Methods of Performance Assurance for SF6 Circuit-breakers at Switchings of Compensated 500-1150 kV Overhead Power Lines

Ivan Ye. Naumkin, Viktor N. Pod'yachev, Leonid I. Sarin, Danila V. Kochura

***Abstract*-- The paper presents the results of analysis of methods for solving a problem of not-breaking of transient currents with high content of aperiodic components by SF6 circuit breakers at switchings of compensated overhead power lines. Advantages and disadvantages of their implementation and real-life operation are described.**

***Keywords*: SF6 circuit breakers, compensated overhead power lines, transient currents, aperiodic components.**

I. Introduction

Emergency conditions for line SF6 circuit-breakers occur when transient currents in unfaulted phases of an overhead power line are not interrupted by circuit breakers. It is caused by the fact that such currents do not cross zero for a long time because of the higher aperiodic components in comparison with periodic components [1]-[5].

To initiate the process of emergency interruption for SF6 circuit-breaker, the following conditions should be fulfilled:

- there should be at least one unfaulted phase in a compensated overhead power line which is switched on only from one side;
- making should be performed at the moment closer to voltage zero crossing at the side of power supply;
- breaking of this phase is performed after making without time delay .

During the operation of compensated overhead power lines, emergency conditions may occur in the following cases:

1) when power is supplied from one side and relay protection is operated for three phase interruption;
2) at unsuccessful three-phase automatic reclosure in the case of non-cleared asymmetrical short circuit (i.e. in the case of restrikes at making) or operation of three-phase automatic reclosure instead of one-phase automatic reclosure.

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II. Experimental Results

Experimental investigations carried out in Kazakhstan in 2011 are caused by several faults with destructions of 500-750 kV SF6 circuit breakers in electrical networks of Russia and Kazakhstan (note that 1150 kV power lines and 1150 kV substations are operated at 500 kV):

- in 2006 and in 2007 – at 1150 kV Kokshetauskaya Substation in Kazakhstan;
- in 2007 – at 1150 kV Altai Substation in Russia;
- in 2009 – at 500 kV Agadyr Substation in Kazakhstan;
- in 2011 – at 750 kV Novobryanskaya Substation in Russia.

Electromagnetic transient processes during these faults were recorded using disturbance recorders. As an example, the oscillograms of three-phase automatic reclosure of 1150 kV L-1106 Itatskaya – Altai power line at 1150 kV Altai Substation are presented in Fig. 1 (where *a* – experimental oscillograms, *b* – simulated using [6]).

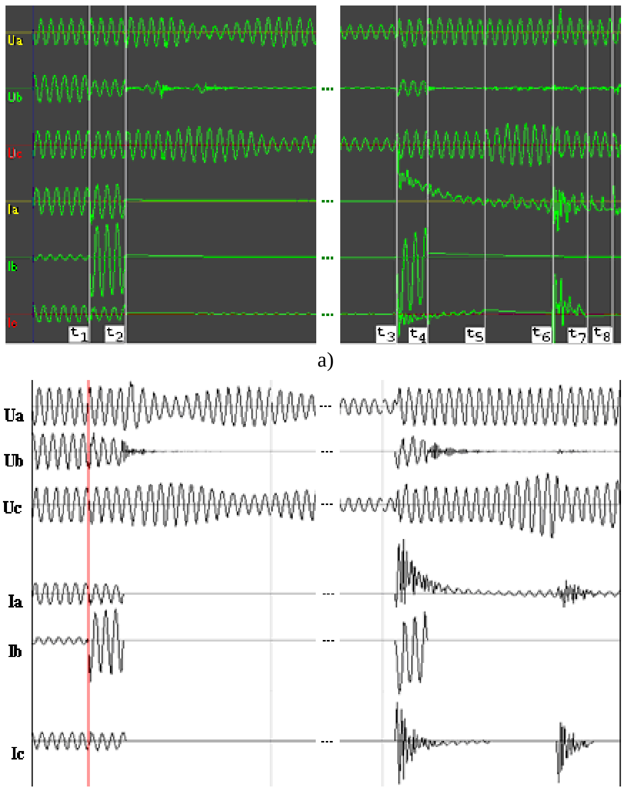


Fig.1. Oscillograms for failed automatic reclosure of the transmission power line.

The following event sequence happened:

t_1 – one-phase short circuit on the phase B;

t_2 – interruption of a transmission line;

t_3 – automatic reclosure of a transmission line. Short-circuit is not cleared at the moment of automatic reclosure;

t_4 – interruption of the phase B;

t_5 – interruption of the phase C;

t_6 – breakdown of a circuit-breaker on the phase C;

t_7 – interruption of the phase C;

t_8 – unknown switching event.

Relay protection and automation group analyzed that the fault was caused by the fact that an SF6 circuit breaker could not interrupt fault current which did not cross zero for a long time because of the presence of high aperiodic components. Numerical calculations demonstrated in [1]-[3] support this analysis.

A. Experimental Investigations of Transient Currents

In 2011, experimental investigations in the 500 kV network (owned by KEGOC joint-stock company in Kazakhstan) were carried out.

Experiment of one-side making of L-1102 by air circuit breaker CB-501 is done for the power-line L-1102 Kokshetauskaya – Kostanayskaya presented schematically in Fig. 2.

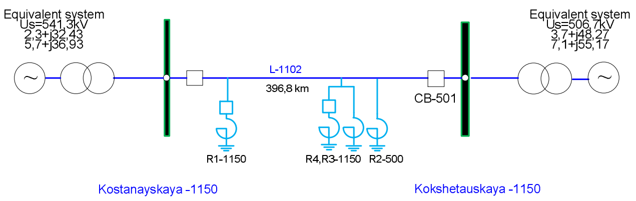


Fig.2. Power Transmission Kokshetauskaya – Kostanayskaya.

Shunting reactors R3-1150, R2-500 and R4-1150 are operated. Phase A is the first closed pole with a making angle of 64°. Phase C is switched on with a making angle of –24.9° and with a time delay of 1.4 ms related to phase A . Phase B is the last closed pole with a making angle of 42° and with a time delay of 5.5 ms related to phase A. The first current-zero is observed in phase B 180 ms after contact closure, for phase C – after 221 ms. Steady-state current is 210 A_{rms} (see Fig. 3).

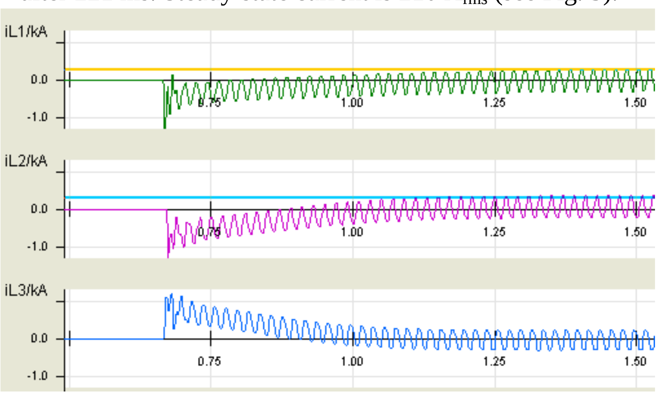


Fig. 3. Experimental oscillograms of currents through a circuit breaker at making of the 1150kV transmission power line L-1102.

Experiment of successful three-phase automatic reclosure of L-1102 by air circuit breaker CB-501 is performed for the power-line L-1102 Kokshetauskaya – Kostanayskaya. At Kokshetauskaya Substation shunting reactors R3-1150, R2-500, and R4-1150 are operated, shunting reactor R4-1150 is disconnected. At Kostanayskaya Substation shunting reactor R-1-1150 is operated. Phase C is the first closed pole with a making angle of –39°. Phase B is switched on with a making angle of 83° and with a time delay of 0.82 ms related to phase C. Phase A is the last closed pole with a making angle of -31.9° and with a time delay of 1.48 ms related to phase C.

Recorded oscillograms show the presence of voltage beats which is common for extra-high-voltage transmission lines in the case of three-phase automatic reclosure. Three phases are opened non-simultaneously: phase B is opened with a time delay of 56.8 ms related to phase A. Aperiodic components in currents depend making angles (see Fig. 4).

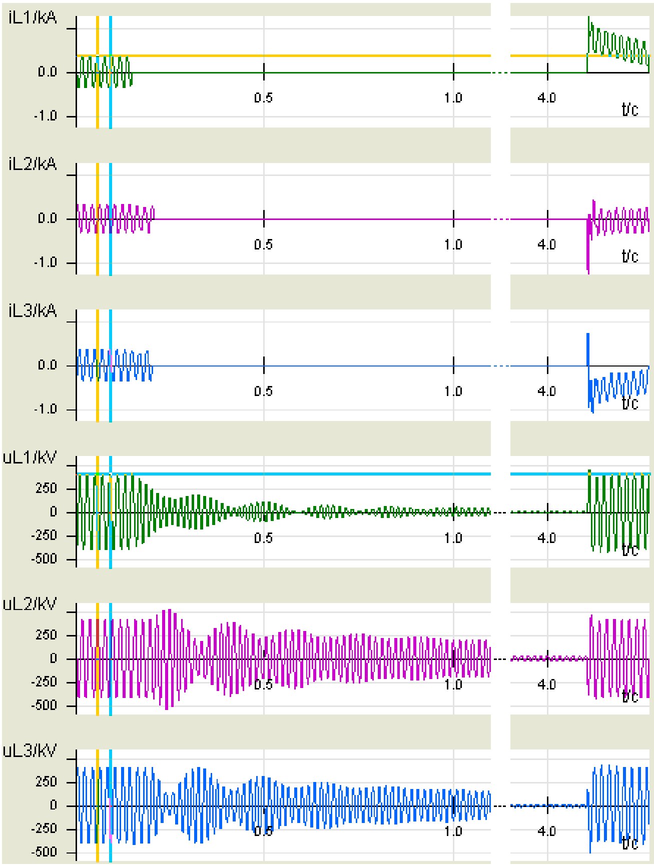


Fig. 4. Experimental oscillograms of currents through circuit breaker CB-501 and voltages at Kokshetauskaya Substation from the side of the power transmission line at three-phase automatic reclosure of L-1102.

Oscillograms shown in Fig. 3, Fig. 4 are representative oscillograms of experimental invesigations at the power line Kokshetauskaya – Kostanayskaya. Similar oscillograms were obtained during experimental investigations in 2011 at 500 kV Agadyr Substation with switchings of the overhead power line L-5170 Agadyr–Ekibastuzskaya.

Oscillograms show that switchings of a compensated overhead power line are accompanied with aperiodic components in a current flowing through a circuit breaker. These aperiodic components exceed periodic components and delay current zero crossing.

B. Experimental Investigations of Circuit-breakers

Based on experimental investigations carried out in Kazakhstan in 2011 at Kokshetauskaya Substation and Agadyr Substation, analysis of switchings for 500 kV circuit breakers is performed.

We are interested in probability of the presence of aperiodic components in the current flowing through a circuit breaker under real switching conditions for compensated overhead power lines and in possible differences between processes of making of an air circuit breaker and an SF6 circuit breaker. It should be noted that there is no aperiodic components in the current if a circuit breaker is switched at the voltage maximum. It is considered that making of a circuit breaker is probable to occur at the voltage maximum because of breakdown of an air contact gap when contacts move towards each other. Perhaps, SF6 circuit breakers cause aperiodic components to be present in the current through a circuit breaker due to the fact that they may be switched with any making angle including voltage zero.

Fig. 5 illustrates diagrams of probabilities as the result of oscillogram processing. Oscillograms of making for each pole of air circuit-breakers VVBK-500 (21 oscillograms) and SF6 circuit-breakers HPL-550B2 (12 oscillograms) and GL-317 (36 oscillograms) were processed. Obtained results do not represent general statistics on making of circuit breakers, but represent main features of these statistics. Initial making angle is determined for each switching. Switching of each phase (A, B, C) is considered to be an independent event. The period of changing of sinusoidal voltage from zero to maximum is divided into four equal parts with the following electrical degrees: 0…14.5, 14.6…30, 30.1…48.6, 48.7…90.

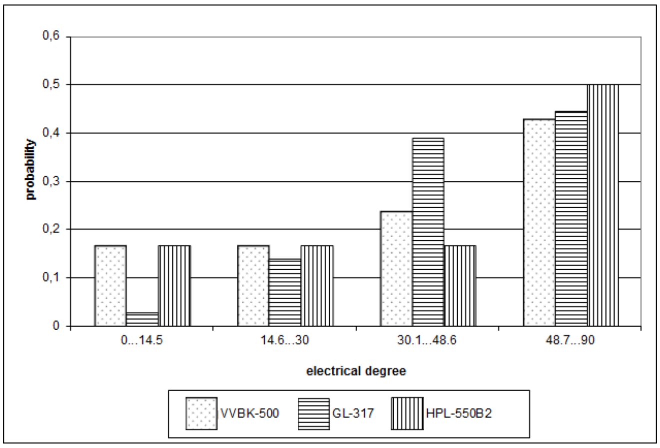


Fig.5. Diagrams of contact closing probability depending on making angle of voltage source.

Diagrams of contact closure probability depending on making angle of voltage source show that the hypothesis of the fact that SF6 circuit breakers may be switched with any making angle is not confirmed. There is also established opinion that in most cases (i.e. with a probability of 0.7–0.9) circuit-breaker making is realized closer to the voltage maximum. It is not also confirmed. Contacts of air and SF6 circuit breakers are closed with making angle of 48.7°–90° (in other words, 0.75–1.0 times maximum voltage with the probability of about 0.5). It refers to a fault with gas gap prestrike. Probabilities of contact closure near voltage zero (≤30º) for SF6 circuit breakers HPL-550B2 and GL-317, and air circuit breakers VVBK-500 are approximately the same.

Table I illustrates the results of oscillogram processing for three-phase making of the same SF6 and air circuit-breaker poles. Probabilities of making for at least one pole of a circuit-breaker within given range of making angles are determined.

TABLE I
PROBABILITY OF MAKING AT LEAST ONE POLE OF A CIRCUIT BREAKER WITH VARIOUS MAKING ANGLES

Type of a circuit breaker	*Making angle*			
	≤14,5º	≤30º	≤48,6º	≤90º
VVBK-500	0,43	0,71	1,00	1,00
HPL-550B2	0,50	0,75	1,00	1,00
GL-317	0,08	0,58	1,00	1,00

Table I shows that in the case of three-phase switching, making for at least one pole of a circuit breaker with making angle of ≤30º happens with the probability of 0.58-0.75 for both air and SF6 circuit-breakers.

Consequently, there is a high probability of making at least one pole of a circuit breaker with high aperiodic components in the transient current.

III. METHODS FOR SOLVING THE PROBLEM OF NOT-BREAKING OF TRANSIENT CURRENTS WITH HIGH CONTENT OF APERIODIC COMPONENTS BY SF6 CIRCUIT BREAKERS

Transient currents with high content of aperiodic components are not usually interrupted by SF6 circuit breakers. To solve this problem, the following methods can be used:

1) introduction of a time delay into breaking operation for unfaulted phases;
2) the change in the number of shunting reactors connected to an overhead power line at making-breaking operation;
3) controlling the moment of making (i.e. making phase); making of an overhead power line close to voltage maximum from the side of power supply;
4) using of circuit breakers with preinsertion resistors;
5) temporary introduction of resistors into the circuit of shunting reactors.

Methods 1-4 are described in detail in [1]-[5]. Method 5 is proposed in [7] and implemented in the Moscow power system.

Further we will provide a brief description for advantages and disadvantages of methods 1-4 and a more detailed analysis for method 5.

1) Introduction of a time delay into breaking operation for unfaulted phases. When introducing a time delay into a breaking operation, asymmetrical conditions for an overhead power line occur in unfaulted phases. It is known that resonance overvoltages under open-phase conditions at one-side making or breaking of a power transmission line with shunting reactors are caused by the following factors:

- power supply for a transmission line is applied from two phases (two phases are energized, one phase is deenergized);
- power supply for a transmission line is applied from one phase (one phase is energized, two phases are deenergized).

Conditions with resonant voltage increase should be usually eliminated during network operation. Moreover, it is necessary to improve the relay algorithms (deactivation of relay protection from open-phase conditions for the period of delay in interruption of unfaulted phases) which leads to reliability degradation of power transmission lines. Therefore, this method is not recommended for implementation.

2) The change in the number of shunting reactors connected to an overhead power line at a making-breaking operation. The place of installation and switching conditions for shunting reactors at bus bars of substations and power lines are determined in accordance with normal and post-fault conditions (providing of reactive power flows and voltage levels), and fault conditions (reducing of overvoltages). Any changes in power systems concerning shunting reactors should be supported by investigations. Departments of power system dispatching do not usually agree with changes of operating conditions for shunting reactors. Especially, it concerns cases of backbone transmission lines and power lines with one shunting reactor. Therefore, this method is not also recommended for implementation.

3) Controlling the moment of making (i.e. making phase); making of an overhead power line close to the voltage maximum from the side of power supply. If making of an overhead power line is realized close to the voltage maximum from the side of power supply, aperiodic components will be of minimum values providing successful current-zero crossing. For these purposes, manufactures of SF6 circuit breakers produce controlled switching devices (ABB – Switchsync; Siemens – PSD; Alstom Grid – RPH). Usually, they are used in line circuit breakers as controlled switching in the moment of voltage zero for providing minimum overvoltages. The way we propose to use such devices is non-standard and it should be discussed with manufacturers of SF6 circuit breakers.

The key feature of controlled switching for a power line in the case of the three-phase automatic reclosure is a requirement of making in the moment of voltage maximum at contacts of a circuit breaker. For this purpose, voltage should be supplied to a controlled switching device from two sides of a circuit breaker – from the side of a substation and from the side of an overhead power line. Such devices are manufactured on special request.

Another feature of controlled switching device is a requirement for making under conditions of voltage phase $\psi = \pi/2$ with ±1 ms time spread during circuit breaker service life. Manufacturer must guarantee this requirement.

Requirement of making in the moment of voltage maximum leads to maximum switching overvoltages which influence on operation and life time of arresters and intensify insulation deterioration for power lines and substation equipment.

Using this method, one should fully understand all its negative features.

4) Using of circuit breakers with preinsertion resistors. At present, circuit breakers with preinsertion resistors are manufactured with resistances of 250-500 Ohm (i.e. in the order of line impedance) with operating times of 8-12 ms. The main advantage of this method is that among with suppression of aperiodic components overvoltages may be also reduced.

Resistor parameters (rated resistance, energy intensity, operating time) are chosen for compensated overhead power lines individually. It complicates purchase of circuit breakers (especially, in the case of SF6 insulated switchgear and control gear). In this case, the delivery of circuit breakers with preinsertion resistors takes more time and their price is higher in comparison with common circuit breakers.

5) Temporary introduction of resistors into the circuit of shunting reactors. This method will be described in detail in Section IV.

IV. Temporary Introduction of Resistors into the Circuit of Shunting Reactors

Introduction of power resistors into the circuit of shunting reactors is used for decreasing of the time constant $\tau_r = L_r/R_{res}$ (where L_r is inductance of a shunting reactor, R_{res} is resistance in a circuit of a shunting reactor) down to values which lead to attenuation of aperiodic components to safe levels by the breaking time of a circuit breaker (~0.06-0.08 s). In this case, if these aperiodic components are lower than the amplitude of periodic components, the levels of aperiodic components are safe by the breaking time of a circuit breaker. Current zero crossing is ensured, and an SF6 circuit breaker is normally operated.

Then, consider power transmission between 500 kV Substation Ochakovo and 500 kV Substation Zapadnaya of the Moscow power system for illustrating this method:

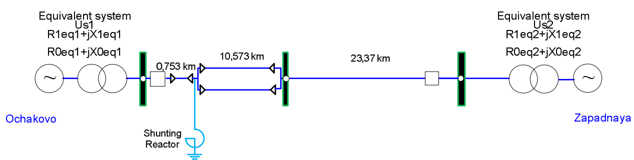


Fig.6. Power transmission Ochakovo – Zapadnaya through cable and overhead power line.

Consider the case of power supplying to cable and overhead power line Ochakovo – Zapadnaya with one-phase short circuit. Fig. 7 shows simulated oscillogram for phase C at making of a line circuit breaker at 500 kV Substation Zapadnaya when there is one-phase short-circuit on phase B at 500 kV Substation Ochakovo. Calculations are done with the special multipurpose power system simulator MAES [6]. Parameters of a shunting reactor are the following: X_r = 917 Ohm, R_r = 1.6 Ohm. Parameters of the power transmission line are presented in Table II.

TABLE II
PARAMETERS OF OCHAKOVO–ZAPADNAYA POWER LINE

Parameter	Cable line 1	Cable line 2 1st circuit, 2nd circuit	Overhead line
length *l*, km	0.753	10.573	23.37
r_1/r_0, Ohm/km	0.015/0.13	0.015/0.13	0.0243/0.28
x_1/x_0, Ohm/km	0.11/0.066	0.11/0.066	0.306/0.81
b_1/b_0, µS/km	75.4/75.4	75.4/75.4	3.623/2.672
g_1/g_0, µS/km	0.514/7.426	0.514/7.426	0.036/0.115

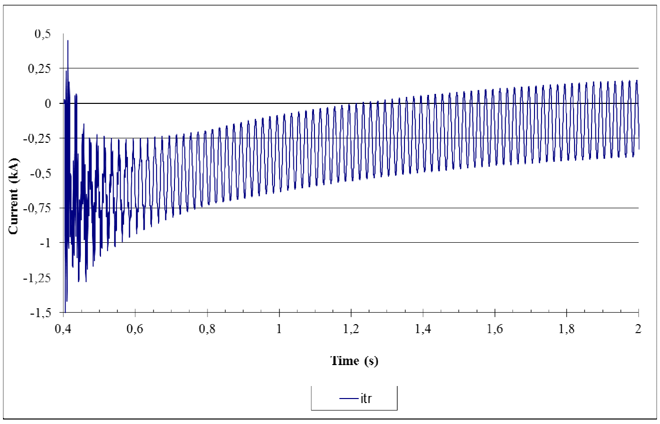


Fig. 7. Simulated oscillogram of transient current in the case when cable and overhead power line is supplied from 500 kV Substation Zapadnaya under conditions of one-phase short-circuit at 500 kV Substation Ochakovo.

Components of transient current obtained from Fig.7 are presented in Fig. 8.

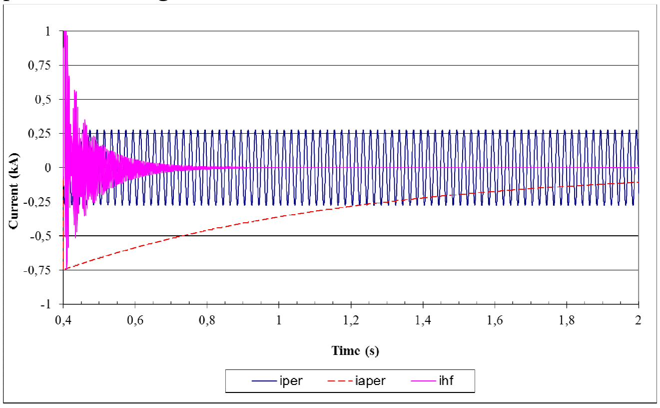


Fig. 8. Components of transient current through a circuit breaker in the case when cable and overhead power line is supplied from 500 kV Substation Zapadnaya under conditions of one-phase short-circuit at 500 kV Substation Ochakovo.

The aperiodic current component becomes equal to periodic current after only 0.8 seconds following making of a circuit breaker. Since making of a cable and overhead power line is realized with short circuit, then breaking will be after 0.04–0.08 s. Current does not pass through zero, thus arcing for a time more than 0.7s will result in damages of a circuit breaker.

High-frequency component of current ensures current zero crossing after CB making within only 0.04s. It is not enough for successful arc quenching by a circuit breaker because possible breaking time is not less than 0.06…0.08 seconds.

Therefore, it is shown that in the case when cable and overhead power line Ochakovo – Zapadnaya is supplied from 500 kV Substation Zapadnaya, transient processes with no current zero crossing for a long time are possible. During breaking operation, an arc will be burning in an arc-extinguishing chamber of a circuit breaker for a long time resulting in circuit breaker damages.

To suppress aperiodic components, resistors are connected into circuits of shunting reactors. Connection of resistor units is realized as shown in Fig. 9.

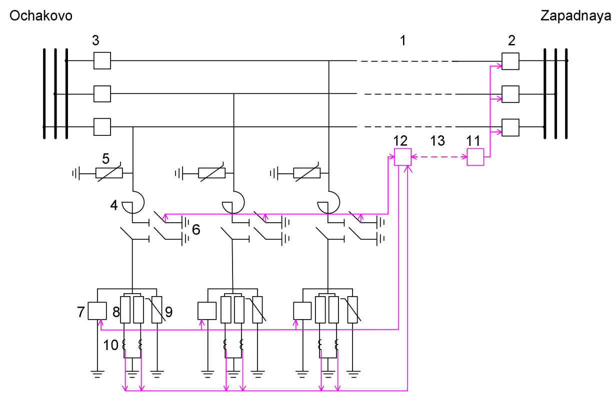


Fig.9. Connecting of resistor units into circuits of shunting reactors.
1 – Cable and overhead power line Ochakovo – Zapadnaya;
2 – line SF6 circuit breaker at 500 kV Substation Zapadnaya;
3 – line SF6 circuit breaker at 500 kV Substation Ochakovo;
4 – 500 kV shunting reactor;
5 – 500 kV arrester for protection of shunting reactors against overvoltages;
6 – disconnecting switch with earthing blades (with closed earthing blades, automation control device of a resistor unit blocks three-phase automatic reclosure);
7 – 35 kV vacuum circuit breaker;
8 – resistor unit with two parallel circuits;
9 – 35 kV arrester for protection of shunting reactor neutrals against overvoltages;
10 – 35 kV current transformers;
11 – relay protection at 500 kV Substation Zapadnaya;
12 – digital automation control of a resistor unit;
13 – communication line between 500 kV Substation Zapadnaya and 500 kV Substation Ochakovo.

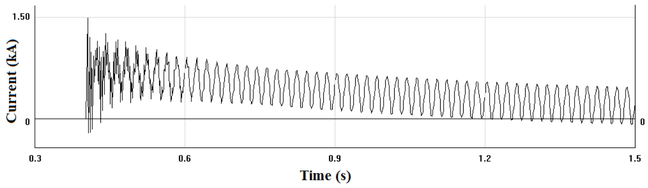
Let us set $U_{max.op.v.}$ as maximum operating voltage, U_N as neutral-to-ground voltage for a shunting reactor. Evaluation of required resistance for a resistor unit can be obtained from operating conditions of shunting reactors with connected resistance R_{res} in their neutrals:

$$R_{res} \le \frac{U_N / U_{max.op.v}}{\sqrt{1-(U_N / U_{max.op.v})^2}} \cdot X_r \cdot \quad (1)$$

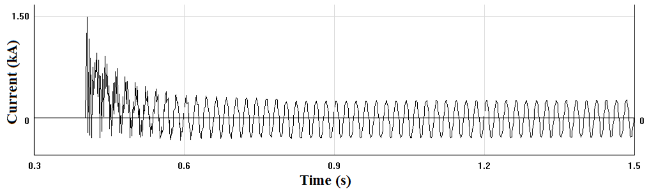
This relation shows possible values of resistances to be connected into neutrals of shunting reactors for suppression of aperiodic components.

For power transmission Ochakovo – Zapadnaya for given U_N=35 kV, $U_{max.op.v}$=550 kV, obtain: $R_{res} \leq 58.5$ Ohm.

Fig. 10b illustrates oscillogram of transient current at making of cable and overhead power line Ochakovo – Zapadnaya with the resistor unit R_{res} = 58.5 Ohm connected to neutrals of shunting reactors. Making time is 0.4s, released energy for a resistor unit is W = 3.6 MJ.



a)



b)

Fig.10. Simulated oscillograms of transient current at making of cable and overhead power line Ochakovo – Zapadnaya with shunting reactor without resistors (a) and with the resistor unit R_{res} = 58.5 Ohm connected to neutrals of shunting reactors (b).

Therefore, temporary introduction of resistances into the circuit of shunting reactors is shown to be an efficient method for solving the problem of aperiodic components in currents flowing through circuit-breakers.

V. CONCLUSIONS

1. Emergency conditions for line SF6 circuit-breakers occur when transient currents in unfaulted phases of an overhead power line are not interrupted by circuit breakers. It is caused by the fact that such currents do not cross zero for a long time because of the higher aperiodic components in comparison with periodic components

2. Probabilities of making in the moments of voltage zero and voltage maximum for air and SF6 circuit breakers are approximately the same. Making of a compensated overhead power line from one side causes transient currents in at least one phase with aperiodic components higher than periodic components with the probability of 0.58-0.75.

3. Transient currents with high content of aperiodic components are not usually interrupted by SF6 circuit breakers. To solve this problem, the following methods can be used:

- introduction of a time delay into breaking operation for unfaulted phases;
- the change of the number of shunting reactors connected to an overhead power line at making-breaking operation;
- controlling the moment of making (i.e. making phase); making of an overhead power line close to voltage maximum from the side of power supply;
- using of circuit breakers with preinsertion resistors;
- temporary introduction of resistors into the circuit of shunting reactors.

4. Each method of suppression of aperiodic components has advantages and disadvantages. The best methods for practical implementation are controlled switching devices and circuit breakers with preinsertion resistors. The most perspective and cheap method is temporary introduction of power resistors into the circuits of shunting reactors.

VI. REFERENCES

[1] Report ABB Power Technologies «Investigation of Breaker Failure when Disconnecting a Highly Compensated Line», № 1JNR100009-697 Rev. 01.

[2] I. Naumkin, M. Balabin, N. Lavrushenko, R. Naumkin, Simulation of the 500 kV SF6 circuit breaker cutoff process during the unsuccessful three-phase autoreclosing. IPST2011, Delft, The Netherlands, June 14-17, 2011.

[3] Kachesov V.E., Kachesov D.V. Requirements for Switching Algorithms of EHV Shunt Compensated OHL by SF6 Circuit Breakers. IPST2011, Delft, The Netherlands, June 14-17, 2011.

[4] I.Ye.Naumkin. Emergency failures of SF6 circuit breakers during the commutations of the compensated 500-1150kV transmission lines. (in Russian). Elektrichestvo, №10, 2012, p.22-32.

[5] I.Ye.Naumkin at al. Obespechenie rabotosposobnosti lineynykh elegazovykh vyklyuchateley pri otklyuchenii toka s bol’shoy aperiodicheskoy sostavlyayushchey: osnovnye pravila provedeniya raschyotov pri proektirovanii reaktirovannykh liniy elektroperedachi. (in Russian). Energoexpert, №3, 2012, p.60-67.

[6] Naumkin I., Balabin M., Lavrushenko N., Naumkin R. Multipurpose power system simulator: implementation based on modern principles. IPST2009, Kyoto, Japan June, 3-6, 2009.

[7] Patent № 123597RU I.Ye.Naumkin, V.N. Pod’yachev, L.I. Sarin Elektroperedacha sverkhvysokogo napryazheniya s vysokim urovnem kompensatsii zaryadnoy moshchnosti (in Russian).01.06.2012. Bul.№36, 2012.