta}, \quad (1)$$

where $\vec{A}_{pk}$, $\vec{A}_{mk}$ is complex amplitudes of positive and negative sequence voltages; k is harmonic number; $\theta = \omega t$; $\omega = 2\pi f$; f is network frequency.

The negative sequence voltage at the fundamental frequency is considered to be one of the negative harmonics, which enables a unified approach to the design of the harmonic filtering and balancing adjustment algorithm.

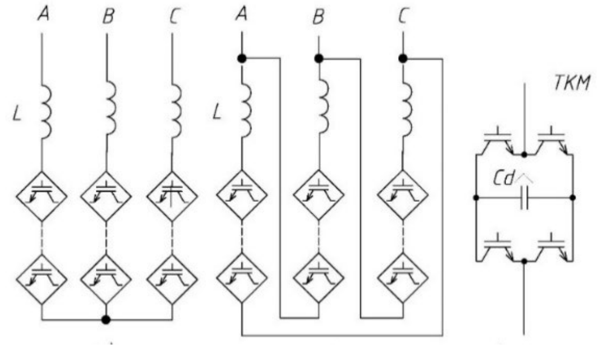
II. APF Designs

Three MMC circuits with a series connected single-phase full-bridge (Fig. 1) and half-bridge (Fig. 2) voltage source converters (transistor and capacitor modules, or TCM) are most suitable for APF design. Each of such converters operates in the PWM mode, so that the average output voltage of the module is set equal to the input control variable, i.e., the voltage reference signal [3, 11]. Several TCMs are connected in series to form a phase branch (arm) of the MMC, and then three phase branches can be connected in a star (Y) or delta (D) topology, thus forming a tri-pole network, which is then connected to a three-phase network (Fig. 1), or into a bridge circuit, i.e., the Marquardt circuit (Fig. 2) [13, 14].

The basic component of the MMC is a single-phase transistor-clamped voltage source converter (VSC), which represents the basic state-of-the-art means for controlling the flow of electricity. A simple voltage source converter is made up of four or two transistors, each shunted by a backward diode (Fig. 3). The transistors are connected in a single-phase full-bridge (or half-bridge) circuit, forming a 4-pole network with two bipolar ports for connection to an external system (sources, loads, or intermediate nodes):

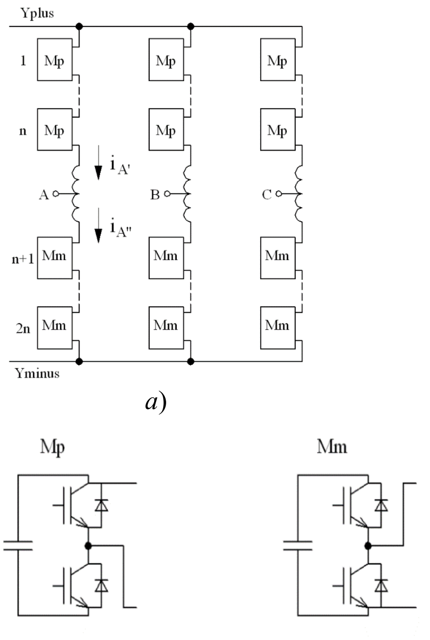
– a constant voltage (sign-constant voltage) port with two variables $u_1(t)$, $i_1(t)$;
– AC voltage port with two variables $u_2(t)$, $i_2(t)$.

Single-phase PWM converter (Fig. 3) is a controllable component that neither stores nor dissipates energy and whose AC port power is identically equal to the DC port power [16]:



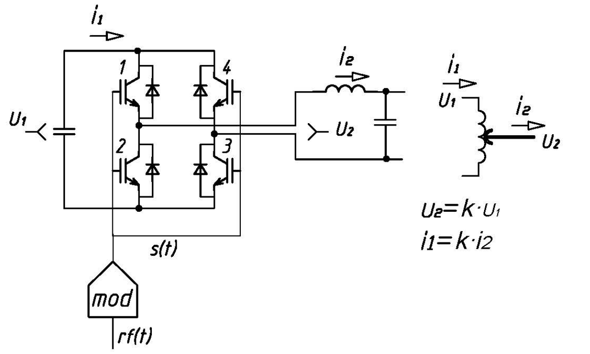
a) b) c)

Fig. 1. Modular multi-level circuit composed of series-connected TCMs (c) combined into a star (a) or delta (b) configuration.



b) *c*)

Fig. 2. Bridge-based modular multi-level circuit – Marquardt circuit (a), composed of half-bridge modules (b) and (c), the positive Y_{plus} and negative Y_{minus} poles of the circuit.



a) *b)*

Fig. 3. The simplest single-phase PWM voltage converter (a) and its equivalent circuit (b).

$$p_2 = u_2 i_2 \equiv u_1 i_1, \tag{2}$$

with the voltage and current transfer ratio set by the control system that generates the switching PWM function of the transistors $s(t)$:

$$\begin{aligned} u_2 &= s(t)u_1, \\ i_1 &= s(t)i_2, \end{aligned} \tag{3}$$

linking the DC-side variables to the AC-side variables.

The switching function $s(t)$ is a step function with values [0, ±1] (three-step modulation) and the variables u_2, i_2 are step variables along with $s(t)$. After the local averaging operation [6] of the step function within the modulation period, which is obtained as:

$$\hat{x}(t) = \frac{1}{2h}\int_{t-h}^{t+h} x(\tau)d\tau\,, \tag{4}$$

each variable of the function $x(t)$ is divided into its basis $\hat{x}(t)$ and ripple $\tilde{x}(t)$:

$$x(t) = \hat{x}(t) + \tilde{x}(t).$$

The ripples $\tilde{x}(t)$ are suppressed by the output LC filter (inductor filter) and do not reach the load. Only the basic components of the variables are useful.

As a result, the average value of the switching function can be gradually changed in the range of [–1, 1], and accordingly, the PWM converter voltage can be gradually changed by the control system in the range of [$-u_2$, u_2]. If the modulator is properly designed, the switching function $s(t)$ generated by it has a locally averaged value

$$\hat{s}(t) = u_2/u_1. \tag{5}$$

In this case, the locally averaged voltage of the PWM converter coincides with the reference signal

$$\hat{u}_2 = u_z, \tag{6}$$

which is what is required to use it as an active element of the filter. Equalities (2), (3), (5), (6) describe the single-phase modules of the multilevel circuit and the entire modular multilevel circuit as a whole.

The PWM carrier frequency is usually high and well above the fundamental frequencies of the system. The power flows are controlled by the data signal of $rf(t)$, which is formed by the control system and acts through the modulator (*mod*) generating pulses to switch on transistors of the corresponding width. Equations (3) describe the PWM converter as a controlled electrical network 4-pole terminal that neither stores nor dissipates energy. The equations are exactly the same as the equations of the ideal transformer with variable controlled turns ratio as shown in Fig. 3b.

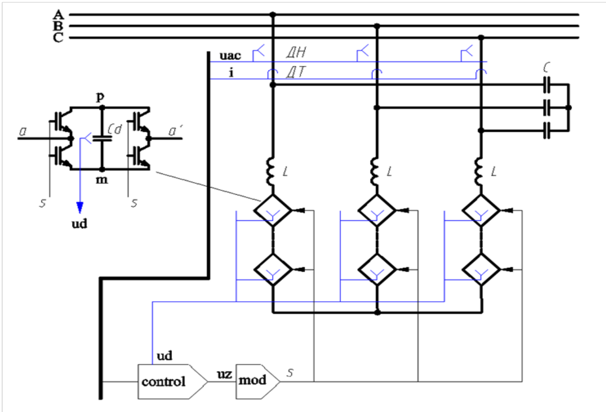


Fig. 4. Diagram of connection of the MMC Y-circuit to a three-phase network: TCM - left; electrical diagram - right.

Figure 4 shows the connection diagram for an active element based on the MMC Y-circuit connected to a 3-phase network.

The input of the control unit (*control*) receives feedback signals *i*, u_{ac} from the current (CS) and voltage (VS) sensors of the AC side and signals of constant voltages on the TCM capacitors – u_d, based on which the reference signal u_z of the PWM modulator (*mod*) is formed.

PWM pulses of the TCM of the phase branch are shifted between each other, creating a multilevel voltage with high

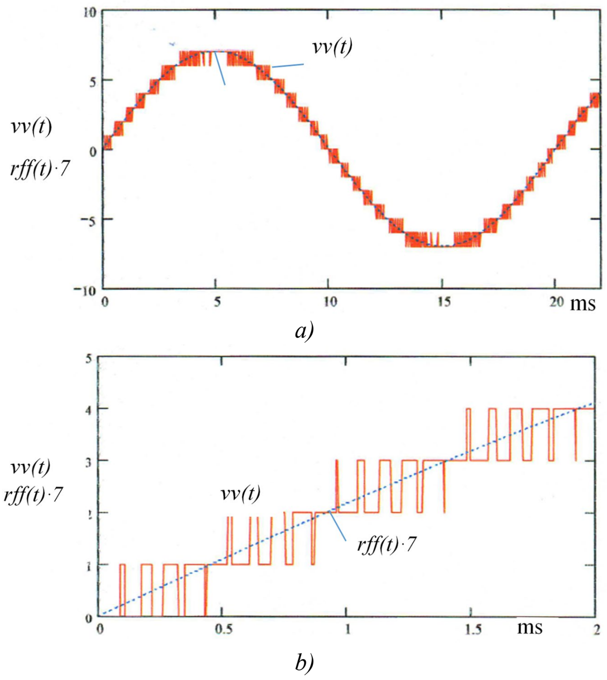


Fig. 5. Width modulation in a 7-module circuit (rff(t)-7 – reference voltage; vv(t) – output width-modulated voltage): (a) period of the output voltage; (b) enlarged detail.

equivalent frequency and a small modulation step (Fig. 5).

The MMC output voltage averaged over a short interval repeats the output voltage reference data signal at the power output:

$$\hat{u}(t) = u_z(t). \tag{7}$$

The LC filter still need to filter the width modulation ripple but the energy impact of the filter in the multi-module circuit is negligible.

The shunt active filter can be represented integrally as an active element (*ae*) of an electrical network with frequency-dependent conductivity, just like any passive filter. The process of transformation into this form is shown in Fig. 6. Internal current i_{ae} and voltage u_{ae} feedback is used to transform the active element as an ideal voltage source (voltage follower) into a controllable current source (current follower):

$$i(t) = i_z(t). \tag{8}$$

The current reference signal i_z is generated by the main MMC regulator. If the voltage $u(p)$ at the point-of-coupling pole is used as the initial quantity for the current reference signal, the current reference signal is written as follows:

$$i_z(p) = G_{ae}(p)u(p), \tag{9}$$

where *p* is the Laplacian operator.

After feedback closing, the MMC acts as a circuit that shunts the point-of-coupling pole. This circuit has the

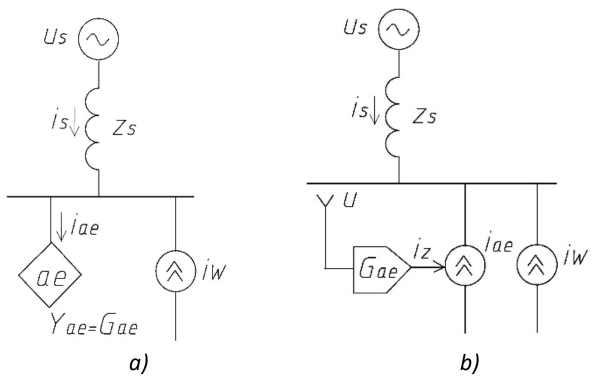


Fig. 6. Representation of the MMC as a network component with frequency-dependent conductivity: (a) a diagram of MMC connection to an electrical network; (b) an integral model of the MMC as an electrical network component with a conductivity function $Y_{ae}(p)$ equal to the transfer function $G_{ae}(p)$ of the main MMC controller.

frequency-dependent conductivity function equal to the controller transfer function $G_{ae}(p)$:

$$Y_{ae}(p) = G_{ae}(p). \quad (10)$$

It is physically possible to have a transfer function $G_{ae}(p)$ that is zero at both the positive line frequency

$$G_{ae}\ (j \cdot f_{nom}) = 0, \quad (11)$$

and at the negative line frequency

$$G_{ae}\ (-j \cdot f_{nom}) = 0. \quad (12)$$

In this way, it is possible to suppress the negative sequence voltage at the line frequency, i.e. to perform balancing adjustment of the three-phase voltage system.

III. DSB-Algorithm of MMC Control

The practical implementation of MMC-based STATCOM capabilities to ensure standard-compliant power quality parameters requires the synthesis of a branched multi-loop automatic control system capable of simultaneously controlling a set of a large number of parameters. In order to build such a system for solving practical problems, we have devised what we call the DSB algorithm of MMC control, which integrates classical automatic control theory and the theory of three-phase circuits. The DSB-algorithm is based on the sequential creation of three types of tracking automatic controllers [11, 17]: D (damp) – damping, S (select) – selective suppression, B (balance) – balancing, and the subsequent combination of their actions. The flow chart of the MMC control algorithm for the DSB algorithm is shown in Fig. 7.

The key MMC control variable, which is the voltage reference signal $u_z(t)$, is formed as a three-component sum of the voltages of regulators D, S, and B:

$$u_z = u_{damp} + u_{bal} + u_{sel}, \quad (13)$$

fed to the PWM modulator (mdl) input of the MMC circuit. The input signals that form the voltage reference signal are line current i_s, MMC output current i_{ae}, line voltage u_s, voltages of reservoir capacitors of MMC constant voltage links u_d. An LC filter (Y_{ae}, x_{ae}) is installed at the output of the MMC to provide PWM ripple smoothing.

Component D is formed by the output current feedback of the active element *iae* according to the equality:

$$u_{demp}(t) = R_{ae} \cdot i_{ae}(t). \quad (14)$$

This feedback acts like the resistor R_{ae} in (14) introduced into the output circuit of the active element. This "virtual resistor" dampens transient network fluctuations as efficiently as a real one. Figure 8 demonstrates the effect of the damping feedback. The Figure shows oscillograms of voltage on the 6 kV busbars of the Oktyabrsky mine

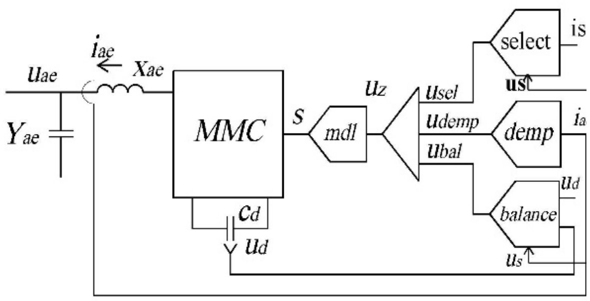


Fig. 7. Flow chart of the MMC control algorithm for the DSB algorithm.

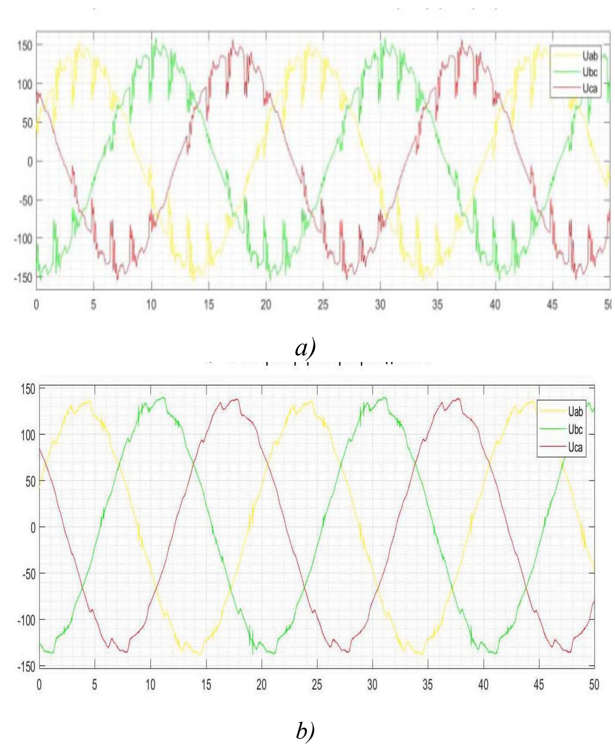


Fig. 8. Damping during operation of 2.4 MVA APF in the 6 kV network at the mine of PJSC Mining and Metallurgical Company "Norilsk Nickel": (a) voltage on the busbars before switching on the AF; (b) voltage on the busbars after switching on the AF.

network of PJSC Mining and Metallurgical Company “Norilsk Nickel” [6]. It reveals the significant impact of the active filter designed and manufactured by LLC “NPP LM Inverter” as depicted in Fig. 1b. This filter operates exclusively in the damping mode, demonstrating its efficiency. The busbar voltage is initially distorted by the thyristor rectifier of the skip hoist drive. The damping regulator effectively suppresses high-frequency voltage distortions that occur during switching of the rectifier thyristorsin the skip hoist drive.

The broadband damping feedback enables the design of a system for selective suppression of line current harmonics *is*(θ), which is based on the principle of quasi-stationarity. Damping causes the AC line current to be composed of the same harmonics that are generated by the distortion sources, which occurs after sufficiently short time intervals or with sufficiently slow changes in conditions. This enables a fast response to harmonic suppression by the selective filtering block *S (select)*.

The block *S (select)* is formed by means of the line current feedback *is* with the contribution from the line voltage u_s. The structure of the regulator of selective filtering of the *k*-th harmonic of the line current is shown in Fig. 9. The harmonic amplitude of the line current $i_{k,}$, represented in the control system by the harmonic sum $I_k \cdot e^{j\cdot k\cdot\theta}$, is obtained from the current measured by the current sensor, multiplied by the *k*-th unit vector $e^{-j\cdot k\cdot\theta}$ of the negative sequence in Multiplier 1. To obtain the complex amplitude of the voltage harmonic $\vec{U}_k$, the output variable of the complex integrator block IN is multiplied by the assumed transfer resistance $Z_k = 1/Y_k$, which is determined in Multiplier 2 by dividing the active element voltage by the line current at the frequency of the *k*-th harmonic (Y_k is the assumed line conductivity at the frequency of the *k*-th harmonic). Multiplier 3 restores the *k*-th harmonic reference voltage U_k of the active element by multiplying the value of the complex voltage amplitude $\vec{U}_k$ by the k-th unit vector $e^{j\cdot k\cdot\theta}$.

The structure of the regulator of selective suppression of the *k*-th harmonic of the line current is illustrated in Fig. 9. The amplitude of the harmonic current is obtained from the line current i_k (as measured by the line current sensor) multiplied by the negative sequence current in Multiplier 1. To obtain the complex amplitude of the voltage harmonic $\vec{U}_k$, the output variable of the complex integrator (IN) block is multiplied by the assumed transfer resistance $Z_k = 1/Y_k$ from the active element voltage to the line current at the frequency of the *k*-th harmonic in Multiplier 2, where Y_k is the assumed network conductivity. Multiplier 3 uses the obtained value of the complex voltage amplitude to restore the reference voltage of the *k*-th harmonic U_k of the active element.

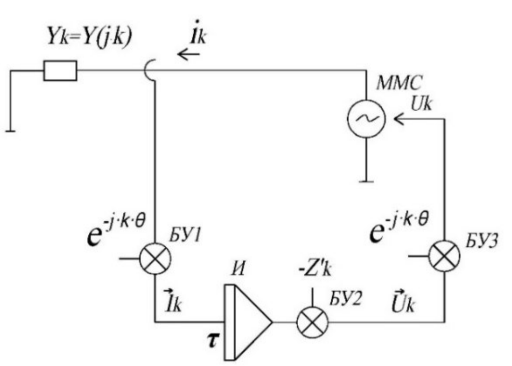


Fig. 9. Structure of the regulator of the selective filter of the k-th harmonic of the network current with feedback on the line current.

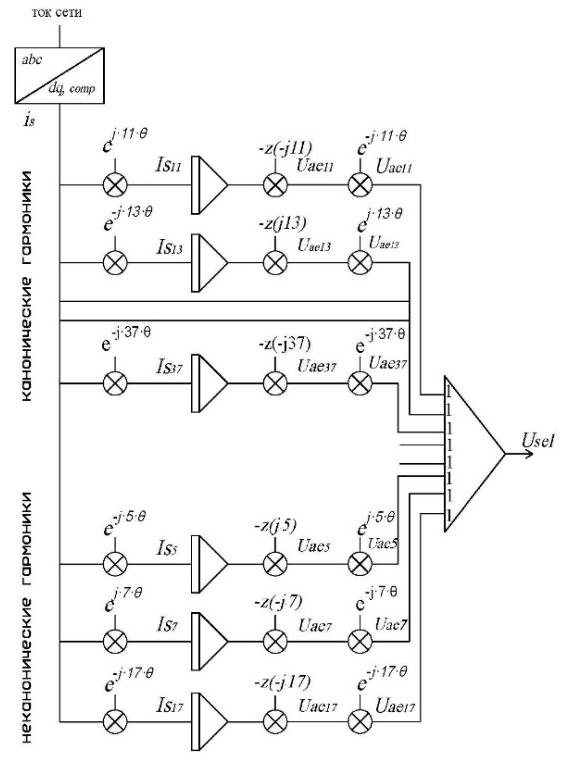


Fig. 10. The flow diagram of the calculator for selective harmonic suppression component U_{sel} that uses line current feedback.

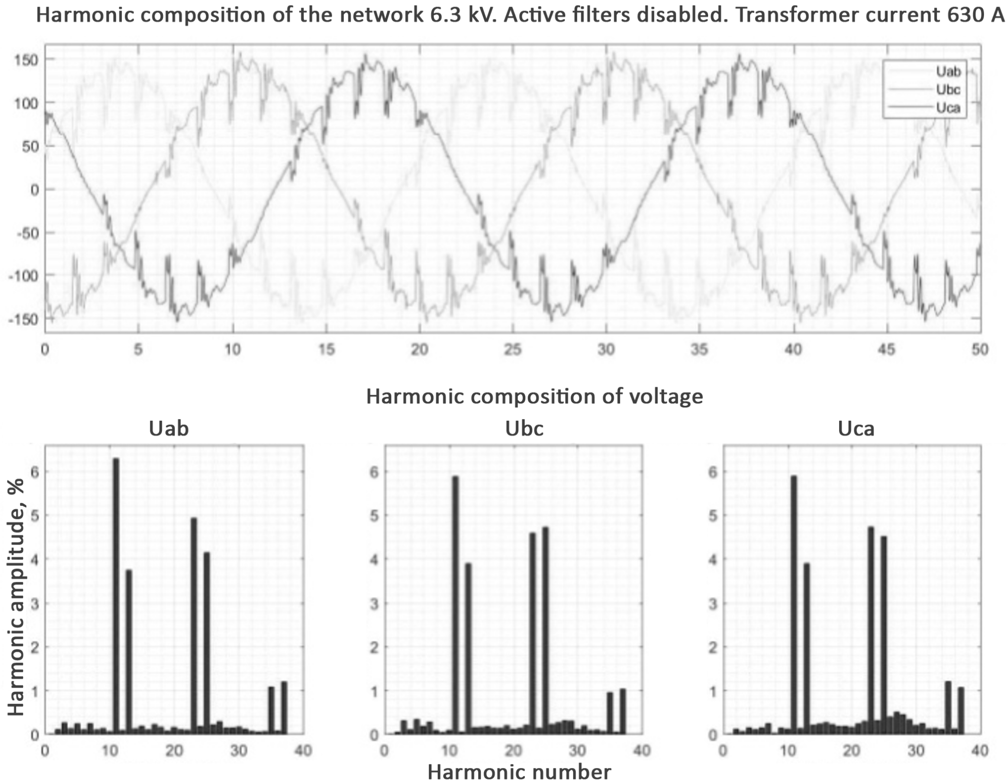


Fig. 11. Voltage oscillograms on 6 kV busbars before initiating the active filter for the modes of damping and selective filtering of the 11th and 13th harmonics at PJSC MMC "Norilsk Nickel."

The complete flow diagram of the calculator of each component of selective harmonic suppression is built by summing the regulators of the form presented in Fig. 9 for the entire set of selected harmonics (one regulator for each of the suppressed harmonics). This flow diagram is shown in Fig. 10.

The action of selective filtering can be exemplified by a case study of active filter operations at the facility of PJSC Mining and Metallurgical Company "Norilsk Nickel." Figures 11 and 12 show voltage oscillograms and histograms of the voltage harmonic content on the 6 kV busbars before and after initiating the active filter for the damping mode and the selective filtering mode targeting the 11th and 13th harmonics.The level of the 11th harmonic exceeded 6% before activating the active filter, but after enabling the filter, the maximum voltage harmonic level did not exceed 1%.

Component B is formed by the feedback on the voltages u_d of the reservoir capacitors of the constant voltage links of the MMC with the contribution from the line voltage u_s in this feedback. The component maintains the balance of energy, and hence the voltages of the reservoir capacitors in the vicinity of a specified level. The task of maintaining the energy balance of the reservoir capacitors arises as a consequence of the fact that the reservoir capacitors of the converter modules are not connected to the DC voltage energy source or sink.

A proportional-integral (PI) controller is used to regulate the balance power:

$$Pbal = \left(Kd + \frac{1}{p \cdot td} \right) \cdot \left(Ez - Ed \right), \qquad (15)$$

where p – the Laplacian; Ez – reference energy; Ed – energy of capacitors Cd; Kd, td – gain and time constant of the PI controller.

IV. Specific Features of Balancing Adjustment

The branches in the Y-circuit, D-circuit, and Marquardt circuit are reactive. Under all steady-state conditions, the average branch power must be zero. However, with balancing adjustment, the average phase powers can be non-zero. Balancing adjustment requires the exchange of

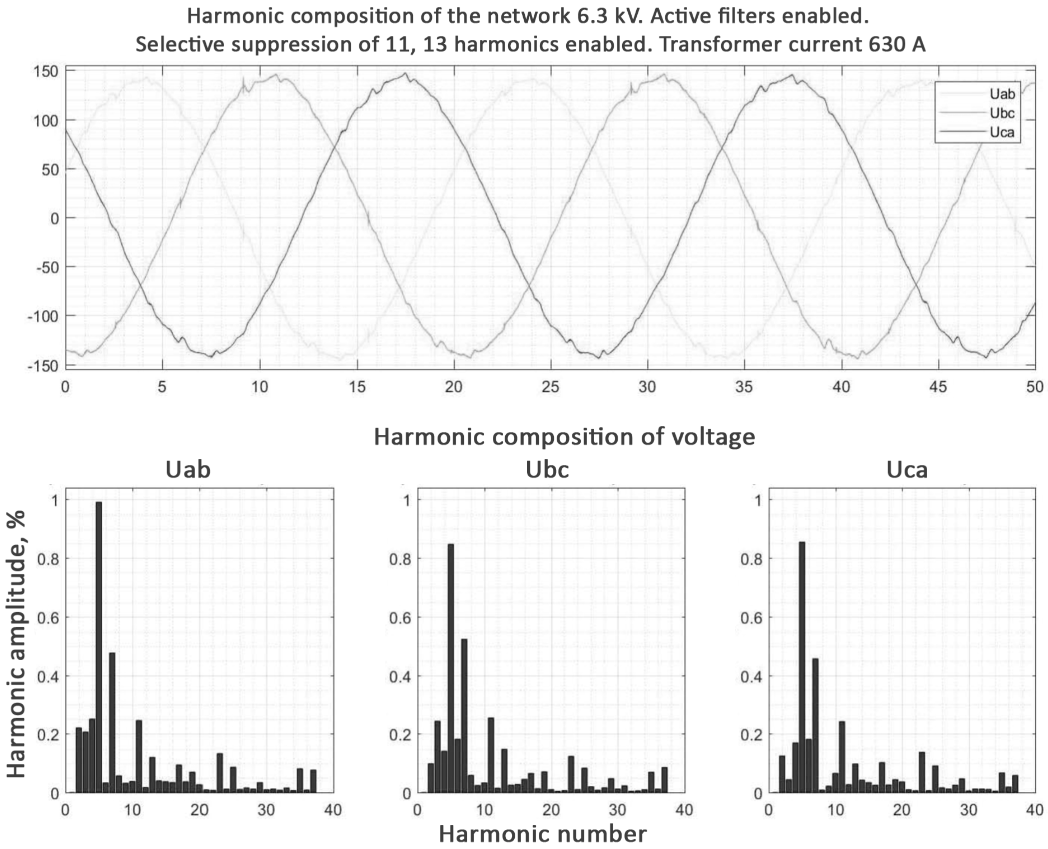


Fig. 12. Voltage oscillograms on 6 kV busbars after initiating the active filter for the modes of damping and selective filtering of the 11th and 13th harmonics at PJSC Mining and Metallurgical Company "Nornickel."

average powers between phases by introducing constant offset current in the Marquardt circuit, neutral offset in the Y-circuit, and circulating current in the D-circuit [10]. These currents affect significantly the technical and economic performance of the devices. In order to evaluate the technical and economic performance, we compared the three circuits with respect to the test conditions of compensation/balancing adjustment for a single-phase mixed resistive-inductive load with the conductivity Y_l, which is inserted between two phases.

$$\vec{Y}l = \begin{pmatrix} Y_0 \\ Y_1 \\ Y_2 \end{pmatrix} = \begin{pmatrix} \exp(j\varphi) \\ 0 \\ 0 \end{pmatrix}. \qquad (16)$$

A STATCOM was connected in parallel to the load. Its design could be based either on the Marquardt circuit, the Y-circuit, or the D-circuit.

The STATCOM current $i_{sts}(t)$ must provide compensation for the reactive components of the load current:

$$i_{sts}(t) = -(i_{yma}(t) + i_{ymr}(t) + i_{ypr}(t)), \qquad (17)$$

where i_{yma} and i_{ymr} are the negative sequence current components, i_{ypr} is the reactive component of the positive sequence current.

A. The Marquardt circuit

The test circuit is shown in Fig. 13. The balancing adjustment mode requires introducing a constant current offset ism_k common to these valves to balance the power in the branches of the Marquardt circuit:

$$\begin{aligned} iw_{2k} &= \frac{1}{2} istc_k - ism_k, \\ iw_{2k+1} &= -\frac{1}{2} istc_k - ism_k \end{aligned}. \qquad (18)$$

The introduction of offsets guarantees that the conditions of zero average power of the valves are satisfied, i.e., it

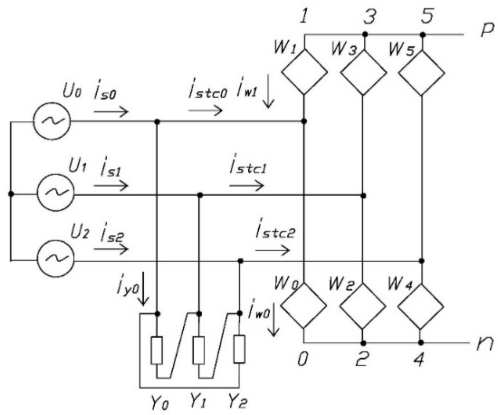


Fig. 13. A test circuit to analyze the operation of the Marquardt circuit.

ensures that they stay reactive.

$$\int_T w(t)_k \, iw(t)_k \, dt = 0, \quad k = 0, 1, \ldots, 5, \tag{19}$$

where $w(t)_k$ is the voltage of the *k*-th valve.

The value of the offset current is defined by the equality

$$ism_k = \frac{1}{wsr} \cdot \int w(t)_{2k} \cdot \frac{1}{2} istc(t)_k \,, \tag{20}$$

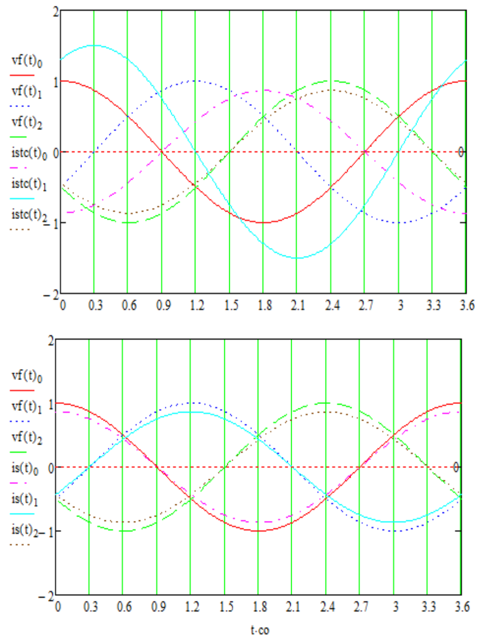
where $wsr = \int_T w(t)_{2k} \, dt$.

Figure 14 shows the results of mathematical modeling for Marquardt circuit operation under balancing adjustment of a single-phase inductive load.

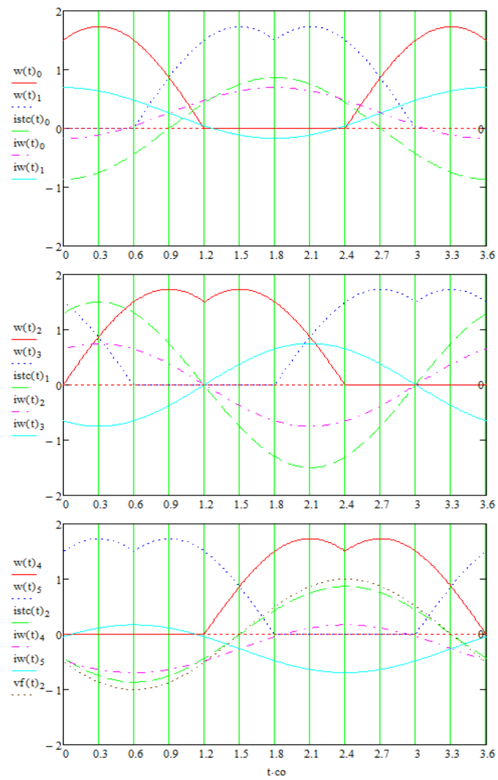
The network current $is(t)_k$ is a balanced clockwise-rotating current with zero phase shift with respect to the network voltage. Figure 14b shows one-by-one the loads of the controlled reactive valves for three phases during the operation in this mode: the voltage of the alternate valves w_{2k}, w_{2k+1} and their currents iw_{2k}, iw_{2k+1}. The phases are labeled as 0, 1, 2. The Figure also shows the phase currents of STATCOM $istc_k$. At a single-phase mixed resistive-inductive load at φ = π/6, with the load connected between phases 0, 1, offsets of currents in phases 0, 2 were needed: $ism_0 = -0.262$; $ism_2 = +0.262$. In this case, the active powers of the controlled reactive valves are zero for all three phases.

B. STATCOM Y-circuit

STATCOM Y- and D-circuits formed from three controlled reactive AC branches by connecting them in a star or delta topology are identical in terms of their functions, since they can be transformed into each other



a)



b)

Fig. 14. Marquardt circuit operation in the balancing adjustment/compensation mode under reference conditions: (a) STATCOM currents istc(t)ₖ and line currents is(t)ₖ against phase voltages vf(t)ₖ in the balancing adjustment mode; (b) STATCOM phase currents istc(t), voltages w(t) and currents iw(t) of valves.

according to the known rules of electrical engineering. However, the use of Y-circuits in high- and medium-voltage electrical networks requires lower voltage applied to the controlled reactive branches, compared to the D-circuit, and fewer cells, which reduces the cost of MMC implementation. The Y-circuits need neutral offsets to be introduced to balance the power of the controlled reactive branches.

An analysis of the Y-circuit performance [10] shows that a Y-circuit composed of controlled reactive AC branches cannot act as a universal balancing and reactive power compensation device. There are no solutions to the equation that determines the neutral offset in this mode. The balancing mode requires a neutral offset equal to the phase voltage to absorb the negative sequence current no matter how small its value. The voltages on the controlled reactive branches and their powers increase as much as two-fold, making the application of the Y-circuit pointless. However, the Y-circuit can be used for reactive power compensation in conjunction with harmonic filtering and has an advantage over other circuits because of fewer cells required to achieve the result.

Figure 15 shows a Y-circuit made up of three reactive branches w_0, w_1, w_2 connected in a star configuration. The single-phase load is defined by expression (16).

Figure 16 shows the oscillograms of the Y-circuit operation when the balancing adjustment and mixed resistive-inductive load compensation are combined with the 30° phase. The neutral offset required for balancing is doubled, $|\,|v_n| = 2$, and the amplitude of the voltage applied to the valves reaches $ampw_1 = 3$. The residual power of the network is active. The required neutral offset of the Y-circuit in the hybrid mode reaches the value twice the phase voltage.

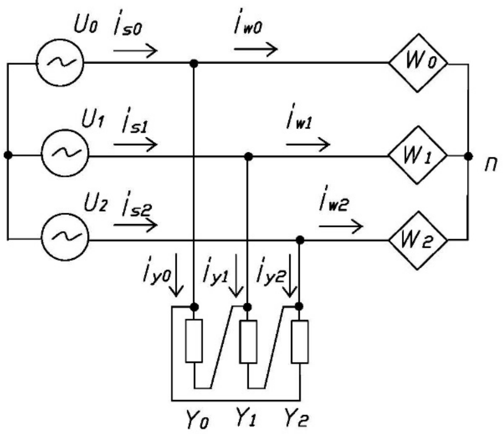


Fig. 15. Test Y-circuit.

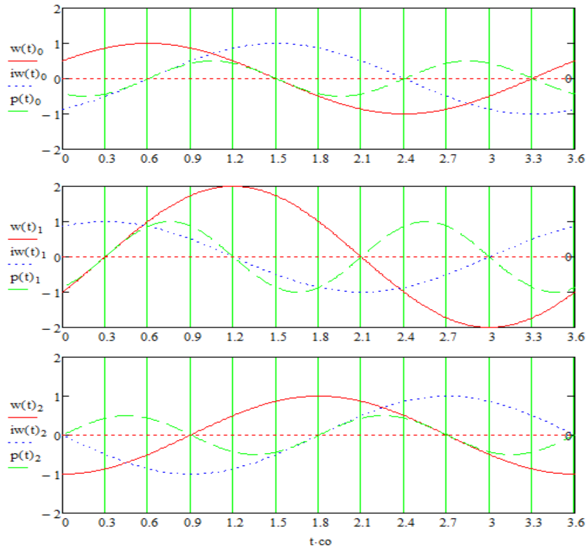


Fig. 16. Y-circuit operation with single-phase mixed resistive-inductive load in the balancing/compensation mode.

C. STATCOM D-circuit.

Figure 17 shows a test STATCOM D-circuit composed of three controlled reactive branches w_0, w_1, w_2 connected in a delta configuration. The load is the same as in the previous circuits.

The STATCOM current must provide compensation for reactive components (17):

$$istc(t) = -(iyma(t) + iymr(t) + iypr(t)).$$

The negative component, being reactive with respect to the sum of the three average phase powers, may have non-

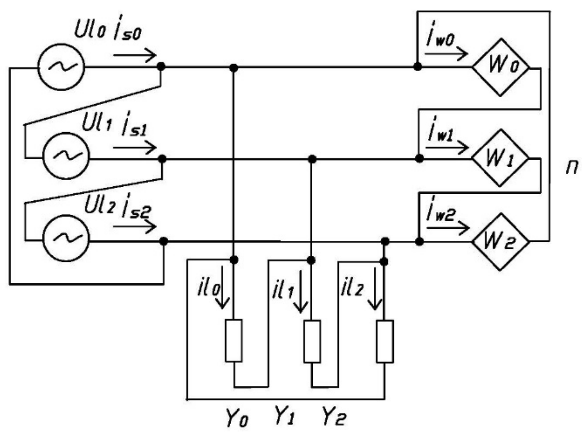


Fig. 17. STATCOM test D-circuit.

zero average powers of two or three phases. Balancing adjustment requires the exchange of average powers between phases. The D-circuit has one free variable to realize the inter-phase average power flow, i.e., the circulation current in the triangle *in*(·). It is easy to see that if *ma, mr* are amplitudes of two components of the negative sequence current, then the required harmonic of the circulation current is

$$in(t) = ma \cdot \cos t + mr \cdot \sin t. \qquad (21)$$

Valve currents including circulation currents are

$$iw_k(t) = istc_k(t) + in(t), \quad k = 0,1,2. \qquad (22)$$

When the circulation current is introduced in the mode of balancing/filtering of harmonics and complete suppression of unbalance, the current in one of the phase branches of the STATCOM doubles (Fig. 18), and, consequently, its rated power as a whole doubles as well. However, limiting the suppression of unbalance and harmonics to the standard-compliant level (K_{2U} = 4% for a 110 kV network) increases the phase current only by 20%. Figure 18 shows the waveforms of the STATCOM D-circuit operation in the mode of balancing and harmonic filtering with complete suppression of unbalance. The network voltage becomes balanced without waveform distortion. The STATCOM current in one of the phases has a double amplitude.

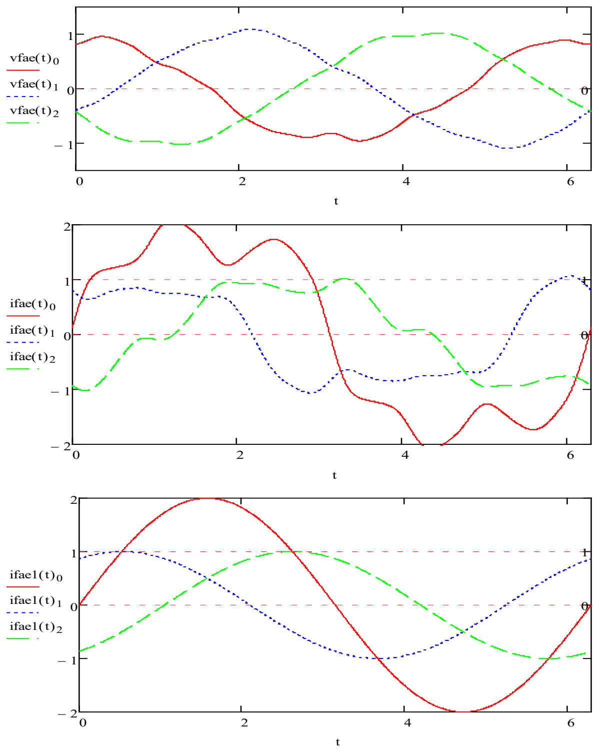


Fig. 18. STATCOM voltages and currents vfae(t), ifae(t) and the first harmonic of current ifae₁(t) under perfect filtering.

Figure 19 shows the D-circuit operation in the balancing/filtering mode with incomplete unbalance suppression (i.e., down to the standard-compliant value).

The STATCOM current increases from 8 to 20% depending on the ratio of unbalance and harmonic suppression factors. In all three phases, the power pulsates at twice the frequency, the average powers are zero, the line current *is*(–) is balanced and active.

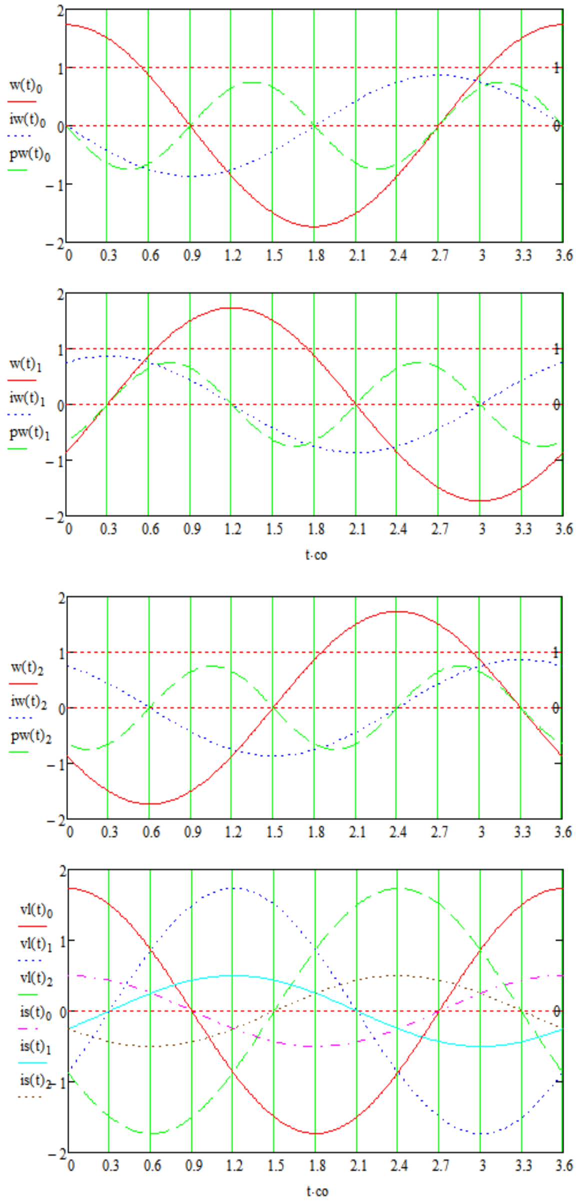


Fig. 19. Operation of the D-circuit in the balancing/filtering mode with incomplete suppression of unbalance under reference conditions.

V. Comparative Assessment of the Use of MMC Circuits for Balancing Adjustment and Reactive Power Compensation

When choosing a design of the STATCOM circuit for practical use, first of all, it is necessary to evaluate the costs of the basic power elements of the circuit, which are transistors and DC capacitors. The costs of STATCOM transistors are a function of two parameters: the highest voltage applied to the valves U_w and the highest current of the valves I_w. The capacitor costs are a function of the charge ripple dq. Table 1 lists the main parameters of the loads as per-unit quantities for the D-circuit and the two design options of using the Marquardt circuit (with isolated DC poles and with a capacitor shunting the DC poles) when operating in the balancing/compensation of a single-phase mixed resistive-inductive load under reference conditions.

All three options have the same applied voltages of the branches and cells, so that the voltage factor can be eliminated from the comparison.

The number of transistors is the same in all three options. Each symmetric cell with two pairs of D-circuit transistors corresponds to two Marquardt cells with one pair of transistors in each. The current loads I_w and the charge ripple dq are treated separately. The mrq0 option has the minimum current load of the transistors. However, it overestimates the charge ripple dq Option mrq1 has a low value of the dq parameter, but the current load I_w is overestimated and there is an additional cost incurred by the shunt capacitor.

A generalized comparison is made based on the current prices of IGBT power transistors and DC capacitor prices. There is also a number of somewhat artificial underlying assumptions:

- The sizing step of transistors and capacitors is not factored in;
- Transistor costs are assumed to be proportional to the nominal current, and capacitor bank costs are assumed to be proportional to their capacitance;
- The heuristic factor of 1.45 is used to take account of extra costs related to transistors (drivers, coolers, fans);
- Voltage ripple factor of capacitor banks during operation under steady-state conditions (the range) is assumed to be 8.3%.

The above assumptions were used to calculate the comparative costs of capacitor banks (Z_c), transistors (Z_t), and total costs (Z_s) for the three STATCOM design options as shown in Table 2.

The parameters shown in Table 2 are not stable. In any given case, the sizing step of transistors and capacitors can significantly affect the cost-effectiveness. Changes in capacitor and transistor technology can also involve significant cost changes.

Furthermore, the third function of STATCOM, that is filtering, was not considered in the study. Each of the STATCOM options under consideration can perform filtering in addition to balancing adjustment and compensation. The harmonics to be absorbed have almost no effect on the ripples dq, but can noticeably increase the required peak transistor currents, thus increasing the cost component Z_t in Table 2. Nevertheless, even under the above assumptions, the advantage of the D-circuit over the Marquardt circuit is much more compelling as evidenced by the findings of the study performed. The use of the Marquardt circuit as the STATCOM, compared to the D-circuit from controlled reactive AC branches, appears unfeasible.

Table 1. Load Parameters for the Basic D-circuit and Two Options of the Marquardt Circuit in the Balancing/Compensation of Single-Phase Mixed Resistive-Inductive Load under Reference Conditions

Circuit, algorithm	Paramer, per unit			
	U_w	I_w	dq	$dqpm^*$
D-circuit	1.732	0.866	0.433	-
mrq0 (with isolated DC poles)	1.732	0.75	0.717	-
mrq1 (with a capacitor between DC poles)	1.732	1.125	0.352	0.866

*$dqpm$ – charge ripple of the capacitor shunting the DC poles

Table 2. Comparative Costs of Capacitor Banks, Transistors, and Their Sum for Three STATCOM Design Options

Circuit, algorithm	Costs in notional units		
	Z_c	Z_t	Z_s
D-circuit	806	742	1 548
mrq0	2 671	642	3 313
mrq1	1 729	964	2 693

VI. Shunt or Series AF Connection

Both shunt and series connections of AF can be used for reactive power compensation, balancing adjustment, and filtering the voltage in outgoing lines. The modular multilevel converter can operate in either of the connection configurations.

In the case of a shunt connection, the AF operates with a sine-wave positive sequence voltage applied to it. Distortion components, i.e. negative sequence voltage and voltage harmonics are eliminated by the action of the AF. The AF current in this case consists of the negative sequence current and current harmonics. The shunt AF acts by creating an appropriate voltage drop across the total reactance at the connection point. The great bulk of the shunt-connected AF capacity is utilized to absorb the negative sequence current and the third harmonic of the current. The limiting resistance increases in proportion to the harmonic number. The contribution of harmonics to the AF load is negligible.

In the case of a series connection, the AF is activated via an isolating matching transformer in the break between the network and the outgoing lines. The series-connected AF operates by counteracting the distorting components of the network voltage with the same components of the AF voltage. The voltages of the outgoing lines are adjusted as part of this process. If the loads of the outgoing lines have no significant distorting factors, the current of the outgoing lines will be sinusoidal when supplied with sinusoidal voltage. The series AF voltage is formed from distortion components only:

- negative sequence voltage;
- voltage harmonics.

The network reactance does not affect the normal operation of the series circuit. However, operation with a series connection under emergency and abnormal conditions make it necessary for the AF to be equipped with a thyristor key that shunts the windings of the matching transformer and ensures unobstructed flow of currents in the event of a short circuit in the network.

In the series configuration, the main part of the AF power is consumed to suppress harmonics that determine the amplitude of the voltage applied to the phase valves; only a small fraction of power is consumed for balancing purposes. In contrast, in the shunt-connected circuit, due to the large network conductivity, the AF absorbs the negative sequence current for the fundamental frequency. As a result, the power of the shunt option significantly exceeds that of the series option.

Just as in the shunt-connected design, the negative sequence suppression mode is a unique feature of the series design, because of the need to ensure the balance the power in the active element branches. Furthermore, the series design has specific balancing features for the D- and Y-circuits, as is the case of the shunt-connected design. The series-connected D-circuit needs circulation current to be introduced to ensure balance and the current of the active branches is double the network current

$$I_{ae1} = 2 \cdot I_s \tag{23}$$

regardless of the unbalance level, similar to the voltage doubling on the active branches of the shunt Y-circuit. In a series Y-circuit, one has to introduce neutral offset to ensure balance. The balancing adjustment-only mode can make voltage amplitude of the phase branch of the AF reach twice this value. The Y-circuit requires twice the AF power to suppress unbalance.

In the hybrid balancing/filtering mode, the required voltage and currents of active phase branches $U_{ae,max}$, $I_{ae,max}$ of the D-circuit of the AF are determined by the following equations:

$$\begin{cases} U_{ae,\max} = U_{1m,\max} + U_{h,\max}, \\ I_{ae,\max} = 2I_{1p,\max}. \end{cases} \tag{24}$$

Regardless of the relationship between the components of the balancing voltage U1m and the harmonic distortion voltage U_h, it is essential to double the calculated current of the D-circuit AF branches. This means that the installed capacity of the active phase branches must also be doubled.

When the Y-circuit of the series-connected AF operates in the hybrid balancing/filtering mode, the corresponding equalities are as follows:

$$\begin{cases} U_{ae,\max} = 2U_{1m,\max} + U_{h,\max}, \\ I_{ae,\max} = I_{1p,\max}. \end{cases} \tag{25}$$

In this case, only one component of the negative sequence voltage U_{1m} is doubled. Thus, the Y-circuit becomes more preferable than the D-circuit when used in the hybrid balancing/filtering mode.

A comparison was made between the APF power required for unbalance suppression and harmonic filtering during distortions on 110 kV busbars of the 110 kV

Skovorodino substation. The results clearly showed that the required power of the series-connected design was more than two times lower than that of the shunt-connected option to achieve compliance with voltage quality standards. However, when the series-connected design was presented to the customer, it became evident that there were issues with the protective relaying system and emergency control facilities of the series-connected transformer. Due to these issues, the series-connected design was rejected despite its clear economic performance advantages.

Thus, to create active power filters providing harmonic filtering, balancing adjustment, and fast reactive power regulation, we can use STATCOMs based on three MMC circuits with a series connection of single-phase full-bridge and half-bridge voltage source converters, each of which operates in the PWM mode. The key defining feature of MMC-based active filters is that they are capable of selective fast real-time harmonic filtering. The AF allows suppressing any given set of harmonics, including the negative harmonic of the fundamental frequency (negative sequence), with a given degree of suppression (down to zero or standardized value) by appropriate setting in the control program.

For practical implementation of MMC-based STATCOM capabilities to make power quality parameters standard-compliant, we apply the so-called DSB control algorithm. This algorithm enables fast reactive power compensation, harmonic filtering and balancing adjustment of network voltage in real time.

The voltage balancing using MMCs is unique as to ensure the reactive nature of the valves during balancing adjustment it is necessary to introduce:

- the neutral voltage offset in the MMC Y-circuit;
- the constant current offset shared by these valves in the Marquardt circuit;
- the circulation current in the D-circuit.

At the same time, the shunt-connected Y-circuit requires the introduction of a neutral offset equal to the phase voltage, even when there is a small value of the negative sequence voltage. This leads to doubling the voltage on the phase branches and doubling the number of transistors, which renders the use of the shunt Y-circuit inefficient. When the circulation current is introduced into a shunt D-circuit, the design current (and power) of the D-circuit branches increases up to 1.08–1.2 with respect to the rated value, depending on the harmonic suppression factors specified.

The series-connected Y-circuit requires the introduction of the neutral offset equal to the value of the negative sequence voltage component. However, compensation of high-frequency distortions does not require the balancing neutral offset. Furthermore, provided that the harmonic voltage component is significant, the use of the Y-circuit proves quite effective to achieve compliance with voltage quality standards at individual coupling points and it also allows reducing the required power by 2–3 times compared to the case of shunt-connected AF.

The study of shunt-connected options for MMC circuits has demonstrated that the STATCOM D-circuit outperforms other alternatives in economic terms when used in the compensation/balancing mode. The use of the Y-circuit is inefficient due to the doubling of the required power even under minor unbalance. Preferring the Marquardt circuit over the D-circuit of MMC to ensure standard-compliant power quality parameters proves uneconomical. The shunt Y-circuit MMC is inefficient for balancing adjustment but can be successfully used for reactive power compensation and harmonic filtering.

VII. Conclusion

1. The advent of modular multilevel PWM converters provided the electric power industry with a versatile tool for achieving compliance with power quality standards in electrical networks. This technology allows simultaneously and effectively solving the problems of:

- reactive power management;
- harmonic suppression (filtering);
- negative sequence current suppression (balancing adjustment);
- transient damping.

2. We have devised a DSB algorithm based on classical automatic control theory and three-phase circuit theory to synthesize MMC control programs. The DSB algorithm suggests a sequential creation of three types of regulators (D – damping; S – selective suppression; B – balancing) followed by the combination of their actions.

The multi-loop regulation system based on the DSB algorithm creates fast active filters providing real-time reactive power compensation, voltage balancing adjustment, and harmonic filtering.

3. Our analysis of three MMC circuits for the design of

active filtering/compensating and balancing devices has shown that the most versatile and cost-effective option is the MMC circuit with a series connection of single-phase bridge PWM voltage source converters, whose phase branches are connected in a delta configuration.

REFERENCES

[1] *Quality regulation of electric power in general-purpose electric power supply systems*, State Standard (GOST) 32144–2013. Moscow, Russia: Standardinform, 2014, 16 p. (In Russian)

[2] H. Akagi, E. H. Watanabe, M. Aredes, *Instantaneous Power Theory and Applications to Power Conditioning. Piscataway*. NJ: IEEE Press, 2007, 379 p.

[3] H. Akagi, "Classification, Terminology, and Application of the Modular Multilevel Cascade Converter (MMCC)," *IEEE Transactions on Power Electronics*, vol. 26, no. 11, pp. 3119–3130, 2011.

[4] E. Kontos, G. T. Tsolaridis, R. Teodorescu, P. Bauer, "High Order Voltage and Current Harmonic Mitigation Using the Modular Multilevel Converter STATCOM," *IEEE Access*, vol. 5, pp. 16684–16692, 2017.

[5] D. Braeckle, S. Mersche, M. Schnarrenberger, P. Himmelmann, M. Hiller, "Modular Multilevel Converters as active filters to mitigate low frequency current harmonics in converter fed grid applications," in *PCIM Europe 2018*, 5–7 June 2018, Nuremberg, Germany, pp. 218–225.

[6] I. L. Arkhipov, Yu. A. Goryushin, S. I. Gusev, G. M. Mustafa, Yu. M. Sennov, R. G. Shamonov, "Capacity rating of the active filtering and balance-adjusting device to achieve standard-compliant voltage on the busbars of 220 kv Skovorodino substation," *Elektricheskiestancii*, no. 3, pp. 46–53, 2016. (In Russian)

[7] G. M. Mustafa, S. I. Gusev, "Active series- and shunt-connected filtering and compensation devices," *Energetik*, no. 8, pp. 3–10, 2019. (In Russian)

[8] V. S. Chuprikov, "The use of fast-acting phase-regulated semiconductor reactive power compensation devices for standard-compliant power quality parameters in the UNPG," *Energy Expert*, no. 4, pp. 40–46, 2020. (In Russian)

[9] V. V. Aksenov, A. I. Demin, V. S. Chuprikov, "Ensuring power quality in power systems adjacent to the Trans-Siberian Railway and the Baikal-Amur Mainline. Hands-on experience gained in development and implementation of compensation devices," *Energetik*, no. 3, pp. 14–22, 2023. (In Russian)

[10] G. M. Mustafa, S. I. Gusev, "Filtering of higher harmonics in electrical networks under dynamically changing conditions," *Energiya Edinoy Seti*, no. 4 (33), pp. 44–52, 2017. (In Russian)

[11] G. M. Mustafa, S. I. Gusev, *Active filtering and balance adjustment devices for the power sector*, 2nd ed., revised and expanded. Moscow, Russia: MPEI Publishing House, 2022, 198 p. (In Russian)

[12] *Transmission of electric power by high voltage direct current. Active power filters. Requirements and guidelines for application*, GOST R 59031-2020. Moscow, Russia: Standardinform, 2020. (In Russian)

[13] R. Marquardt, "Current rectification circuit for voltage source inverters with separate energy stores replaces phase blocks with energy storing capacitors," Publication number DE10103031, 2002-07-25.

[14] R. Marquardt, A. Lesnicar, "New Concept for High Voltage – Modular Multilevel Converter," In *Proceedings of the 2004 IEEE 35th Annual Power Electronics Specialists Conference PESC'04*, Aachen, Germany, Jun. 20–25 2004.

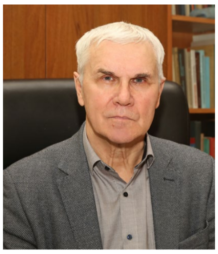
[15] G. Tsolaridis, H. A. Pereira, A. F. Cupertino, R. Teodorescu, M. Bongiorno, "Losses and cost comparison of DS-HB and SD-FB MMC based large utility grade STATCOM," in *2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC)*, Florence, Italy, 2016, pp. 1-6

[16] G. M. Mustafa, "Technique for approximate analysis of pulse-modulated inverters with sine-wave output voltage." *Russian Electrical Engineering*, no. 10, pp. 2–8, 1987. (In Russian)

[17] G. M. Mustafa, "Filtering and compensation device for high-voltage DC power transmission," Patent 2521428C2. Russian Federation, MPK H02J 3/18/. Applied for on 05.07.2012, published on 27.06.2014. 35 p. (In Russian)

[18] *High Power Semiconductors for Industrial Applications*. www.infineon.com/power semiconductors.

Georgy M. Mustafa, Ph.D., Chief Research Officer, LLC NPP LM Inverter, Moscow, Russia, Gmm-mail@yandex.ru



Stanislav I. Gusev, Ph.D., Chief Executive Officer, LLC NPP LM Inverter, Moscow, Russia, Gusev-si@lm-inverter.ru