DOI: https://doi.org/10.15407/techned2026.04.067

DIRECT CONTROL METHOD FOR STATCOM TO MITIGATE VOLTAGE FLUCTUATIONS AT A DISTRIBUTION NETWORK LOAD BUS

M.Y. Burbelo *, O.V. Babenko **
Vinnytsia National Technical University,
Khmelnytskyi Highway, 95, Vinnytsia, 21021, Ukraine.
E-mail: burbelom@ukr.net; oleksij_babenko@ukr.net.

The article proposes a method of direct control of the static synchronous compensator (STATCOM) to reduce voltage fluctuations due to load and supply voltage instability in distribution electric networks. The operation of the STATCOM operating in the voltage stabilization mode of the 10 kV distribution electric network node is analyzed. The value of the compensator EMF is obtained, which provides a stable value of the load node voltage when the consumer load conductivity changes. The specified EMF is determined by the values of the increments of the active and reactive components of the load current, the voltage of the compensator connection node at a zero value of the STATCOM reactive current and the parameters of the electric network. The process of voltage stabilization in the load connection node under the condition of changes in the power source voltage and the corresponding compensator control law are analyzed, which involves the use of such informative parameters as the current and base values of the power source voltage, network parameters, and the voltage of the STATCOM connection node. Expressions for determining the EMF of the STATCOM, which provides a stable voltage at the compensator connection point and the load, as well as a zero value of the active power in the compensator circuit under unstable load conditions, as well as changes in the power supply voltage, are obtained. It is shown that for the efficient operation of the compensator, it is necessary to perform measurements of the load currents and the load bus voltage. The STATCOM operation is simulated under the condition of changing the active and reactive load of the consumer in the range of ±25% and fluctuations in the power supply voltage within 2%, which is most often observed in electrical networks. It is shown that for an average load power of 4+j2 MVA and a stabilized voltage of 10.25 kV, the compensator power ranges from −0.57 MVAr to 2.4 MVAr. If the voltage stabilization level needs to be increased to 10.3 kV, the compensator power rises to 2.8 MVAr. References 16, Fig. 7, Table 1.

Keywords: static synchronous compensator (STATCOM), direct control, reactive power, voltage stabilization.

Introduction. Voltage quality in the power grid affects the reliability and cost-effectiveness of power consumers, including electric drives, lighting, electronic equipment, industrial plants, and others. Rapidly varying loads present in electrical networks cause voltage fluctuations, leading to operational instability and reduced efficiency and productivity of technological equipment [1]. Therefore, it is of great relevance to develop measures aimed at improving voltage quality in consumer power networks and, consequently, the economic efficiency of industrial enterprises.

To stabilize voltage at distribution network nodes and ensure reactive power balance, numerous solutions are employed, among which Distribution Static Synchronous Compensators (STATCOM) have gained widespread adoption [2–3]. The primary advantage of a STATCOM is its rapid reactive power compensation, which allows for the mitigation of voltage fluctuations. For the effective operation of STATCOMs, it is essential to ensure sufficient capacity and a control algorithm tailored to the specific operating conditions.

Two strategies are possible for voltage stabilization using a STATCOM: 1) measuring the voltage and, based on its deviation from the setpoint, increasing reactive power generation; 2) measuring both load and voltage and, based on their deviations from the reference values, increasing reactive power output. In terms of automatic control theory, the described strategies are classified as feedback control and combined control, the latter of which incorporates both feedback (voltage-based) and feedforward (load-based) control.

Voltage stabilization is primarily achieved through feedback control, for which advanced algorithms have been developed, e.g., [4–9]. Notable among these algorithms are input-output linearization control [4], adaptive control algorithms [5], robust control algorithms [6–7], sliding mode control algorithms [8–9], and others. In [10–15], a combined STATCOM control strategy is employed, which involves measuring the voltage

ORCID: * https://orcid.org/0000-0002-4510-2911; ** https://orcid.org/0000-0003-2773-6571

at the connection bus and the load current. At the same time, these studies focus on the development of various types of feedback controllers, while the disturbance-based feed-forward control algorithm for STATCOM remains insufficiently substantiated.

Combined control enables the implementation of more intelligent and 'soft' control algorithms. For instance, a decision may be made to forgo full voltage restoration to its nominal level (which may be unfeasible) and instead transition to a support mode by providing a lower reactive power output [16]. However, this raises the challenge of ensuring high-speed generation of control actions. This can be achieved by employing direct control of the STATCOM.

The objective of this work is to develop a method and mathematical models for direct control of STATCOM for voltage stabilization under conditions of varying load power and supply voltage that lead to voltage fluctuations.

1. Performance analysis of STATCOM in voltage regulation mode. The operation of a STATCOM in the voltage regulation mode of a power system bus, the equivalent circuit of which is shown in Fig. 1, is analyzed.

Complex admittances of the equivalent circuit branches:

$$\underline{Y}_0 = \frac{1}{R_0 + jX_0}; \quad \underline{Y}_1 = \frac{1}{R_1 + jX_1}; \quad \underline{Y}_2 = \frac{1}{R_2} + \frac{1}{jX_2}. \quad (1)$$

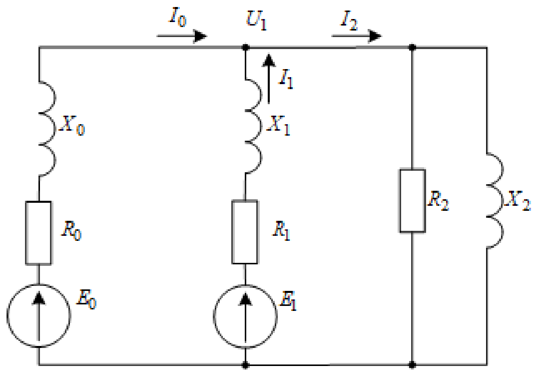

Fig. 1. Equivalent circuit of a power grid load bus with STATCOM

One of the most critical aspects of voltage stabilization at a power grid bus is the selection of the voltage setpoint corresponding to zero STATCOM reactive current. In [16], it is proposed to select the STATCOM EMF based on the condition:

$$\dot{E}_1^{(0)} = \dot{U}_1^{(0)} = \frac{\dot{E}_0^{(0)} \cdot \underline{Y}_0}{\underline{Y}_0 + \underline{Y}_2^{(0)}}, \quad (2)$$

where $\dot{E}_0^{(0)}$ is the base EMF of the power source, e.g., 10.5 kV; $\underline{Y}_2^{(0)}$ is the base value of the complex load admittance, e.g., the average value.

The problem of voltage stabilization at a power system node using STATCOM reduces to satisfying two conditions:

$$\left|\dot{U}_1^{(1)}\right| = \left|\dot{U}_1^{(0)}\right| \text{ or } \left|\frac{\dot{E}_0^{(1)} \cdot \underline{Y}_0 + \dot{E}_1 \cdot \underline{Y}_1}{\underline{Y}_0 + \underline{Y}_1 + \underline{Y}_2^{(1)}}\right| = \left|\frac{\dot{E}_0^{(0)} \cdot \underline{Y}_0}{\underline{Y}_0 + \underline{Y}_2^{(0)}}\right|; \quad (3)$$

$$P_1 = 0 \text{ or } \mathrm{Re}\left[\left(\frac{\dot{E}_0^{(1)} \cdot \underline{Y}_0 + \dot{E}_1 \cdot \underline{Y}_1}{\underline{Y}_0 + \underline{Y}_1 + \underline{Y}_2^{(1)}}\right) \cdot \left(\left(\dot{E}_1 - \frac{\dot{E}_0^{(1)} \cdot \underline{Y}_0 + \dot{E}_1 \cdot \underline{Y}_1}{\underline{Y}_0 + \underline{Y}_1 + \underline{Y}_2^{(1)}}\right) \cdot \underline{Y}_1\right)^*\right] = 0. \quad (4)$$

Voltage instability is caused by changes in load admittance or source voltage. By solving the system of equations (3) and (4), the STATCOM EMF value can be determined, which ensures a constant voltage level at the power grid bus for specific values of $\dot{E}_0^{(1)}$ and $\underline{Y}_2^{(1)}$.

However, our focus is on developing a high-speed STATCOM control system with control setpoints that are adjusted within the shortest possible time and remain stable across a specific range of supply voltage and load variations.

2. Determination of STATCOM EMF for voltage stabilization under supply voltage variations and variable consumer load. First, let us consider the feasibility of fast STATCOM tuning for load change compensation.

The increments of the active and reactive components of the voltage drop in the transmission line under load instability, considering the presence of STATCOM, are [10]:

$$\Delta U_{0\text{a}} + j\Delta U_{0r} = \left(R_0\Delta I_{2\text{a}} - X_0\Delta I_{2r} + R_0\Delta I_{1\text{a}} - X_0\Delta I_{1r}\right) + \\ + j\left(X_0\Delta I_{2\text{a}} + R_0\Delta I_{2r} + X_0\Delta I_{1\text{a}} + R_0\Delta I_{1r}\right), \tag{5}$$

where $\Delta I_{2\text{a}}, \Delta I_{2r}$ are the increments of the active and reactive components of the load current; $\Delta I_{1\text{a}}, \Delta I_{1r}$ are the increments of STATCOM active and reactive current components.

The longitudinal component of the voltage drop across the transmission line determines the instability of the RMS voltage at the network bus:

$$\left|\Delta U_0\right| \approx \Delta U_{0\text{a}} = R_0\Delta I_{2\text{a}} - X_0\Delta I_{2r} + R_0\Delta I_{1\text{a}} - X_0\Delta I_{1r}. \tag{6}$$

The STATCOM must generate a current that provides compensation for load current instability, while its active power must remain zero.

From the equality $\left|\Delta U_0\right| \approx \Delta U_{0\text{a}} = 0$, it follows that the following condition is necessary for voltage stabilization at the network node:

$$\Delta I_{1r} = \frac{R_0}{X_0}\left(\Delta I_{1\text{a}} + \Delta I_{2\text{a}}\right) - \Delta I_{2r}. \tag{7}$$

Given that $\Delta I_{1\text{a}} = \frac{R_1}{X_1}\Delta I_{1r}$ and setting $k = 1 - \frac{R_1}{X_1}\frac{R_0}{X_0}$, we obtain:

$$\Delta I_{1r} = \frac{1}{k}\left(\frac{R_0}{X_0}\Delta I_{2\text{a}} - \Delta I_{2r}\right). \tag{8}$$

Substituting this expression into the expression for the transverse component of the voltage drop on the transmission line, we obtain:

$$\Delta U_{0r} = \left[X_0 + \frac{R_0}{k}\left(\frac{R_1}{X_1} + \frac{R_0}{X_0}\right)\right]\Delta I_{2\text{a}} + \left[R_0 + \frac{X_0}{k}\left(\frac{R_1}{X_1} + \frac{R_0}{X_0}\right)\right]\cdot\Delta I_{2r}. \tag{9}$$

STATCOM complex current:

$$\dot{I}_1 = \frac{\dot{E}_1 - \dot{U}_1}{R_1 + jX_1}. \tag{10}$$

Hence, the expression for the STATCOM EMF is derived in terms of the increments of the network bus voltage and STATCOM current:

$$\dot{E}_1 = \dot{U}_1^{(0)} + \Delta\dot{U}_1 + \left(R_1 + jX_1\right)\Delta\dot{I}_1, \tag{11}$$

where $\Delta\dot{U}_1$ is the complex value of the voltage increment at a network bus, determined by the voltage drop increment $\Delta\dot{U}_0$.

Therefore, to stabilize the voltage at the network bus ($\Delta U_{1\text{a}} = \Delta U_{0\text{a}} = 0$) the active component of the STATCOM EMF must be determined as follows:

$$E_{1\text{a}} = U_{1\text{a}}^{(0)} - \frac{X_1}{k}\left(1 - \left(\frac{R_1}{X_1}\right)^2\right)\cdot\left(\frac{R_0}{X_0}\Delta I_{2\text{a}} - \Delta I_{2r}\right), \tag{12}$$

while to ensure zero active power for the STATCOM, which is conditioned by the equality $\Delta U_{1r} = \Delta U_{0r}$, the reactive component of the STATCOM EMF must be formulated as follows:

$$E_{1r} \approx U_{1r}^{(0)} + \Delta U_{0r} + \frac{2R_1}{k}\cdot\left(\frac{R_0}{X_0}\Delta I_{2\text{a}} - \Delta I_{2r}\right). \tag{13}$$

Let us consider the possibility of compensating for supply voltage variations.

In [16], it is proposed to implement STATCOM control for supply voltage variation compensation using the following formula:

$$\dot{E}_1 \approx \dot{U}_1^{(0)} + \left(\dot{E}_0^{(0)} - \dot{E}_0\right) \cdot \left[\frac{X_1}{X_0} + jq\right], \tag{14}$$

where the informative parameters are the current value of the power supply voltage $\dot{E}_0$. Its value can be determined using expression $\dot{E}_0 = \dot{U}_1 + \left(R_0 + jX_0\right)\dot{I}_0$.

The value of q can be determined by solving the system of equations (3) and (4) for two values $\dot{E}_0^{(0)}$ and $\dot{E}_0^{(1)}$ with respect to $\dot{E}_1^{(1)}$ and using expression:

$$q = \frac{\mathrm{Im}\left(\dot{E}_1^{(0)}\right) - \mathrm{Im}\left(\dot{E}_1^{(1)}\right)}{\dot{E}_0^{(0)} - \dot{E}_0^{(1)}}. \tag{15}$$

From Equation (3), it follows that:

$$\dot{E}_1 = \dot{U}_1^{(0)} e^{j\Delta\psi_1} + \dot{E}_0^{(0)} \frac{\underline{Y}_0}{\underline{Y}_1} e^{j\Delta\psi_1} - \dot{E}_0 \frac{\underline{Y}_0}{\underline{Y}_1}, \tag{16}$$

where $\Delta\psi_1$ is the initial phase angle increment of voltage $\dot{U}_1$ relative to $\dot{U}_1^{(0)}$ due to the increase in the compensator current.

Applying Euler's formula and considering that $\cos\Delta\psi_1 \approx 1$, we obtain:

$$\dot{E}_1 = \dot{U}_1^{(0)} + \left(\dot{E}_0^{(0)} - \dot{E}_0\right)\frac{\underline{Y}_0}{\underline{Y}_1} + j\left(\dot{U}_1^{(0)} + \dot{E}_0^{(0)} \frac{\underline{Y}_0}{\underline{Y}_1}\right)\sin\Delta\psi_1. \tag{17}$$

To determine $\sin\Delta\psi_1$ the approximate expression $\sin\Delta\psi_1 \approx \left(X_0 \cdot \mathrm{Re}(\dot{I}_1) + R_0 \cdot \mathrm{Im}(\dot{I}_1)\right) / \left|\dot{U}_1^{(0)}\right|$ can be used, however, employing this expression or the relation $\sin\Delta\psi_1 \approx \left(X_0 \cdot R_1 / X_1 + R_0\right) \cdot \left|\dot{I}_1\right| / \left|\dot{U}_1^{(0)}\right|$ is problematic due to the lack of a priori information regarding the STATCOM current, as well as the significant influence of $\sin\Delta\psi_1$ on the imaginary component value. At the same time, the difference between the values of the real components calculated by formulas (14) and (17) is negligible.

Thus, equations (12)–(14) describe the proposed method for mitigating voltage fluctuations at the STATCOM point of common coupling under conditions of load and supply voltage instability in distribution networks.

Equations (12) and (13) can be simplified without significant loss of accuracy by neglecting the $\Delta I_{2\mathrm{a}}$ component in expression (5), assuming that the STATCOM current leads the voltage $\dot{U}_1$ by a phase angle of φ=π/2:

$$\begin{aligned} \Delta U_{0\mathrm{a}} + j\Delta U_{0r} \approx \left(R_0\Delta I_{2\mathrm{a}} - X_0\Delta I_{2r} - X_0\Delta I_{1r}\right) + \\ + j\left(R_0\Delta I_{2r} + X_0\Delta I_{2\mathrm{a}} + R_0\Delta I_{1r}\right), \end{aligned} \tag{18}$$

Then, expression (9) for the transverse component of the voltage drop on the transmission line takes the following form:

$$\Delta U_{0r} \approx X_0\left(1 + \left(\frac{R_0}{X_0}\right)^2\right) \cdot \Delta I_{2\mathrm{a}}. \tag{19}$$

To stabilize the voltage at a network bus in the event of load instability, the expression for the real component of the STATCOM EMF can be formulated as follows:

$$E_{1\mathrm{a}} \approx U_{1\mathrm{a}}^{(0)} - X_1 \cdot \left(\frac{R_0}{X_0}\Delta I_{2\mathrm{a}} - \Delta I_{2r}\right), \tag{20}$$

and to ensure zero active power of the STATCOM, the imaginary component of the STATCOM EMF is defined as follows:

$$E_{1r} \approx U_{1r} + X_0 \left(1 + \left(\frac{R_0}{X_0}\right)^2\right) \cdot \Delta I_{2\mathrm{a}} + R_1 \left(\frac{R_0}{X_0} \Delta I_{2\mathrm{a}} - \Delta I_{2r}\right) = \\ = U_{1r} + \left(X_0 + \frac{R_0}{X_0}(R_0 + R_1)\right) \cdot \Delta I_{2\mathrm{a}} - R_1 \Delta I_{2r}. \quad (21)$$

3. Modeling of STATCOM operation under conditions of variable load and supply voltage instability. The STATCOM operation was simulated under the following conditions: a load with an average power of P_2=4 MW and Q_2=2 MVAr varies within the range of (0.75÷1.25)P_2 and (0.75÷1.25)Q_2, respectively. The load is supplied by a 110/10 kV, 10 MVA power transformer with a short-circuit voltage u_k=10.5%. The STATCOM coupling transformer is rated at 2.5 MVA, u_k=5.5%.

Fig. 2 shows the network bus voltage and STATCOM EMF as functions of load variations at a supply voltage of 10.5 kV for two grid operating modes: the first, where the active load varies within the range of (0.75÷1.25)P_2, while the reactive load remains constant; and the second, where both active and reactive loads vary within the ranges of (0.75÷1.25)P_2 and (0.75÷1.25)Q_2 respectively.

The voltage variation range in both $U_1(P)$ and $U_1(P,Q)$ modes is identical, spanning 10.25÷10.253 kV, which corresponds to an instability coefficient $k_{\mathrm{inst}}=(\Delta U/U_{\mathrm{nom}})\cdot 100\%$=0,03%. The STATCOM EMF varies within 52 V under active load changes only, and within 273 V under combined active and reactive load variations. The variation characteristic is linear.

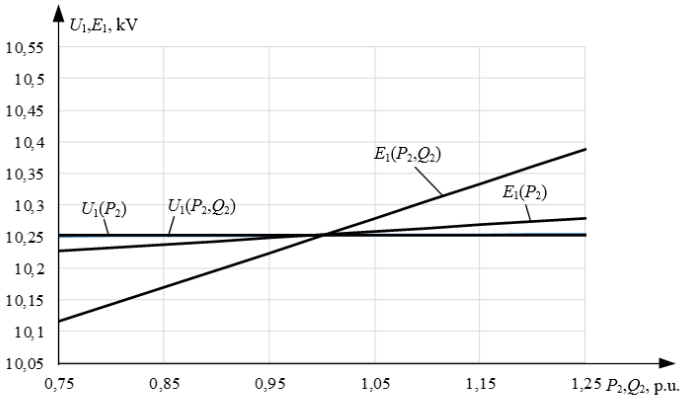

Fig. 2. Plots of load bus voltage and STATCOM EMF for a 10.5 kV source voltage

The STATCOM reactive power generation/absorption process is illustrated in Fig. 3. Under varying consumer active load, the reactive power regulation range is within -103 to 110 kVAr. Under varying active and reactive load conditions, the reactive power variation range is -573 to 580 kVAr. The range of active power generated/consumed by the STATCOM under varying consumer active load is between 13 kW (generation) and 12 kW (consumption), and under variable consumer active and reactive power, it ranges from 13 kW (generation) to 4.8 kW (consumption).

A study was conducted on the impact of supply voltage instability on the voltage stabilization process at the load connection node. For comparison, the simulation was performed at a supply voltage of 10.3 kV, as previously, under two operating modes: with variable active node load, and with variable active and reactive consumer loads.

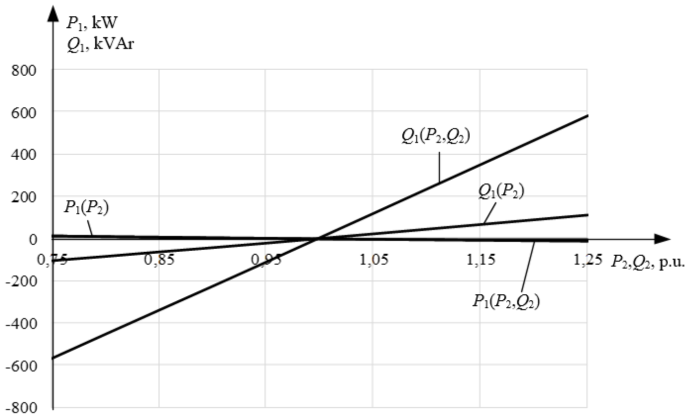

Fig. 3. Active and reactive power generation/consumption curves of the STATCOM at 10.5 kV supply voltage

The voltage variation range in both $U_1(P)$ and $U_1(P,Q)$ modes is similar to the previous case: 10.249÷10.256 kV (Fig. 4). Meanwhile, the STATCOM EMF continues to vary within approximately the same range: within 60 V under consumer active load variation, and within 291 V under combined active and reactive load variation.

Under variations in the consumer's active load and combined active/reactive load, the compensator's reactive power range shifted to 1671÷1908 kVAr and 1188÷2391 kVAr, respectively (Fig. 5). Simulation results showed that the active power range generated/consumed by the STATCOM under variable consumer active load varies from 8 kW (generation) to 5 kW (consumption). Under variable active and reactive power conditions, this range is between 5.6 kW (generation) and 4.3 kW (consumption).

Thus, by applying the STATCOM control laws (10)–(14), voltage stabilization at the considered power grid node can be achieved with the following compensator power variations: 200 kVAr per ±25% change in active load and 1200 kVAr per 2% change in supply voltage.

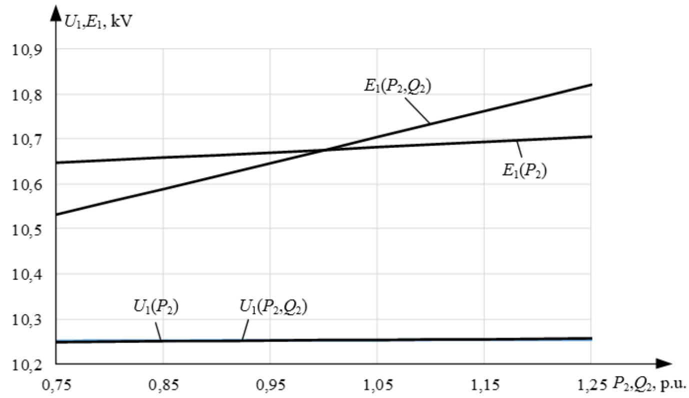

Fig. 4. Plots of load bus voltage and STATCOM EMF for a 10.3 kV source voltage

The STATCOM EMF magnitude can be increased proportionally. In this case, the value of q remains the same as in the previous scenario. For example, if the reactive power generation increases by 450 kVAr, the voltage variation range for both load conditions, $U_1(P)$ and $U_1(P,Q)$, will be identical at 10,3÷10,303 kV, which is slightly higher than in the previous case.

The reactive power variation range of the compensator in both $U_1(P)$ and $U_1(P,Q)$ modes is within 350÷571 and -128÷1049 kVAr, respectively (Fig. 6).

The active power operating range of the STATCOM under varying consumer active load conditions spans from 12 kW (generation) to 10 kW (consumption), while under varying active and reactive consumer power, the range is between 11 kW (generation) and 2.7 kW (consumption).

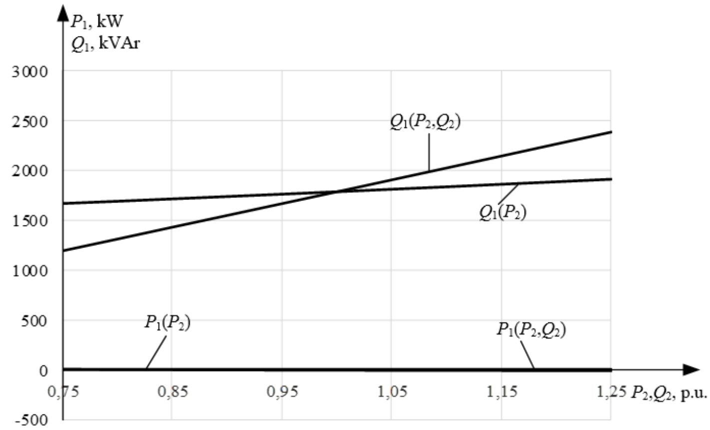

Fig. 5. Active and reactive power generation/consumption plots of the STATCOM at 10.3 kV supply voltage

Simulations were also performed at a supply voltage of 10.3 kV in two modes: under variable active bus load, and under variable active and reactive consumer loads. The voltage variation ranges in both modes, $U_1(P)$ and $U_1(P,Q)$, are close to the previous case: 10.299÷10.306 kV.

The reactive power adjustment range of the compensator for $U_1(P)$ and $U_1(P,Q)$ is within 2132÷2378 kVAr and 1641÷2869 kVAr, respectively (Fig. 7).

Simulation results showed that the range of active power flow through the STATCOM under varying consumer active load is between 8.5 kW (generation) and 1.3 kW (consumption), while under varying active and reactive power, it ranges from 1.9 to 8.5 kW (generation).

The comparison table presents the obtained results, which indicate that in the considered power system node, an increase in reactive power Q_1 by approximately 450 kVAr leads to a 0.05 kV increase in voltage U_1.

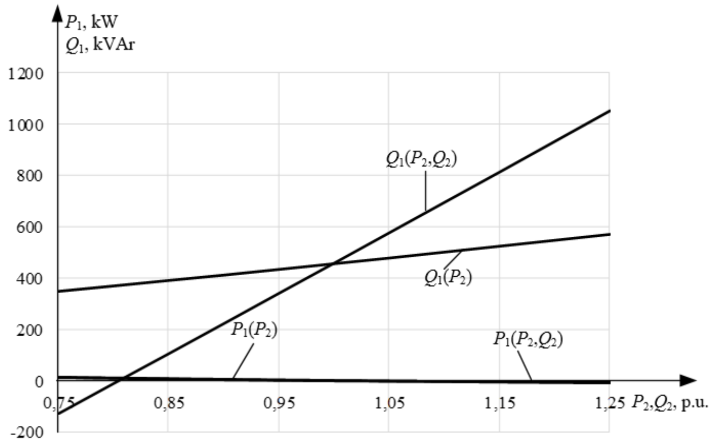

Fig. 6. Active and reactive power generation/consumption curves of the STATCOM during an EMF increase at a supply voltage of 10.5 kV

Conclusions.

The operation of a STATCOM in the voltage stabilization mode at a power grid bus has been analyzed. A control method is proposed that involves determining the compensator's EMF based on the increments of the active and reactive load current components, as well as the base voltage at the load bus, derived from the supply source base voltage. The simulation of the synchronous condenser operation was conducted using the proposed mathematical models under conditions of active load power of 4 MW ±25%, reactive load power of 2 MVAr ±25%, a STATCOM transformer rating of 2,5 MVA, and supply voltage variations from 10.5 kV to 10.3 kV. To ensure voltage stabilization at 10.25 kV, the compensator's reactive power varies within the range of -0.57 to 2.4 MVAr.

To increase the stabilized voltage level at the load bus, the base voltage at the STATCOM point of common coupling was increased. This voltage is calculated using parameter *q*, which, in turn, is determined by the EMF values of the compensator and the power supply. In this case, to maintain a stable load voltage of 10.3 kV, the STATCOM output increased by 450 kVAr, ranging from -0.13 to 2.87 MVAr.

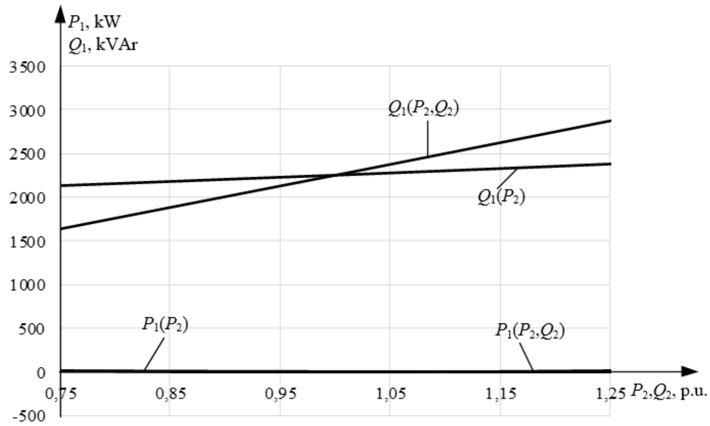

Fig. 7. STATCOM active and reactive power generation/consumption curves in case of an EMF increase at a 10.3 kV supply voltage

$\dot{E}_0$, kV	$Q_1(P)$, kVAr	$Q_1(P,Q)$, kVAr	U_1, kV
10.5	-103÷110	-573÷580	10.250÷10.253
10.3	1671÷1908	1188÷2391	10.249÷10.256
10.5	350÷571	-128÷1049	10.300÷10.303
10.3	2132÷2378	1641÷2869	10.299÷10.306

1. Pivniak H.H., Zhezhelenko I.V., Papaika Yu.A. Energy efficiency of the electricity supply system. Dnipro: Natsionalnyi tekhnichnyi univesytet Dniprovska politekhnika, 2018. 148 p. (Ukr)
2. Ghosh A., Ledwich G. Power Quality Enhancement Using Custom Power Devices. Boston: Kluwer Academic Publishers, 2002. 460 p. DOI: https://doi.org/10.1007/978-1-4615-1153-3
3. Singh B., Chandra A., Al-Haddad K. Power Quality: Problems and Mitigation Techniques. Chichester: John Wiley & Sons, 2015. 600 p. DOI: https://doi.org/10.1002/9781118922064.
4. Wang K., Crow M.L. Power System Voltage Regulation via STATCOM Internal Nonlinear Control. *IEEE* Transactions *on Power Systems*. August 2011. Vol. 26. No 3. Pp. 1252–1262. DOI: https://doi.org/10.1109/TPWRS.2010.2072937.
5. Xu Y., Li F. Adaptive PI Control of STATCOM for Voltage Regulation. *IEEE Transactions On Power Delivery*. June 2014. Vol. 29. No 3. Pp. 1002–1011. DOI: https://doi.org/10.1109/TPWRD.2013.2291576.
6. Gui Y., Kim C., Han Y., Chung C.C. Robust Nonlinear Control of STATCOMs. In book: Static Compensators (STATCOMs) in Power Systems. Springer, 2015. Pp. 187–224. DOI: https://doi.org/10.1007/978-981-287-281-4_6.
7. Guo A., Tian Y., Zhao H. Highly Robust Active Damping Approach for Grid-Connected Current Feedback Using Phase-Lead Compensation. *Electronics*. 2025. Vol. 14. Issue 2. Article no: 309. DOI: https://doi.org/10.3390/electronics14020309.
8. Yazdani A. Energy and voltage management methods for multilevel converters for bulk power system power quality improvement: PhD dissertation. Rolla: Missouri University of Science and Technology, 2009. 90 p.
9. Kerrouche K. D. E., Lodhi E., Kerrouche M. B., Wang L., Zhu F., Xiong G. Modeling and design of the improved D-STATCOM control for power distribution grid. *SN Applied Sciences*. 2020. Vol. 2. No 9. Article no: 1546. DOI: https://doi.org/10.1007/s42452-020-03315-8.
10. Dash S.K., Mishra S., Abdelaziz A.Y. A Critical Analysis of Modeling Aspects of D-STATCOMs for Optimal Reactive Power Compensation in Power Distribution Networks. *Energies*. 2022. Vol. 15. No 19. Article no: 6908. Pp. 1–23. DOI: https://doi.org/10.3390/en15196908.
11. Chen J.-H., Tan K.-H., Lee Y.-D. Intelligent Controlled DSTATCOM for Power Quality Enhancement. *Energies*. 2022. Vol. 15. Issue 11. Article no: 4017. DOI: https://doi.org/10.3390/en15114017.
12. Wang S., Cui K., Hao P. Grid-Connected Inverter Grid Voltage Feedforward Control Strategy Based on Multi-Objective Constraint in Weak Grid. *Energies*. 2024. Vol. 17. Issue 13. Article no: 3288. DOI: https://doi.org/10.3390/en17133288.
13. Alturki Y.A., Alhussainy A.A., Alghamdi S.M., Rawa M. A Novel Point of Common Coupling Direct Power Control Method for Grid Integration of Renewable Energy Sources: Performance Evaluation among

Power Quality Phenomena. *Energies*. 2024. Vol. 17. No 20. Article no: 5111. DOI: https://doi.org/10.3390/en17205111.
14. Zhang Z., Gong P., Lu Z. A Lyapunov Theory-Based SEIG–STATCOM Voltage Regulation Control Strategy. *Energies*. 2024. Vol. 17. Issue 19. Article no: 4992. DOI: https://doi.org/10.3390/en17194992.
15. Wang X., Feng F., Peng L., Xiao P., Li Z. Stability Analysis and Virtual Inductance Control for Static Synchronous Compensators with Voltage-Droop Support in Weak Grid. *Electronics*. 2025. Vol. 14. Issue 11. Article no: 2203. DOI: https://doi.org/10.3390/electronics14112203.
16. Burbelo M.Y., Babenko O.V., Lebed D.Yu. Analysis of STATCOM control process under rapid voltage changes. *Visnyk Kremenchukskoho Mykhailo Ostrohradskoho Natsionalnoho Universytetu*. 2025. Vyp. 1 (150). Pp. 284–291. (Ukr) DOI: https://doi.org/10.32782/1995-0519.2025.1.35.

УДК 621.316

МЕТОД ПРЯМОГО КЕРУВАННЯ STATCOM ЗАДЛЯ ЗМЕНШЕННЯ КОЛИВАНЬ НАПРУГИ У ВУЗЛІ НАВАНТАЖЕННЯ РОЗПОДІЛЬНОЇ МЕРЕЖІ

М.Й. Бурбело, докт. техн. наук**, О.В. Бабенко**, канд. техн. наук
Вінницький національний технічний університет,
вул. Хмельницьке шосе, 95, Вінниця, 21021, Україна.
E-mail: burbelom@ukr.net; oleksij_babenko@ukr.net.

Запропоновано метод прямого керування статичним синхронним компенсатором (STATCOM) задля зменшення коливань напруги внаслідок нестабільності навантаження та напруги живлення в розподільних електричних мережах. Проаналізовано роботу STATCOM, який працює в режимі стабілізації напруги вузла розподільної електричної мережі 10 кВ. Отримано значення ЕРС компенсатора, яка забезпечує стабільне значення напруги вузла навантаження за зміни провідності навантаження споживача. Вказана ЕРС визначається за значеннями приростів активної та реактивної складових струму навантаження, напругою вузла приєднання компенсатора за нульового значення реактивного струму STATCOM та параметрів електричної мережі. Проаналізовано процес стабілізації напруги в вузлі приєднання навантаження за умови змін напруги джерела живлення та відповідний закон керування компенсатором, що передбачає використання таких інформативних параметрів як поточне та базове значення напруги джерела живлення, параметри мережі, а також напруга вузла приєднання STATCOM. Отримано вирази задля визначення ЕРС STATCOM, яка забезпечує стабільну напругу вузла приєднання компенсатора і навантаження, а також нульове значення активної потужності в колі компенсатора за нестабільного навантаження, а також змін напруги джерела живлення. Показано, що задля ефективної роботи компенсатора необхідно здійснювати вимірювання струмів навантаження та напруги вузла навантаження. Виконано моделювання роботи STATCOM за умови зміни активного та реактивного навантаження споживача у діапазоні ±25% і коливання напруги джерела живлення в межах 2%, що найбільш часто спостерігається в електричних мережах. Показано, що за середньої потужності навантаження 4+j2 МВ·А і стабілізованої напруги 10,25 кВ потужність компенсатора знаходиться в межах від -0,57 МВАр до 2,4 МВАр. За необхідності підвищення рівня стабілізації напруги до 10,3 кВ потужність компенсатора зростає до 2,8 МВАр. Бібл. 16, рис. 7, табл. 1.

***Ключові слова**:* статичний синхронний компенсатор (STATCOM), пряме керування, реактивна потужність, стабілізація напруги.

Received 12.12.2025
Accepted 09.03.2026