Charging Capacity Compensation Device for Application during Energization and Single-Phase Automatic Reclosing of Power Transmission Lines

D.V. Kochura, I.Ye. Naumkin, L.I. Sarin, R.I. Naumkin

Abstract-- **During alternating current transmission of more than 110 kV rated voltage with a high level of charging capacity compensation, a problem occurs with the zero-delay in the current to be interrupted by a linear circuit breaker. The paper reviews all the known methods and devices for solving the current zero-delay problem in the interrupted current. An analysis of those measures has been made, and their advantages and disadvantages have been pointed out. A new charging capacity compensation device for power transmission lines to be used during energization and single-phase automatic reclosing is proposed.**

The paper contains calculation results of electromagnetic transients. They demonstrate that the proposed device solves the current zero-delay problem for a linear circuit breaker. It is also shown that the considered device reduces the problem of resonant overvoltages during single-phase automatic reclosing of a power transmission line. In addition, application of the new device makes it possible to increase the probability of a secondary arc extinction during the single-phase reclosing dead time that maintains reliable operation of the power transmission line.

Keywords: **high voltage circuit breaker, DC-component, current zero-delay, energization of a power transmission line, automatic reclosing, shunt reactor, short circuit, secondary arc, resonant overvoltage keywords.**

I. Introduction

THE current zero-delay problem in an interrupted current resulting in a delay of the arc-extinction process in the contact gap of a high voltage (HV) circuit breaker has been studied for the first time for *generator circuits* [1]. Under unbalanced conditions of short circuit (SC) clearance by generator circuit breakers, some currents may occur that do not cross zero for several periods.

Due to the development of compensated HV *power transmission cable lines* in Japan, Denmark, England, Italy and other countries, the processes of their energization with connected shunt reactors (SR) were studied [3–5]. It is stated in [5] that a number of measures for solving the current zero-delay problem can be used in practice.

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Paper submitted to the International Conference on Power Systems Transients (IPST2017) in Seoul, Republic of Korea June 26-29, 2017

Faults that happened in 500–750 kV extra high-voltage power grids at compensated *overhead power lines* in Russia and Kazakhstan resulted in the urgent studies of the current zero-delay phenomenon during interruptions by new SF6 circuit breakers. The first paper was presented 2 months after the fault (explosive destruction of the SF6 circuit breaker at the Altay 1150 kV substation in Russia on February 2007) where the reasons of this fault were considered and recommendations for preventing such accidents were given [6]. Later, this fault situation was studied in detail [7–10].

Emergency operating conditions for linear SF6 circuit breakers occur when transient currents in *unfaulty phases* of compensated overhead power lines, which do not cross zero for a long time, are not interrupted. That is caused by occurrence of higher DC-components in such currents in comparison with forced components.

In order to provide emergency interruption of a linear SF6 circuit breaker, the following conditions should be observed:

- at least one phase without SC (unfaulty) in the compensated power transmission line which would be energized only from one side;
- energization with close-to-zero voltage from the power supply end;
- interruption of this phase without any special time-delay after energization.

Emergency operating conditions of SF6 circuit breakers may occur in the following cases:

- one-side line energization and three-phase interruption by high-speed relay protection;
- single-phase automatic reclosing when the secondary arc is successfully extinguished during the dead time, but the automatics is actuated for three-phase interruption after the reclosing;
- unsuccessful three-phase automatic reclosing in the case of a non-cleared unbalanced short circuit or operation of three-phase automatic reclosing instead of single-phase automatic reclosing.

II. Methods Ensuring Operability of Linear Circuit Breakers During Switching of Compensated Power Transmission Lines

The following methods may be used to solve the problem of transient current uninterruption by linear SF6 circuit breakers in the case of DC-components of long duration in unfaulty phases:

1) introduction of *a delay* into the interruption process in unfaulty phases;

2) *prior* switching of shunt reactors connected to overhead power lines;

3) *controlling the phase of closing* through overhead power line energization close to the voltage maximum on the power supply end (when energizing the overhead power line) or to the voltage maximum at circuit breaker terminals (during auto-reclosing cycles);

4) using *circuit breakers with preinsertion resistors;*

5) temporary *insertion* of resistors into shunt reactor circuits;

6) temporary connection of *resistors in parallel with shunt reactors*;

7) application of *controlled* shunt reactors;

8) *sequential* switching;

9) *combined* method.

Let us consider the methods in detail.

A. Introduction of a delay into the interruption process in unfaulty phases

In this method, the closing-opening cycle (C-O) is changed. During automatic reclosing, the changed cycle has to be as follows: O-t_{dt}-C-O (faulty phase), O-t_{dt}-C-t_{dc}-C (unfaulty phase), where t_{dt} is the dead time; t_{dc} is the time of damping of DC-component in the current through a circuit breaker.

The change in the standard operating procedure of the automatics may result in several unexpected events that might have an adverse effect on the operation of the grid. For instance, if such method of the DC-component elimination is used, the unbalanced power supply conditions for the overhead power line occur. In this case, there may be a resonant voltage increase, which is unacceptable in practice. In addition, it becomes necessary to make the relay protection algorithms more complicated (disconnection of the protection against open-phase conditions for the period of the delay in the unfaulty phase interruption) that results in the decrease of the operating reliability of overhead power lines.

B. Switching of shunt reactors connected to overhead power lines

The method is implemented through the connection or disconnection of SRs both during normal line closing and during line energization in the auto-reclosing cycle. Due to various reasons, this method is not considered to be efficient.

Firstly, the System Operator (the institution that performs centralized operational and dispatch control of the United power system in Russia) often bans SR switching which does not comply with the normal grid conditions. Secondly, reactor disconnection prior to overhead power line closing results in an increase of overvoltage events at the open end of the overhead power line during energization. Therefore, acceptability and efficiency of such method should be considered not only in terms of a DC-component decrease in the interrupted current, but also in terms of overvoltage events, operating conditions of protecting devices and the improvement of requirements to their technical specifications. Thirdly, during the complex cycle of switching (SC, circuit breakers at both ends of the overhead power line, circuit breakers in the SR circuit) at line energization and auto-reclosing, some features of operation with a high SR inductance are defined that do not ensure acceptable operating reliability for the overhead power line.

Let us demonstrate some simulated oscillograms representing features of SR switching. The calculation results were obtained using MAES software [11]. Calculations with the use of Simulink showed the same results.

1) Fig. 1 shows that in the case of solid SC that happened during voltage zero crossing in a place close to a SR, the current through the circuit breaker in the SR circuit has no zero crossings in the faulty phase for an extended period of time, thus its interruption is impossible.

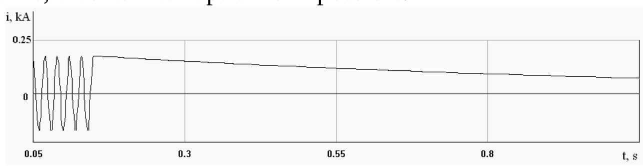

Fig. 1. Oscillogram of current through a SR circuit breaker in the faulty phase during a solid SC that happened with the supply voltage zero.

2) Fig. 2 presents oscillograms of transient currents through a linear circuit breaker during SR connection during the following switching events:

- when energizing a non-loaded overhead power line, the linear circuit breaker is closed with a disconnected SR, then a SR is connected (Fig. 2, a);
- when energizing a non-loaded overhead power line, the linear circuit breaker is closed with a disconnected SR, then an overhead power line is energized into transit operation, after that a SR is connected (Fig. 2, b).

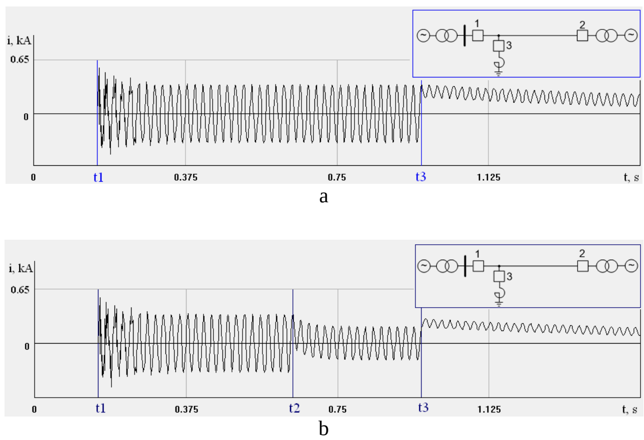

Fig. 2. Oscillograms of currents through a linear circuit breaker during SR connection to a power line under no-load conditions (a) and after line energization into transit operation (b).
Closing time: t1 – circuit breaker 1; 2 – circuit breaker 2; 3 – circuit breaker 3

In both cases, switching of high inductance of SR causes a high DC-component in the current through the linear circuit breaker, which is impossible to be interrupted if necessary. The cases considered do not represent all the problems that arise in the case of SR switching. They only demonstrate that simple and cheap solutions are not always acceptable.

C. Controlling the phase of closing through overhead power line energization close to the voltage maximum on the power supply end (when energizing the overhead power line) or to the voltage maximum at circuit breaker terminals (during auto-reclosing cycles)

If the line is closed at the voltage maximum, the DC-component in the current is inconsiderable, and the following interruption will be possible. Currently, manufacturers of SF6 circuit breakers produce controlled switching devices (CSD) or Point-on-Wave Controllers, for example: SwitchSync (ABB), RPH02/RPH03 (Alstom Grid), integrated systems of circuit breaker diagnostics ("EnergoMash-Ural ElectroTyazhMash" CJSC, Yekaterinburg). One should consider that standard application of CSD implies closing a circuit breaker at voltage zero to decrease switching overvoltages.

CSD application for closing at the voltage maximum is non-standard, therefore approval of the manufacturer is required. The use of CSD for mitigating DC-components in current is complicated by strict requirements to the accuracy of the voltage maximum (less than 1 ms) that is not guaranteed by manufacturers. Moreover, closing at the voltage maximum will always lead to maximum levels of switching overvoltages, which will impact on the lifetime of surge arresters (SA).

D. Using of circuit breakers with preinsertion resistors

Temporary insertion of a high value resistor into the circuit allows reducing the damping time constant of the DC-component to 15–20 ms, that will further allow successful opening of the circuit breaker. Today, circuit breakers with preinsertion resistors being preset to 8–12 ms and having resistances equal to surge resistances of overhead power lines are usually used. This method is applied to reduce switching overvoltages. It would be reasonable to use such circuit breakers to remove the DC-component of the interrupted current.

However in practice resistor parameters (rated resistance, power, operation time) are chosen individually for each variant of a compensated overhead power line. These parameters may be extremely different from standard parameters. This substantially complicates the process of circuit breaker ordering (impossible to be a part of a complete switchgear and control gear), the supply period increases, and the prices increase compared to prices for conventional circuit breakers.

E. Temporary insertion of resistors into shunt reactor circuits

The purpose of per-phase insertion of resistors from neutral sides in series into a SR circuit is to reduce the damping time constant of the reactor current DC-component $\tau_{SR} = L_{SR}/R_{SR}$ (L_{SR} – SR inductance, R_{SR} – resistance in the SR circuit) to the required value. It will provide damping of the DC-component to the safe value by the time of circuit breaker opening.

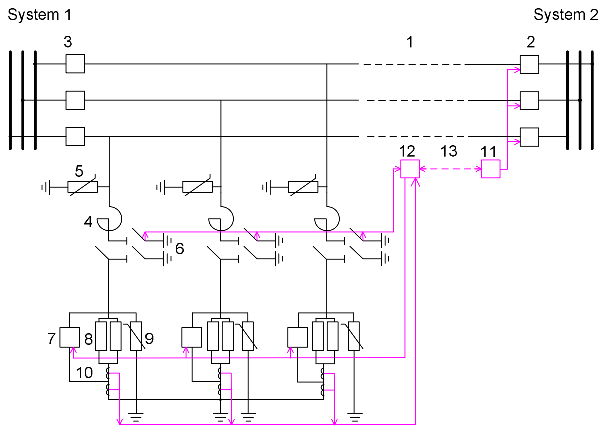

Fig. 3. Diagram of per-phase connection of a resistor unit in a SR neutral
1 – transmission line; 2, 3 – 500 kV line circuit breakers (CB); 4 – 500 kV SR; 5 – 500 kV surge arrester (SA) for SR protection; 6 – 35 kV disconnecting switch (DS) with earthing blades; 7 - shunting circuit breaker; 8 - resistor unit; 9 – 35 kV surge arrester for protection of a SR neutral; 10 – 35 kV current transformer (CT); 11 - relay protection; 12 – digital automation control of a resistor unit (RU); 13 – communication line between System 1 and System 2.

The resistor unit is connected per the diagram shown in Fig. 3. Under standard operating conditions of the overhead power line, the circuit breaker (7) shunting the resistor unit (8) is closed. In the case of a short circuit in the line (1), relay protection (11) gives a command to open it on both ends. At the same time, a command is given to open the shunting circuit breaker (7), and the resistor unit (8) is put into operation. In the case of successful double-side energization of the line (1), a command is given to close the shunting circuit breaker (7).

Controversial requirements are applied to the choice of the resistor: at the top – the resistance is limited by permissible voltage on shunt reactor neutrals (as well as by voltage coordination with the residual voltage of a surge arrester) and by permissible energy dissipated in the resistor (taking into consideration the time of impact); at the bottom – by the efficiency of resistor influence on the DC-component damping of the current through the shunt reactor. Putting this method into practice demonstrated that there are no problems selecting a resistor unit with the required parameters.

F. Temporary connection of resistors in parallel with shunt reactors

This method allows increasing the forced component of the interrupted current in such a manner that the total interrupted current will cross zero. A drawback of such method is the necessity to use a high-voltage resistor and to include an additional high-voltage circuit breaker into the power system. This solution is rather expensive.

G. Application of controlled shunt reactors

Controlled shunt reactors allow stepless change of inductance in comparison with standard shunt reactors with step adjustment. In addition, it is possible to connect a controlled shunt reactor to an overhead line without a circuit breaker. However, the physical nature of this method remains unchanged: when closing a compensated overhead power line in any case (energization or three-phase automatic reclosing), it should be operated under stable conditions, far from the resonance, i.e. the line should be uncompensated.

In this case, the limitations are the same as with conventional shunt reactors that relate to a voltage increase or with requirements to operating conditions introduced by the System Operator. In addition, some requirements to the speed of shunt reactor inductance control arise, as follows: during the dead time of three-phase automatic reclosing, controlled shunt reactors at disconnected phases should have a possibility to change their inductance substantially.

H. Sequential switching

This measure against current zero-delay was used during cable lines energization [5]. Switching is done in four stages:

1) energization of the non-loaded line;
2) interruption of the faulty phase under short circuit conditions;
3) disconnection of shunt reactors at healthy phases (with a prohibition for shunt reactor disconnection at the faulty phase);
4) opening of healthy phases of a line circuit breaker.

Some drawbacks of this measure are specified in [5]. It is necessary to have circuit breakers with increased requirements to interruption of capacitive currents, and have more complex automatics for per-phase switching of line circuit breakers and reactor circuit breakers. It is also necessary to consider the requirement on disconnection of protection against open-phase conditions for the period of the delay of healthy phase interruption described above.

J. Combined method

The combined method may be used when a single measure given above does not allow solving the current zero delay problem completely. For example, when switching an overhead power line with almost 100% compensation, the forced component of the current is very small, therefore current zero crossing is extremely delayed. If it is planned to use controlled switching devices in this case, the increased accuracy of the voltage maximum is required, which is hard to realize in practice. When choosing the method of resistor connection to shunt reactor phases, it is extremely difficult to comply with all the requirements described above. However, combination of two methods allows mitigating the problem of current zero delay efficiently. In this case, the controlled switching device is adjusted to closing within some range close to the voltage maximum. This does not help to damp the DC- component completely, but it allows reducing switching overvoltages substantially. The residual damping of the DC-component is ensured by resistors in the shunt reactor circuit. As resistors are not intended to damp the full value of the DC current component, technical specifications of resistors will comply with all the requirements to applied currents and voltages.

It should be mentioned that not every combination of measures is possible. For example, it is not permitted to use controlled switching devices and circuit breakers with preinsertion resistors simultaneously, as circuit breaker manufacturers cannot ensure conditions for simultaneous operation of such measures.

III. Development of the Idea of Temporary Insertion of Resistors Into the Shunt Reactor Circuit

It is proposed to improve the method described in II.*E* for mitigating current zero delay through temporary insertion of resistors into shunt reactor phase circuits.

Simulation results of processes under single-phase automatic reclosing of the 500 kV compensated power transmission line are presented below. The calculation model was developed for the diagram shown in Fig. 4.

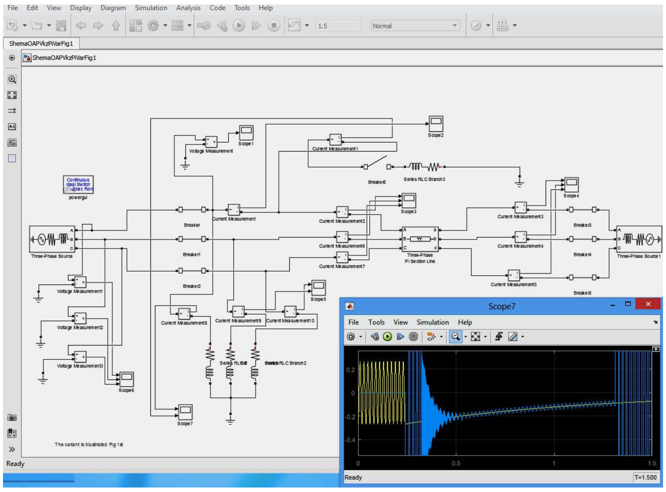

Fig. 4. Simulink diagram.

System 1 and System 2, simulated by EMFs with resistances and inductive reactances, are connected by the 180-km overhead transmission line (positive sequence line parameters: x_1=0.31 Ohm/km; b_1=3.62810-6 S/km; r_1=0.024 Ohm/km; zero-sequence line parameters: x_0=0.81 Ohm/km; b_0=2.67210-6 S/km; r_0=0.28 Ohm/km). The shunt reactor (X_{SR}=1531 Ohm, R_{SR}=4.85 Ohm) with the resistor unit in the SR circuit is connected to the transmission line from the side of System 1.

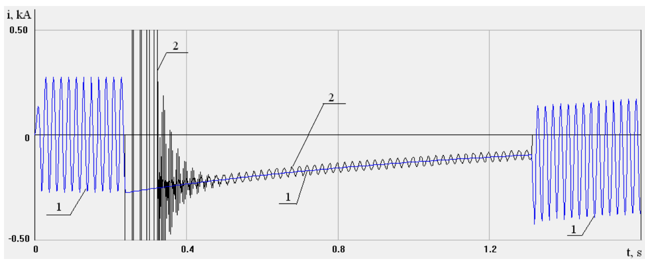

Fig. 5. Current in the nearby short circuit place and current in the circuit of shunting circuit breakers.
1 – current in the faulty phase of resistor unit shunting circuit breaker;
2 – current in the short circuit place

In the case of short circuits located close to shunt reactors, which occur close to voltage zero, a transient current will flow in the faulty phase of the shunt reactor, in the extreme case –

completely without current zeros (oscillogram 1 in Fig. 5). If such event is considered probable, it is also necessary to consider that it is impossible to open the shunting circuit breaker of the faulty phase with the specified short circuits. Thus, it is impossible to connect resistors in series with the shunt reactor. For the same reason, secondary arc extinction during the dead time becomes extremely difficult (oscillogram 2 in Fig. 5).

Based on the statistics of short circuits to ground for overhead lines of high and extra-high voltage (the percentage of single-phase short circuits in 500 kV grids is 80–90%, in 750 kV grids – almost 100%) and considering the problems with the opening of line circuit breakers often occur during unbalanced short circuits, it is proposed to use a modified circuit of the resistor unit connected to shunt reactor phases. It means that capacitors (or static capacitor banks) with unearthed-delta-connection or unearthed-star-connection should be inserted into the electric circuit in parallel with earthed-star-connected resistors (Fig. 6).

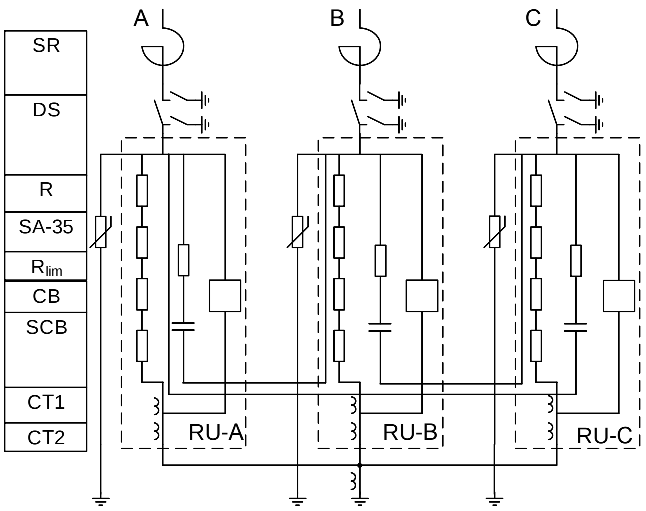

Fig. 6. Connection of the resistor unit and capacitor banks into the shunt reactor circuit
SCB – static capacitor bank, R_{lim} – low-ohmic limiting resistor

The oscillogram, shown in Fig. 7, was obtained under the same conditions as the oscillogram in Fig. 5, but with the use of the modified resistor unit (Fig. 6). It demonstrates fundamentally different behavior of the shunt reactor current and the short circuit current. A delta-connection (or unearthed star-connection) of capacitors allows the current in the faulty phase of the shunt reactor to have the AC-component and to ensure subsequent successful opening of the shunting circuit breaker at the current zero. It also ensures changing of the DC-component in the short circuit current that results in its fast damping and secondary arc extinguishing.

Therefore, the current through the shunting circuit breaker crosses zero without any delay, and the circuit breaker is opened. The short circuit current is damped within 30–40 ms, then the short circuit is cleared. Reclosing of the overhead power line does not result in the occurrence of the DC-component in the current through the line circuit breaker as far as there are resistors in the shunt reactor circuit.

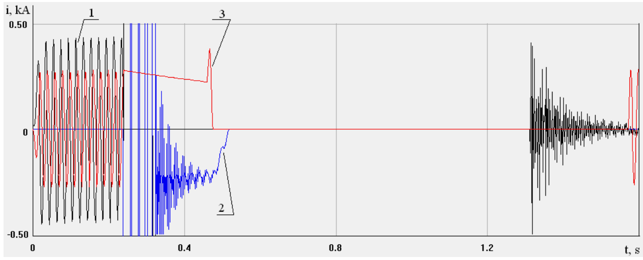

Fig. 7. Oscillograms of currents in the case of the capacitor bank and the resistor unit connected into the shunting reactor circuit
1 – line circuit breaker current; 2 – short circuit current; 3 – faulty phase current through the shunting circuit breaker of the resistor unit

IV. Elimination of Resonant Overvoltages During Single-Phase Automatic Reclosing

It should be noted that the method considered in Section III along with the possibility to open shunting circuit breakers also provides the possibility to open reactor circuit breakers. It is an additional advantage of the proposed technical solution. However, there are more advantages of this method. The use of the resistor unit with the capacitor bank allows eliminating resonant overvoltages at the opened phase within the dead time during single-phase automatic reclosing (Fig. 8).

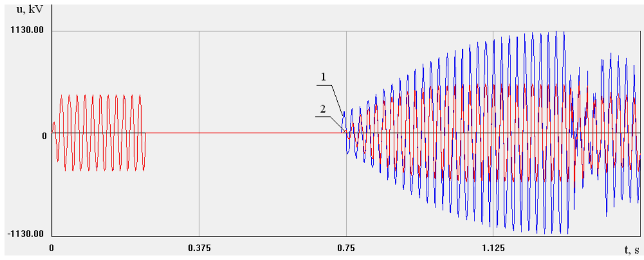

Fig. 8. Oscillograms of voltages at the opened phase within the dead time during single-phase automatic reclosing
1 – voltage without the resistor unit with the capacitor bank in shunt reactor phases; 2 – voltage with the resistor unit with the capacitor bank in shunt reactor phases.

The proposed technical solution has a comprehensive positive impact on the development of electromagnetic transients when energizing overhead power lines and performing the automatic reclosing. It is highly efficient and ensures reliable operation of power grids of high and extra-high voltage.

V. Conclusions

1. An overview of known methods used for mitigation of the current zero delay through the line circuit breaker during a closing-opening cycle of the compensated power transmission line is presented. It is demonstrated that there are no fully reliable methods for solving this problem without some negative effects. An extended study would be required to find an efficient solution in each specific case.

2. A new technical solution is proposed. It has a comprehensive positive effect on the development of electromagnetic transients when energizing overhead power lines and performing the automatic reclosing. It involves

installation of earthed-star-connected resistor units into shunt reactors phases in parallel with unearthed-delta-connected or unearthed-star-connected capacitor banks. Along with solving the current zero problem, the proposed technical solution provides reliable secondary arc extinguishing during the dead time of single-phase automatic reclosing and eliminating the resonant overvoltages at the opened phase.

VI. References

[1] M. Canay, and L. Werren, "Interrupting sudden asymmetric short-circuit currents without zero transition", *Brown Boveri Rev*, vol. 56, 1969, No.10, pp. 484–493.

[2] T. Michigami, S. Imai, and O. Takahashi, "Theoretical Background for Zero-miss Phenomenon in the Cable Network and Field Measurement", *IEEJ General Meeting*, 1997.

[3] F. F. Silva, C. L. Bak, U. S. Gudmundsdottir et al, "Use of a pre-insertion resistor to minimize zero-missing phenomenon and switching overvoltages", *Power & Energy Society General Meeting. PES'09*, July 26–30, 2009, pp. 1–7.

[4] T. Ohno, "Operation and Protection of HV Cable Systems in TEPCO", Available: http://www.ieee.ch/assets/Uploads/pes/downloads/1004/10042ohnoexperiencetepco.pdf

[5] A. Ametani, N. Nagaoka, Y. Baba, and T Ohno, *Power System Transients: Theory and Applications*. London: CRC Press, 2014, p.492.

[6] I. Ye. Naumkin, and A. S. Guyvoronsky, "Report on Analysis of Reasons for 500 kV Live-tank SF6 Circuit Breaker HPL-550 Failure at 1150 kV Altai Substation during Short Circuit Interruption at 500 kV Transmission Line Altai – Itatskaya", Available: http://pnpbolid.com/subdmn/static/pdf/eng/Report-2007.pdf

[7] I. Naumkin, M. Balabin, N. Lavrushenko, and R. Naumkin, "Simulation of the 500 kV SF6 Circuit Breaker Cutoff Process during the Unsuccessful Three-phase Autoreclosing", International Conference on Power Systems Transients (IPST2011) in Delft, the Netherlands, June 14–17, 2011.

[8] I. Ye. Naumkin, "Emergency Failures of SF6 Circuit Breakers During Commutation of 500–1150 kW Grid Interconnection Systems", *Elektrichestvo*, 2012, No. 10, pp. 22–32.

[9] I. Naumkin, V. Pod’yachev, L. Sarin, and D. Kochura "Methods of Performance Assurance for SF6 Circuit-breakers at Switching of Compensated 500–1150 kV Overhead Power Lines". International Conference on Power Systems Transients (IPST2013) in Vancouver, Canada, July 18–20, 2013.

[10] I. Ye. Naumkin, D. V. Kochura, and L. I. Sarin "Nonlinear Limiting Resistor (Limistor) – Application in 500kV Power System". International Conference on Power Systems Transients (IPST2015) in Cavtat, Croatia, June 15 – 18, 2015.

[11] I. Naumkin, M. Balabin M., N. Lavrushenko, and R. Naumkin, "Multipurpose power system simulator: implementation based on modern principles". International Conference on Power Systems Transients (IPST2009) in Kyoto, Japan, June 3-6, 2009.