OPTIMAL CONDITIONS FOR CONTROLLED SWITCHING OF A THREE-PHASE SHUNT REACTOR

M. I. Aleksandrova,[1] V. A. Naumov,[2] V. I. Antonov,[2] and N. G. Ivanov[2]

Translated from *Élektricheskie Stantsii*, No. 4, April 2020, pp. 41 – 47.

The switching of shunt reactors in an electrical network is in many cases accompanied by reignition of the arc in the circuit breaker and the occurrence of dangerous overvoltage in the network. To limit such overvoltage, controlled-switching devices are used to switch off the reactor in the optimal phase of the current. To select the optimal switching conditions, the switching processes are analyzed, taking into account the intuitively clear difference between the switching conditions for three-phase and single-phase shunt reactors due to the electrical and/or magnetic coupling between the phase windings. The proposed method of analysis is universal for all types of three-phase shunt reactors due to the use of a universal four-legged star equivalent circuit. The reactor phases are switched off, synchronized against the phase A voltage curve, in the sequence $A \to C \to B$ to minimize the total switching time.

Keywords: controlled switching; three-phase shunt reactor.

Controlled switching of shunt reactors is used to reduce the probability of occurrence of critical overvoltage in the network [1, 2]. The overvoltage induced by switching can lead to damage of the insulation of the reactor and to unjustified wear of elements of the circuit breaker. The excessive wear of reactor circuit breakers is confirmed statistically: the number of failures of reactor circuit breakers is an order of magnitude higher than that of circuit breakers for power transmission lines and transformers [3].

Controlled-switching devices are set to switch off a shunt reactor in the optimal phase of current. The optimal conditions for switching the phases of a three-phase reactor should be selected taking into account design features of reactors because the reactance coils are united by one core and are influenced by the neighboring phases because of the magnetic coupling. In other words, the optimal phases for switching three-phase shunt reactors depend on the connection of the windings and the design of the cores.

Here we analyze the processes accompanying the switching of a shunt reactor and develop a universal method for establishing the optimal conditions for switching three-phase shunt reactors of all types.

The Processes Accompanying the Switching of a Shunt Reactor. There are two causes of overvoltage during switchings of shunt reactors: (i) current chopping in the circuit breaker (current is forcibly interrupted before the natural current zero) and (ii) reignition of the arc in the circuit breaker [3].

To analyze overvoltage, we will use the circuit in Fig. 1. The reactor is represented by inductance L_R and capacitance C_R, which includes the interturn capacitance and the capacitance of the overhead or cable line section between the circuit breaker and the reactor. The electric system is modeled by an emf source $u(t) = U\sin(\omega t + \psi)$, leakage inductance L_S, and capacitance C_S. The inductance L_S and capacitance C_S connected in parallel to the contacts are the parameters of the circuit breaker. The wires connecting the reactor and the circuit breaker are represented by the inductance L_B. In reality, the electric system, connecting wires, and reactor have some ohmic resistance (R_S, R_B, and R_R) causing the damping of transients. However, it is very low and can be neglected when considering the switching processes for a shunt reactor.

High-voltage circuit-breakers are intended to interrupt high short-circuit currents; therefore, it takes them a short time to interrupt the relatively low working currents of the

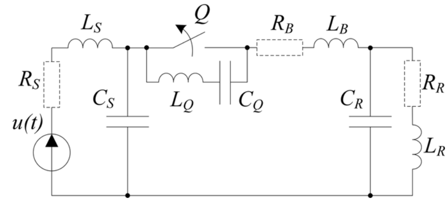

Fig. 1. Equivalent circuit of network.

---
[1] EKRA Ltd., Cheboksary, Russia; e-mail: aleksandrova mi@ekra.ru
[2] EKRA Ltd., Chuvash State University, Cheboksary, Russia.

shunt reactor. At low currents, the arc in the circuit breaker is unstable and, upon switching of the shunt reactor, can be extinguished prematurely (chopping current I_{ch}), even before the current's natural zero crossing. Because of this, the inductance of the reactor maintains the energy of the magnetic field,

$$W_L = \frac{L_R I_{ch}^2}{2},$$

while the capacitance maintains the energy of the electric field,

$$W_C = C_R \frac{U_{ch}^2}{2},$$

where U_{ch} is the chopping voltage.

After switching off of the reactor, oscillations of the following frequency occurs in the circuit formed by the inductance L_R and capacitance C_R (Fig. 2):

$$f_R = \frac{1}{2\pi\sqrt{L_R C_R}}.$$

For oil-insulated reactors, the frequency f_R is equal to 1 to 5 kHz [4].

The law of conservation of energy

$$\frac{C_R U_{\max}^2}{2} = \frac{C_R U_{ch}^2}{2} + \frac{L_R I_{ch}^2}{2}$$

can be used to find the overvoltage amplitude:

$$U_{\max} = \sqrt{U_{ch}^2 + \frac{L_R}{C_R} I_{ch}^2}. \quad (1)$$

The chopping current of vacuum circuit breakers is mainly dependent on the material of the contacts. For all the other types of circuit breakers, the chopping current depends on the parameters of the circuit breaker and the parameters of the network:

$$I_{ch} = \lambda\sqrt{NC_t}, \quad (2)$$

where $C_t = C_Q + C_S C_R/(C_S + C_R)$ is the capacitance of the network to the contacts of the circuit breaker (Fig. 1); N is the number of series-connected arc-control units in each pole of the circuit breaker; λ is a coefficient characterizing the magnitude of the chopping current per one arc-control unit (determined in laboratory).

For most circuit breakers, the value of λ depends on the arc duration. If the dependence of the coefficient λ on the arc duration is not clearly linear, the statistical average of λ can be used. The typical values of λ for high-voltage circuit breakers with various arc-extinction media fall into the range from 0.39×10^4 to 20×10^4 A/F$^{0.5}$, according to [4].

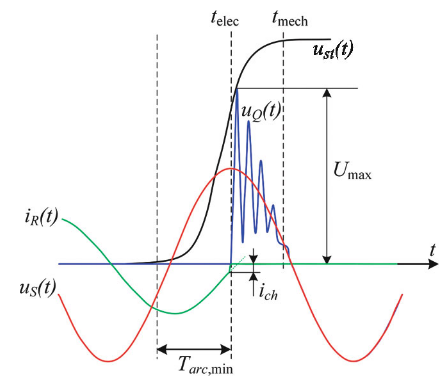

Fig. 2. Illustration of the principle of selecting the minimum arc duration after switching off the reactor: $i_R(t)$ is the reactor current; i_{ch} is the chopping current; $T_{\text{arc, min}}$ is the arc duration; $u_Q(t)$ is the voltage across the breaker contacts; $u_{st}(t)$ is the dielectric strength of the intercontact gap; t_{elec} is the arc extinction time (current chopping time); t_{mech} is the time of the complete mechanical parting of the breaker contacts; $U_{\max}$ is the overvoltage; $u_S(t)$ is the power supply voltage.

With (2), formula (1) becomes:

$$U_{\max} = \sqrt{U_{ch}^2 + N\lambda^2 L_R\left(\frac{C_Q}{C_R} + \frac{C_S}{C_S + C_R}\right)}. \quad (3)$$

The maximum overvoltage ratios are reached for $C_S > C_R$; therefore, the following formula can be used for approximate calculations:

$$U_{\max} \approx \sqrt{U_{ch}^2 + N\lambda^2 L_R\left(\frac{C_Q}{C_R} + 1\right)}.$$

If by the time of current interruption, the overvoltage caused by current chopping exceeds the dielectric strength of the intercontact gap, reignition occurs accompanied by high-frequency oscillations of the reactor voltage and the circuit-breaker current. To prevent the reignition upon switching off of a shunt reactor, it is important that by the time of opening of the circuit, the time it is closed through the arc is no shorter than the minimum time $T_{\text{arc, min}}$ (Fig. 3). This time is sufficient for the contacts to move apart by a distance at which the dielectric strength of the intercontact gap is recovered to the level preventing the reignition. Thus, circuit breaking should occur $T_{\text{arc, min}}$ or longer earlier than the current's natural zero crossing.

The time $T_{\text{arc, min}}$ is determined from data of tests for each type of circuit breaker with allowance for the following condition (Fig. 3):

$$U_{\max}(T_{arc,\min}) = T_{arc,\min}\text{RRDS},$$

where RRDS is the rate of rise of dielectric strength.

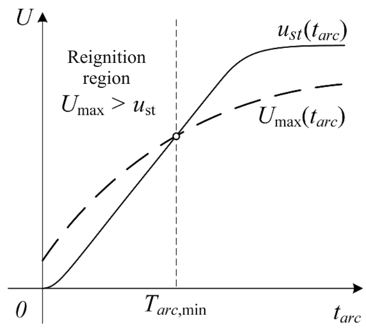

Fig. 3. Determination of the minimum arc duration (all curves are conventional): $u_{st}(t_{arc})$ is the dielectric strength of the intercontact gap; $U_{max}(t_{arc})$ is the overvoltage; t_{arc} is the arc duration.

Although increasing the arc duration increases the overvoltage because of the current chopping (Fig. 3), the reignition overvoltage is usually more dangerous. Therefore, controlled-switching devices are set so as to avoid reignition, selecting the arc duration longer than $T_{arc,\ min}$:

$$T_{arc,\ min} = k_s T_{arc},$$

where k_s is the safety factor; T_{arc} is the setpoint for the arc duration.

Nevertheless, the decision on relative danger of reignition in comparison with the current chopping overvoltage should be made considering the design of the circuit breaker [3].

Principle of Controlled Switching of a Shunt Reactor. The instant tcmd at which the reactor switching command arrives is arbitrary, but the controlled-switching device regards it as the zero-time reference of switching, setting $t_{cmd} = 0$. At the instant t_{cmd}, the phase of the reference signal ψ is estimated (using adaptive structural analysis as a universal method [5, 6]).

During controlled switching (Fig. 4), the total opening time is predicted considering the opening time Topen and the arc duration T_{arc}. The measurement of the total opening time stops at the maximum U_{max} of the voltage $u_s(t)$, optimizing the switching process according to the following condition [7]:

$$\psi_{set} = \pi/2 \tag{4}$$

satisfied at the time the circuit is opened or, what is the same, at the time t_{elec} of extinction of the arc. To this end, it is necessary to determine the delay time T_{delay} before the time t_{start} of generating the command for the electromagnet of the circuit breaker:

$$t_{elec} = t_{start} + T_{open} + T_{arc}.$$

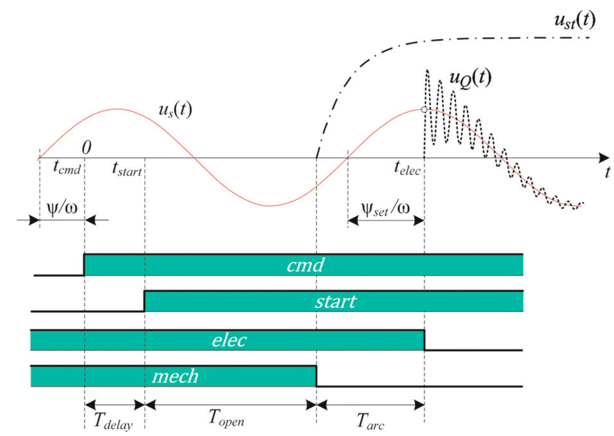

Fig. 4. Illustration of the principle of controlled switching of shunt reactor: t_{cmd} is the time of receiving the opening command; t_{start} is the time the controlled-switching device generates the command for switching off the circuit breaker; t_{elec} is the time of opening of the electric circuit; T_{open} is the opening time of the circuit breaker; T_{delay} is the delay of the opening command; T_{arc} is the arc duration; cmd is the external command to switch off the reactor; *start* is the opening command generated by the controlled-switching device; *elec* is the signal indicating the closing of the electric circuit; *mech* is the signal indicating the closed position of contacts of the circuit breaker.

The time interval ($T_{open} + T_{arc}$) includes several periods of reference signal; therefore,

$$\psi + \omega(T_{open} + T_{arc}) = m\pi + \Delta\psi, \tag{5}$$

where

$$m = \left[\frac{\psi + \omega(T_{open} + T_{arc})}{\pi}\right].$$

The closing time satisfies the equality

$$\psi + \omega(T_{open} + T_{arc} + T_{delay}) = \psi_{set} + n\pi, \tag{6}$$

where n is the number of half-periods of the reference signal.

Thus, the delay time T_{delay} is calculated using formulas (6) and (5) as follows:

$$T_{delay} = \frac{\psi_{set} - \Delta\psi}{\omega} + \zeta\frac{T}{2}, \tag{7}$$

where $\psi_{set} = \pi/2$ is the setpoint (opening phase); $T = 2\pi/\omega$ is the period of the reference signal;

$$\zeta = \begin{cases} 1, \text{ if } \Delta\psi > \psi_{set}; \\ 0, \text{ if } \Delta\psi \le \psi_{set} \end{cases}$$

is a coefficient providing synchronization of opening within a half-period of the reference signal.

The device acts on the electromagnet of the circuit breaker at the time t_{start} that is by T_{delay} later than the time t_{cmd} of arrival of the command, according to (7). The reactor is switched off at the time t_{elec} when the reactor voltage is maximum.

Types of Three-Phase Shunt Reactors and Their Features. The optimal instants of switching off three-phase reactors depend on the connection pattern of the windings and the design of the core. Four connection patterns for the windings of a three-phase shunt reactor with a single core are most popular: grounded-neutral star, isolated-neutral star, four-legged star, and delta (Fig. 5). Obviously, Fig. 5*a* and *b* can be considered as special cases of Fig. 5*c* if the inductive reactance of the neutral reactor $X_n = 0$ and $X_n = \infty$, respectively.

The delta connection can be transformed into an isolated-neutral star using well-known formulas. For the star, we will have

$$X_{\text{ph}} = \frac{X_{\text{ph},\Delta} - X_m}{3}.$$

Therefore, the switching processes for a shunt reactor with phase windings connected to form a delta circuit can also be considered in an equivalent circuit of the reactor with phase windings connected as a four-legged star.

The ratio of the inductive reactance of the neutral reactor to that of the phase is denoted by

$$k_n = X_n / X_{\text{ph}},$$

while the ratio of the mutual inductive reactance to the reactance of the phase is denoted by

$$k_m = -X_m / X_{\text{ph}}.$$

The mutual inductive reactance X_m is always negative because the self-induction and mutual-induction fluxes are directly opposite.

The mutual influence of the phases is absent in reactors with a four- or five-legged core; therefore, $k_m = 0$. In shunt reactors with three-legged core, connecting one phase leads to the occurrence of voltage across the two other phases because of the magnetic coupling of the phases. The coefficient km of such a reactor falls into the range from –0.09 to –0.11 [8].

Thus, three-phase reactors of all types can be reduced to a reactor with four-legged star connected windings. Hence, the optimal conditions for switching off all types of shunt reactors can be established by analyzing the switching processes for a three-phase reactor with four-legged star connection of the windings (Fig. 5*c*) [9].

Switching Processes for a Reactor with Four-Legged Star Connection of Windings. Let, for the sake of definiteness, the power supply be represented by a three-phase symmetric system with a positive phase sequence. Switching is synchronized with the voltage $\underline{U}_A$ in the sequence

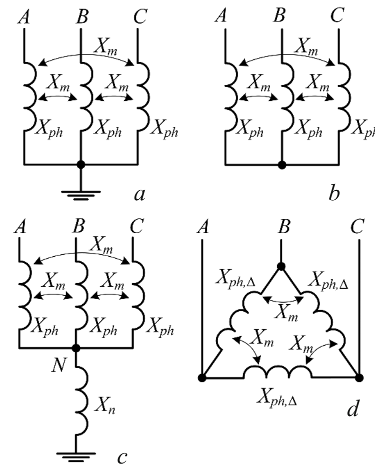

Fig. 5. Connection of windings of shunt reactor: *a*, grounded-neutral star; *b*, isolated-neutral star; *c*, four-legged star; *d*, delta; X_m is the mutual inductive reactance; X_{ph} is the resistance of the reactor phase; X_n is the inductive reactance of the neutral reactor.

$A \to C \to B$. This switching sequence is used because it minimizes the total time of opening all the three phases.

The optimal opening time corresponds to zero argument of the breaker current $\underline{I}_{Q,\sigma}$, $\sigma = \overline{A, B, C}$ of the opened phase:

$$\arg(\underline{I}_{Q,\sigma}) = 0°. \tag{8}$$

The circuit-breaker current for each phase can be expressed in terms of the voltage $\underline{U}_A$:

$$\underline{I}_{Q,\sigma} = \underline{U}_A \underline{\xi}_\sigma. \tag{9}$$

where $\underline{\xi}_\sigma$ is a coefficient of proportionality. The optimal phase to open follows from the optimality condition (8):

$$\psi_{\text{opt},\sigma} = \arg(\underline{U}_A) = \arg(\underline{\xi}_\sigma). \tag{10}$$

While all the phases of the reactor are closed (before the opening of the first phase, Fig. 6*a*), the common-point potential of the star $\underline{U}_N = 0$. Reducing Fig. 6*a* to Fig. 6*b* by the method of decoupling circuits with mutual inductance, we obtain

$$\underline{\Psi}_A = \frac{1}{j(X_{\text{ph}} - X_m)}.$$

Hence, the opening of the phase *A* will be optimal, according to (10), if the phase voltage $\underline{U}_A$

$$\psi_{\text{opt},A} = -\arg\left(\frac{e^{-j90°}}{X_{\text{ph}} - X_m}\right) = 90°.$$

Let us determine the coefficient of proportionality $\underline{\xi}_C$ for opening the phase *C* (Fig. 7*a*). After decoupling of the inductive couplings, the phase *C* opening circuit is transformed into the circuit in Fig. 7*b*. Consider that the opening of the

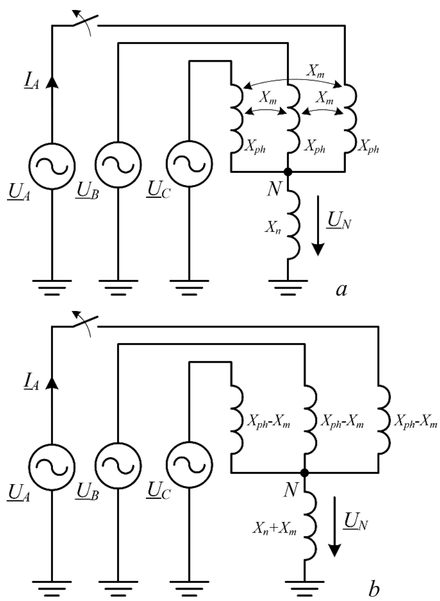

Fig. 6. Circuits before opening the phase *A* of shunt reactor: *a*, initial circuit; *b*, equivalent circuit with decoupled inductive couplings.

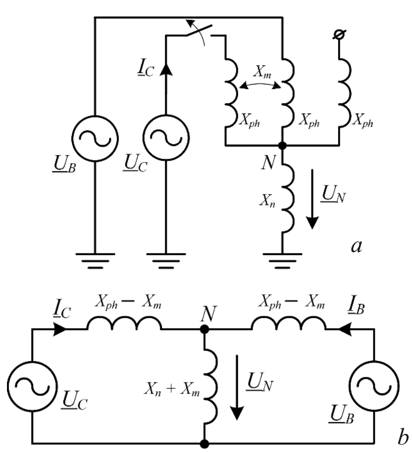

Fig. 7. Opening circuit for the phase *C* of shunt reactor: *a*, initial circuit; *b*, equivalent circuit with decoupled inductive couplings.

first phase (phase *A*) increases the potential of the common point *N* to

$$\underline{U}_N = (\underline{I}_B + \underline{I}_C)(jX_n + jX_m) =$$

$$= -\underline{U}_A \frac{X_n + X_m}{X_{\text{ph}} + X_m + 2X_n}.$$

Then the circuit-breaker current for the phase *C* of the reactor is

$$\underline{I}_C = \frac{\underline{U}_C - \underline{U}_N}{j(X_{\text{ph}} - X_m)}.$$

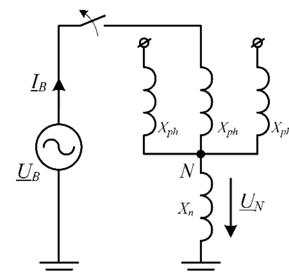

Fig. 8. Opening circuit for the phase *B* of shunt reactor.

Hence, the complex coefficient of proportionality of the phase *C* opening circuit is

$$\underline{\xi}_C = \frac{e^{j\psi_C} + \dfrac{k_n + k_m}{2k_n + k_m + 1}}{j(X_{\text{ph}} - X_m)}.$$

The optimal phase to open, according to (10), is

$$\psi_{\text{opt},C} = 90° - \arg\left(e^{j120°} + \frac{k_n + k_m}{2k_n + k_m + 1}\right).$$

Since the optimal angle for opening the second phase cannot be less than the angle of opening the first phase $\psi_{\text{opt},\,A} = 90°$, the following angle is used as a setpoint:

$$\psi_{\text{opt},C} = 270° - \arg\left(e^{j120°} + \frac{k_n + k_m}{2k_n + k_m + 1}\right).$$

In the phase *C* opening circuit (Fig. 8), the phase current is

$$\underline{I}_B = \frac{\underline{U}_A e^{-j120°}}{j(X_{\text{ph}} + X_n)}$$

and the coefficient of proportionality is

$$\underline{\xi}_B = \frac{e^{-j210°}}{X_{\text{ph}} + X_n}.$$

The optimal phase to open is

$$\psi_{\text{opt},\,B} = 210°.$$

Optimal Conditions for Switching Off Three-Phase Shunt Reactors. The optimal phases to switch off a three-phase shunt reactor for different connections of its windings are presented in Table 1.

Note that after opening of the first phase of a reactor with windings connected into an isolated-neutral star, the remaining windings appear series-connected, which allows them to be opened simultaneously. Therefore, the second and third

TABLE 1. Optimal Phases for Switching of Shunt Reactor

Winding connection	Number of core legs	Phase *A*	Phase *B*	Phase *C*
Grounded-neutral star	4 or 5	90°	210°	150°
	3	90°	210°	$270°-\arg\left(e^{j120°}+\frac{k_m}{k_m+1}\right)$
Isolated-neutral star Delta	3 – 5	90°	180° (phases *B* and *C* are opened simultaneously)	
Four-legged star	4 or 5	90°	210°	$270°-\arg\left(e^{j120°}+\frac{k_n}{2k_n+1}\right)$
	3	90°	210°	$270°-\arg\left(e^{j120°}+\frac{k_n+k_m}{2k_n+k_m+1}\right)$

phases of the reactor are opened simultaneously when the phase of the reference voltage is equal to 180° (peak of phase-to-phase voltage). This is widely used in controlled-switching devices of other manufacturers [10].

CONCLUSIONS

1. Modern controlled-switching technologies allow substantial limitation of the overvoltage caused by switching off a three-phase shunt reactor. The optimal times for switching a shunt reactor should in most cases be selected so as to prevent the reignition of the arc in the circuit breaker as a source of the most critical overvoltage in the network.

2. The method of analyzing the switching conditions for three-phase shunt reactors is made universal by using the four-legged star equivalent circuit of three-phase reactors.

3. The opening of the windings of a three-phase shunt reactor is synchronized with the voltage of the phase A and follows the sequence $A \to C \to B$ to minimize the total switching time for the reactor.

REFERENCES

1. K. Frohlich et al., "Controlled switching of HVAC circuit breakers. Guide for application lines, reactors, capacitors, transformers. 1st Part," *ELECTRA*, No. 183, 65 – 96 (1999).
2. K. Frohlich et al., "Controlled switching of HVAC circuit breakers. Guide for application lines, reactors, capacitors, transformers. 2nd Part," *ELECTRA*, No. 185, 36 – 61 (1999).
3. Hiroki Ito (ed.), *Switching Equipment*, Springer International Publishing AG (2019).
4. *IEEE Standard C37.015–2017. Guide for the Application of Shunt Reactor Switching*.
5. V. I. Antonov, *Adaptive Structural Analysis of Electrical Signals: Theory and Its Applications in Intelligent Electric Power Engineering* [in Russian], Izd. Chuvash. Univ., Cheboksary (2018).
6. V. I. Antonov, "Adaptive structural analysis of electrical signals: Theory for an Engineer," *Rel. Zashch. Avtomat.*, No. 2(35), 18 – 27 (2019).
7. M. I. Aleksandrova, V. A. Naumov, V. I. Antonov. N. G. Ivanov, A. V. Soldatov, and V. Ya. Vasil'eva, "Universal principles of controlled switching of power electrical equipment," *Rel. Zashch. Avtomat.*, No. 1(34), 49 – 54 (2019).
8. *International Standard IEC 60076-6. Power transformers. Part 6. Reactors*, 2007.
9. M. I. Aleksandrova, V. A. Naumov V. I. Antonov, and N. G. Ivanov, "A development of shunt reactor controlled energizing theory," in: *Proc. of the 2nd Int. Youth Sci. and Tech. Conf. on Relay Protection and Automation* (*RPA*), IEEE, Moscow (2019), pp. 1 – 14; DOI: 10.1109/RPA47751.2019.8958105.
10. *Switchsync PWC600. Technical Manual*, http://search-ext.abb.com/library