METHODOLOGY FOR SELECTING MEASURES TO COMBAT APERIODIC CURRENTS ON LINES WITH SHUNT REACTORS

Mikhail Dmitriev, PhD
info@voltplace.com

In the previous issue of the journal, an article was published on the features of the operation of SF-6 switches when disconnecting currents of unloaded 330-750 kV lines with shunt reactors, the mechanism of occurrence of the aperiodic component of the current of line switches was explained, and the main ways of limiting it were given. In particular, readers' attention was drawn to the fact that controlled switching devices (Switch-sync etc.), due to the inaccuracy of their operation, do not always allow SF-6 switches to be protected.

A new publication on this topic gives readers the opportunity for each line with shunt reactors to independently assess the danger of aperiodic currents, as well as to check the effectiveness of controlled switching depending on the accuracy of its operation. The article shows that, unfortunately, with the available accuracy, the scope of application of controlled switching devices is insufficient for their widespread use, and other methods of protecting switches from aperiodic component will have to be used on a number of lines.

Keywords: transmission line, shunt reactor, reactive power, circuit breaker, switching of the line, aperiodic component of the current, controlled switching.

I. INTRODUCTION

In recent years, a series of damages of SF-6 gas switches of 500 kV voltage class have occurred at a number of switchgears [1]. Those switches were responsible for commutation of transmission lines (TL) with shunt reactors connected to them (diagram Fig.1), and were damaged during disconnecting process due to the presence of an aperiodic component of the line current. Let's call such switches as "line switches".

To reduce the danger of aperiodic component of the currents, we can offer [2]:

- energizing of transmission line (TL) with a reactor previously disconnected from the line, and connection of the reactor to the line with a delay of several seconds;
- equip line switches with pre-connected resistors (R);
- equip line switches with controlled switching technologies (switch-sync etc.).

According to [1,2] in the diagram Fig.1, the following components are present in the current of the transmission line switch (they are shown in Fig.2):

- the periodic component of the shunt reactor (SR) current having an amplitude of I_{SR};
- the aperiodic (A) component of the shunt reactor current, which has an initial maximum value of $I_{SR.A}$ and the attenuation time constant τ;
- the periodic component of the no-load (capacitive) current of the transmission line, which has an amplitude of I_{TL}.

The ratio of I_{SR} and I_{TL} corresponds to the K – degree of compensation of the capacitive conductivity of the line by the inductive conductivity of reactor (or reactors):

$$K = \frac{I_{SR}}{I_{TL}}$$

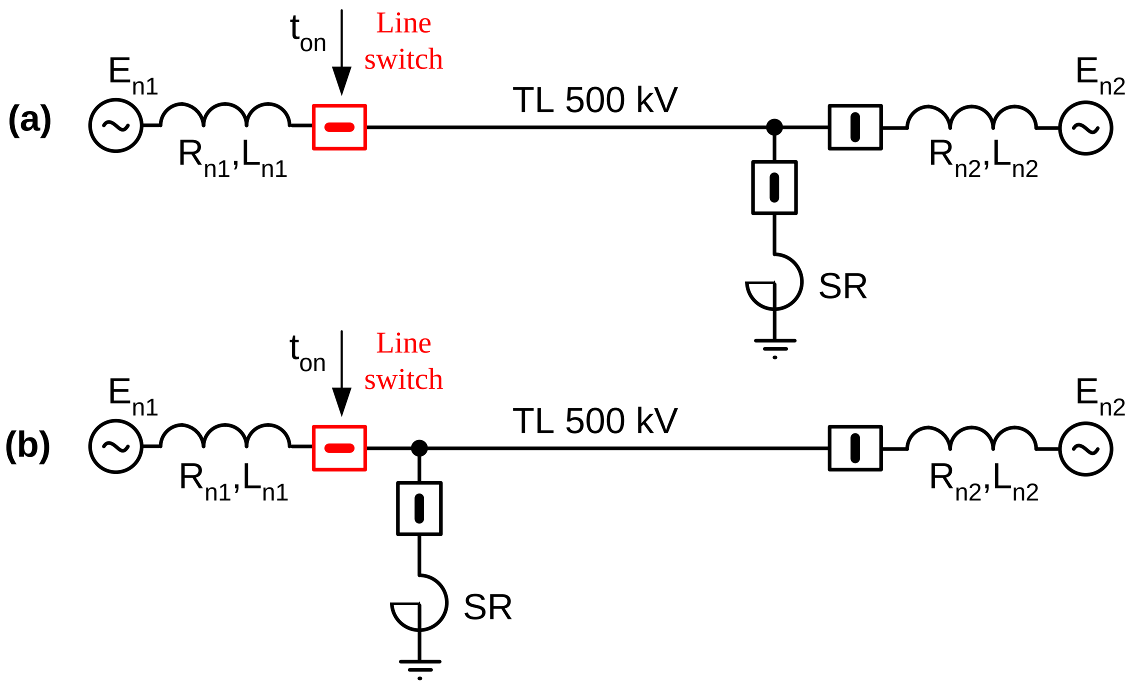

Fig.1. Energizing of the transmission line (TL) with shunt reactor (SR) on it:
(a) – the reactor is installed at the end of the line;
(b) – the reactor is installed at the beginning of the line.

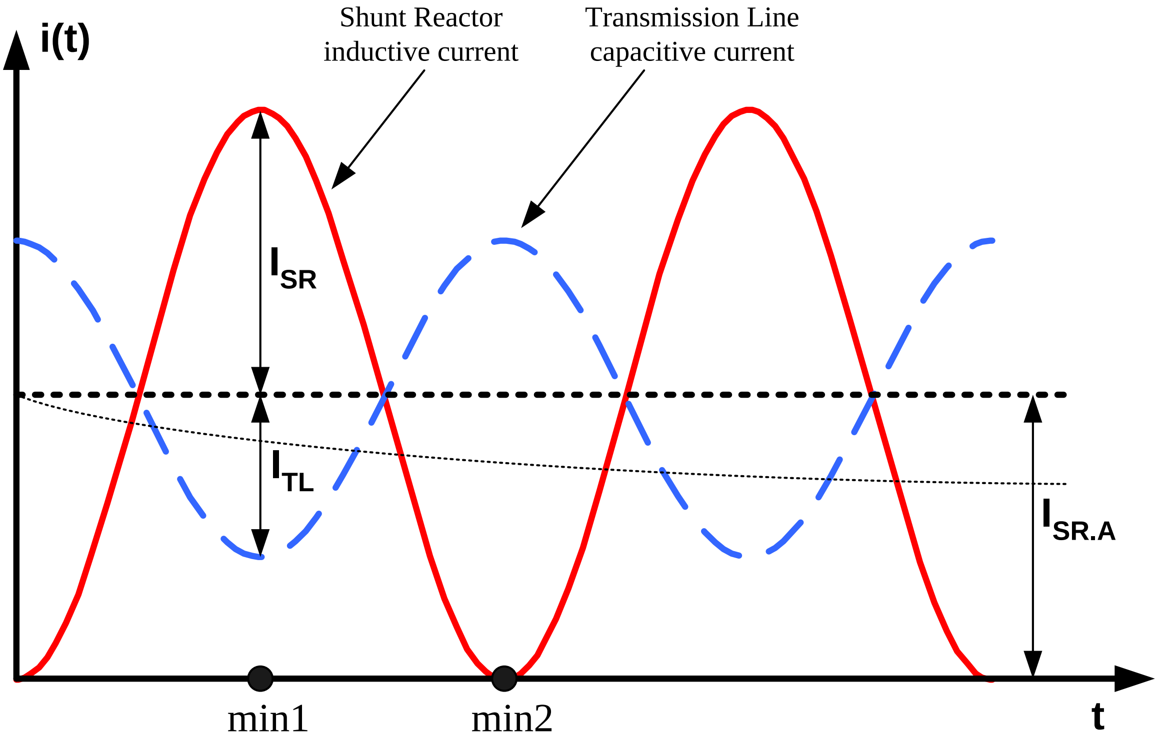

Fig.2. Components of the line switch current for the line with shunt reactor (reactors).

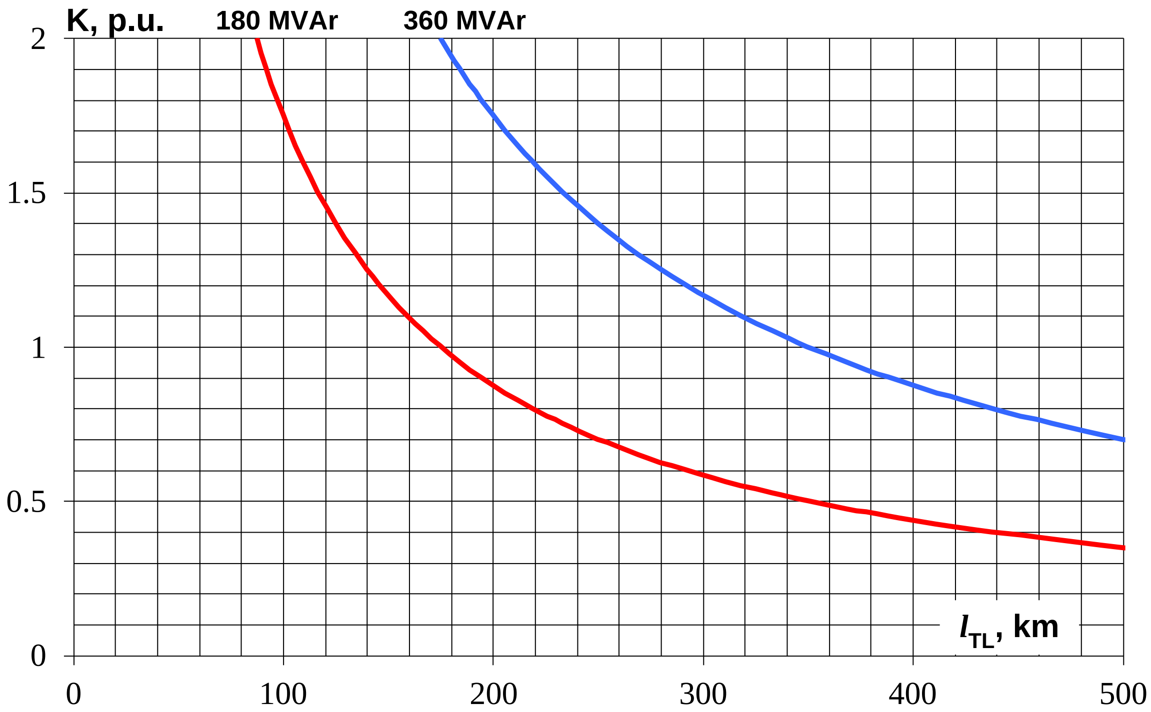

Fig.3. Compensation coefficient K depending on the length of the 500 kV transmission line (of the standard overhead design) and the total reactive power of the connected reactors.

For a typical 500 kV transmission line, the dependence of K on the length of the line and the number of shunt reactors (1x180 MVAr or 2x180=360 MVAr) is shown in Fig.3.

Let's assume in the diagram Fig.1 that the 50 Hz sine wave of the network voltage is described by the expression

$$e(t) = E_m \cdot cos(\omega t + \psi)$$

where E_m – is the amplitude of the phase value of the highest operating voltage of the network, ψ – is the initial phase of the EMF (at time $t_{on} = 0$), $\omega = 2\pi f = 314$ rad/s.

In steady state operation mode, the sine inductive current of shunt reactor (SR) and sine capacitive current of the transmission line (TL) are reactive against network voltage:

$$i_{SR}(t) = -I_{SR} \cdot sin(\omega t + \psi)$$

$$i_{TL}(t) = I_{TL} \cdot sin(\omega t + \psi)$$

In the transient process of switching on lines with connected reactors under network voltage, an aperiodic current component may generally appear in the reactor current (and the current of the line switch), the initial value of which will be $I_{SR.A} = I_{SR} \cdot sin\psi$. Its change in time, taking into account the attenuation, will be described by the expression

$$i_{SR.A}(t) = I_{SR.A} \cdot \exp(-t/\tau) = (I_{SR} \cdot sin\,\psi) \cdot \exp(-t/\tau)$$

At the moment $t_{on} = 0$ of switching of the line switch, the network voltage will be $e(0) = E_m \cdot cos\,\psi$, where ψ – is the angle (rad) at which switching occurs.

At $\psi = \pi/2$, we have $e(0) = 0$, i.e. the switching on of the line occurred at the zero value of the network voltage, and, consequently, the initial value of the aperiodic current of the reactor will be the largest, equal to the amplitude of the periodic component of the reactor current, that is $I_{SR.A} = I_{SR} \cdot \sin\psi = I_{SR}$.

When $\psi = 0$, we have $(0) = E_m$, i.e. the line was switched on at the maximum of the network voltage, and, consequently, there is no aperiodic current $I_{SR.A} = 0$.

To combat aperiodic currents, the controlled switching (CS) technologies are known. configured to turn on the line near the maximum of the sine network voltage $\psi = 0$. Taking into account the possible inaccuracy of the CS operation, the line is actually switched on not at $\psi = 0$, but with some error $\psi = \pm\Delta\psi$. In this case, the instantaneous value of the network voltage will be

$$e(0) = E_m \cdot cos\,\psi = E_m \cdot cos(\pm\Delta\psi)$$

The initial value of the aperiodic current, therefore

$$I_{SR.A} = I_{SR} \cdot sin(\pm\Delta\psi) = \pm I_{SR} \cdot sin\Delta\psi$$

the change in the aperiodic current in time

$$i_{SR.A}(t) = \pm(I_{SR} \cdot sin\Delta\psi) \cdot exp(-t/\tau)$$

II. LINE PROCESSES WITHOUT TAKING INTO ACCOUNT THE ATTENUATION OF THE APERIODIC COMPONENT OF THE CURRENT

Current arc damping is most likely at the moments of the minimum values of the total current of the line switch, which according to Fig.2 can be one of two moments:

$$I_{\min 1} = I_{SR.A} + I_{SR} - I_{TL}$$

$$I_{\min 2} = I_{SR.A} - I_{SR} + I_{TL}$$

At these moments, it is desirable that the total current of the switch changes sign. Since the aperiodic component in Fig.2 is assumed to be of positive polarity, the condition for successful operation of the switch can be considered $I_{\min 1} \le 0$ or $I_{\min 2} \le 0$, from where

$$I_{SR.A} + I_{SR} - I_{TL} \le 0$$

$$I_{SR.A} - I_{SR} + I_{TL} \le 0$$

Consider, for example, the first condition:

$$I_{SR.A} + I_{SR} - I_{TL} \le 0$$

$$I_{SR} \cdot \sin\Delta\psi + I_{SR} - \frac{I_{SR}}{K} \le 0$$

$$K \le \frac{1}{1 + \sin\Delta\psi}$$

Similarly, from the second condition we find

$$K \ge \frac{1}{1 - \sin\Delta\psi}$$

Since $0 \le K < \infty$, we finally have the following conditions

$$\begin{cases} 0 \le K \le \dfrac{1}{1 + \sin\Delta\psi} \\ \dfrac{1}{1 - \sin\Delta\psi} \le K < \infty \end{cases}$$

III. LINE PROCESSES WHEN TAKING INTO ACCOUNT THE ATTENUATION OF THE APERIODIC COMPONENT OF THE CURRENT

If, after energizing the line with reactors under network voltage, it becomes necessary to turn it off, and the time interval between switching on the line (t_{on}) and attempting to extinguish the arc is ΔT_{on}, then when deriving the conditions for extinguishing the arc, it is necessary to use a non-initial value of the aperiodic component $I_{SR.A}$, but the value taking into account the attenuation of the aperiodic component – that is $I_{SR.A} \cdot exp(-\Delta T_{on}/\tau)$. Then the conditions found earlier can be adjusted to the form

$$\begin{cases} 0 \le K \le \dfrac{1}{1 + \exp(-\Delta T_{on}/\tau) \cdot \sin\Delta\psi} \\ \dfrac{1}{1 - \exp(-\Delta T_{on}/\tau) \cdot \sin\Delta\psi} \le K < \infty \end{cases}$$

The active resistance of the winding of a 500 kV reactor (uncontrolled or controlled), is about $R = 4\ \Omega$, and the inductive resistance under rated load is $X = 1530\ \Omega$. The shunt reactor (SR) time constant can be estimated as $\tau_{SR} = L/R = X/(\omega R) \approx 1.2$ sec. The circuit in which the aperiodic current of the reactor passes includes not only the reactor itself, but also the transmission line (if the shunt reactor is installed at its end, Fig.1(a)), as well as the equivalent of the network (R_{n1}, L_{n1}). As a result of their consideration, the time constant τ of the attenuation of the aperiodic current will be less than that for the reactor $\tau < \tau_{SR}$. For certainty, let's put $\tau = 0.8$ sec (typical for the case when the shunt reactor is installed at the beginning of the line, diagram Fig.1(b)).

The minimum time interval between switching on the line (t_{on}) and turning it off (the end of exposure to the arc, that is, the last possibility of its successful extinguishing of the arc) is about $\Delta T_{on} = 0.08$ sec, as shown in [2].

Considering the above, the attenuation of the aperiodic current in time 80 ms can be estimated as $\exp(-\Delta T_{on}/\tau) \approx 0.9$ (corresponds to the most unfavorable case of reactor installation at the beginning of the line), and, therefore, the conditions found earlier will be

$$\begin{cases} 0 \le K \le \dfrac{1}{1 + 0.9 \cdot \sin\Delta\psi} \\ \dfrac{1}{1 - 0.9 \cdot \sin\Delta\psi} \le K < \infty \end{cases}$$

When installing the reactor at the end of the line, the attenuation of the aperiodic currents will be stronger, which means that the area of dangerous values K will be smaller.

These conditions can be used to construct the dependence $\Delta\psi = f(K)$ (see Fig.4) of the required accuracy of controlled switching as a function of the compensation coefficient of the charging power of the line. This dependence will allow us to determine the scope of application of controlled line switching devices, taking into account the currently available accuracy of their operation – at which K controlled switching will solve the problem of aperiodic currents in the line switch, and at which K the action of controlled switching will not be enough to combat aperiodic currents.

The accuracy of controlled switching is usually indicated not in radians, but in milliseconds. Then, before using the conditions, you should recalculate from milliseconds to radians using the following formula

$$\Delta\psi = \Delta\psi_{ms} \cdot \frac{\pi}{10ms}$$

Currently, manufacturers of controlled switching (CS) devices claim an accuracy of $\Delta\psi_{ms} = 2$ ms, much less frequently $\Delta\psi_{ms} = 1$ ms. Therefore, in the case of using the CS, we will focus on the accuracy $\Delta\psi_{ms} = 2$ ms. The case of the absence of controlled switching corresponds to the "accuracy" $\Delta\psi_{ms} = 5$ ms.

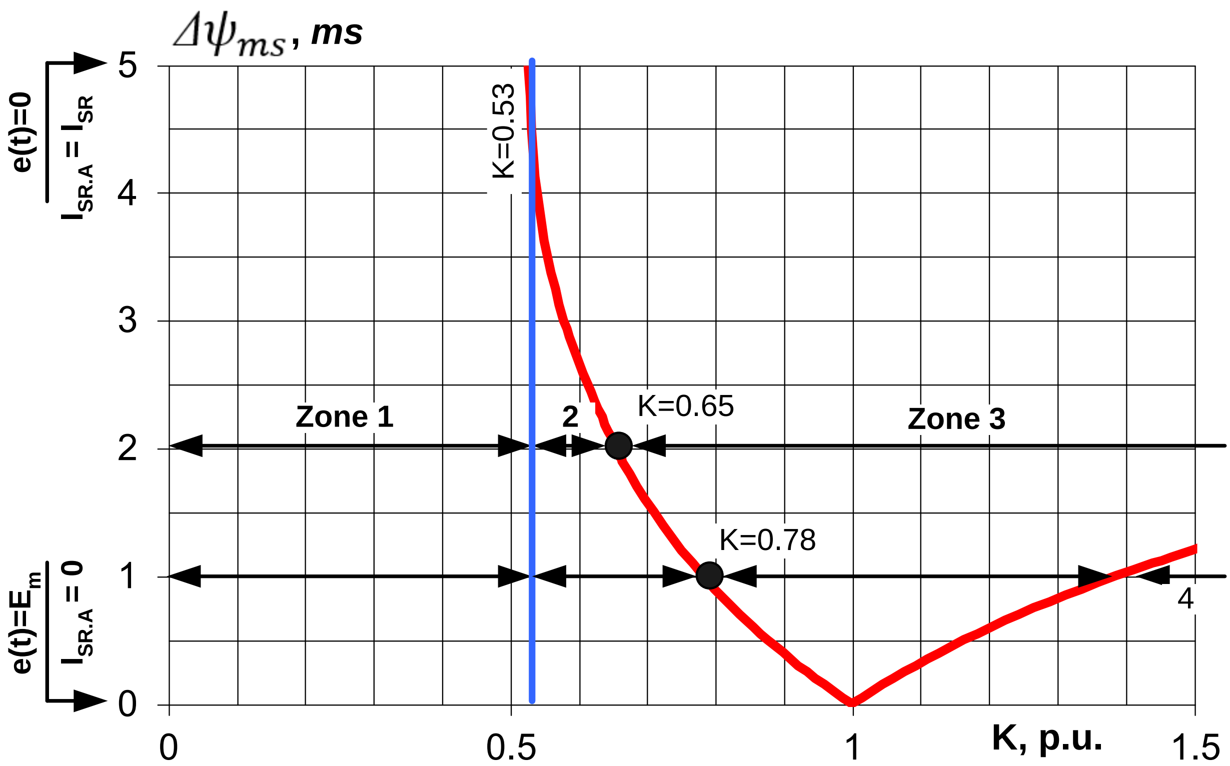

Fig.4. Scope of application of various measures to combat aperiodic currents in the case when the reactor is installed at the beginning of the line (scheme Fig.1(b)).

In Figure 4, four characteristic zones (1,2,3,4) can be distinguished.

Zone 1. At $0 \le K \le 0.53$, aperiodic currents do not pose a danger at any $\Delta\psi_{ms}$, that is, regardless of the moment when the line is switched on under network voltage. Measures to combat aperiodic currents are not required.

Zone 2. At $K > 0.53$, the conditions found earlier are not fulfilled, that is, there is a danger of arc extinguishing failure, and control measures are needed. If controlled switching is considered as such measures, then the effect of its use significantly depends on the accuracy $\Delta\psi_{ms}$ of its operation:

– at $\Delta\psi_{ms} = 2$ ms, controlled switching is advisable to use in a very narrow range of $0.53 < K \le 0.65$ (in case of $K > 0.65$, accuracy is no longer sufficient);
– at $\Delta\psi_{ms} = 1$ ms, the range is slightly wider than $0.53 < K \le 0.78$ (in case of $K > 0.78$, accuracy is no longer sufficient).

Zone 3. For any value of $\Delta\psi_{ms}$ (except for the unattainable in practice $\Delta\psi_{ms} = 0$), the accuracy of controlled switching is obviously not enough, and therefore its use is useless. It requires the use of pre-connected resistors or reducing number of reactors on the line.

Zone 4. On the overwhelming number of lines, $K \leq 0.8$ occurs, the values of $K \leq 1.5$ are already extremely rare – it was $K = 1.5$ that was chosen as the largest for Fig.4. It can be seen that for $1 < K \leq 1.5$, controlled switching at $\Delta\psi_{ms} = 2$ ms (and even at $\Delta\psi_{ms} = 1$ ms) cannot solve the problem of aperiodic currents.

IV. CONCLUSIONS

The article provides a simplified method for choosing the optimal means of protecting a line switch (line circuit breaker) from aperiodic currents. This technique complements the general conclusions on the problem of aperiodic currents made in [2].

Using the example of a typical 500 kV line with conventional uncontrolled reactors, the following preliminary recommendations on the choice of methods for dealing with aperiodic currents are obtained in the article:

- at $0 \leq K \leq 0.53$, no measures are required (aperiodic currents are not dangerous);
- at $0.53 < \boldsymbol{K} \leq \mathbf{0.65}$, measures are required, as which controlled switching can be used with an accuracy not worse than $\boldsymbol{\Delta\psi_{ms}} = \mathbf{2}$ **ms;**
- at $0.53 < \boldsymbol{K} \leq \mathbf{0.78}$, measures are required, as which controlled switching can be used with an accuracy not worse than $\boldsymbol{\Delta\psi_{ms}} = \mathbf{1}$ **ms**;
- at $K > 0.65$ ($K > 0.78$), controlled switching is useless; either pre-connected resistors with parameters [2] or line switching without a dangerous number of shunt reactors are required as measures.

The conclusions were obtained in the case of installing a shunt reactor at the beginning of a switched line. In the case of installation of the reactor(s) at the end of the line (Fig.1(a)), the area of effective operation of controlled switching will be little bit wider.

The possibilities of EMTP-computer modeling allow us to calculate the transients of switching on each specific line, taking into account its features, the number and locations of reactors, and the parameters of systems adjacent to the line. Such detailed calculations, together with the application of the simplified methodology presented in the article, will allow you to have more confidence in the optimality of the technical solutions used on lines.

REFERENCES

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