REQUIREMENTS FOR COMPENSATION OF 500-750 KV OVERHEAD LINE CHARGING POWER

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Currently, there are a certain number of overhead transmission lines (OHL) of 500-750 kV classes in the networks, in which the charging capacity is almost 100% compensated using linear shunt reactors (SR) connected to overhead lines.

According to previous articles, this leads to a number of serious problems that could have been avoided if linear SR provided compensation for no more than 60-70% of the charging power, and the rest of SR were placed on the busbars of switchgear.

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

I. INTRODUCTION

Paragraph 5.37 of the Methodological Recommendations [1] states that *"The power, number and location of shunt reactors are specified when designing specific power transmission lines. In the absence of data, the degree of compensation of the charging capacity of the lines should be taken at least 80-100% – for 500 kV, 100-110% – for 750 kV overhead lines ..."*. As can be seen, in [1] 100% compensation is recommended as a starting point, but the optimal places for installing reactors – on busbars or directly on the line – should be clarified based on the results of calculations of network modes. After reading [1], it seems that it is better to design a network with 100% compensation of the charging power of the line by the inductance of linear SRs.

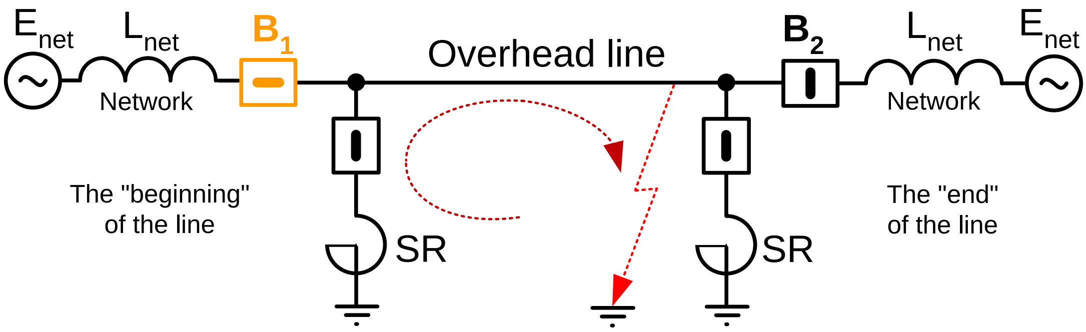

Fig.1. Overhead transmission line with linear shunt reactors at the beginning and end of the line.

It is shown in [2,3] that overhead lines with close to 100% compensation of charging power have significant disadvantages:

- the possibility of damage to overhead line circuit breakers (B1 or B2) by aperiodic currents;
- the possibility of resonant overvoltages on the disconnected phase of the overhead line in some non-three-phase modes (like single-phase automatic reclosure AR of the line).

In [2], to limit the aperiodic currents, it is proposed:

- equipping overhead line breakers with controlled switching devices (CS) that are configured to turn on overhead lines near the amplitude of the network sinusoidal 50 Hz voltage;
- equipping overhead line breakers with pre-connected resistors (R);
- refusal to switch overhead lines with a dangerous number of connected shunt reactors (SR).

In [3], to limit overvoltages, it is proposed:
– grounding of the SR neutral through a special "neutral" reactor;
– refusal to switch overhead lines with a dangerous number of connected shunt reactors (SR).

Equipping power lines with resistors, controlled switching devices, and "neutral" reactors increases their cost and complicates operation. However, another thing is even worse: the named equipment is simply ineffective if it is used on lines with a charging capacity compensation close to 80-120% (there are quite a lot of such lines in countries of former USSR and around the World, and their number is growing). The rejection of overhead line switching with a dangerous number of SR, as will be shown below, is also not a panacea.

The solution to the problem could be a change in the technical policy for the placement of SR in 500-750 kV networks. Where this does not cause a dangerous 50 Hz voltage increase at the open end of one-side energized line (no-load operational mode), the reactors should be removed from the line to the busbars of switchgears.

In other words, one should not strive for 100% compensation of the overhead line charging power by the inductance of linear SR, but should prefer compensation, say, by no more than 60-70%. For example, this degree is indicated on page 203 of the well-known handbook [4]: *"... to ensure acceptable voltages in low-load modes in 110-220 kV networks of power systems adjacent to long-range power substations, and along the power transmission itself, it is necessary to install shunt reactors compensating 60-80% of the charging capacity of the 330-750 kV line ..."*.

Let's look at these issues in more detail.

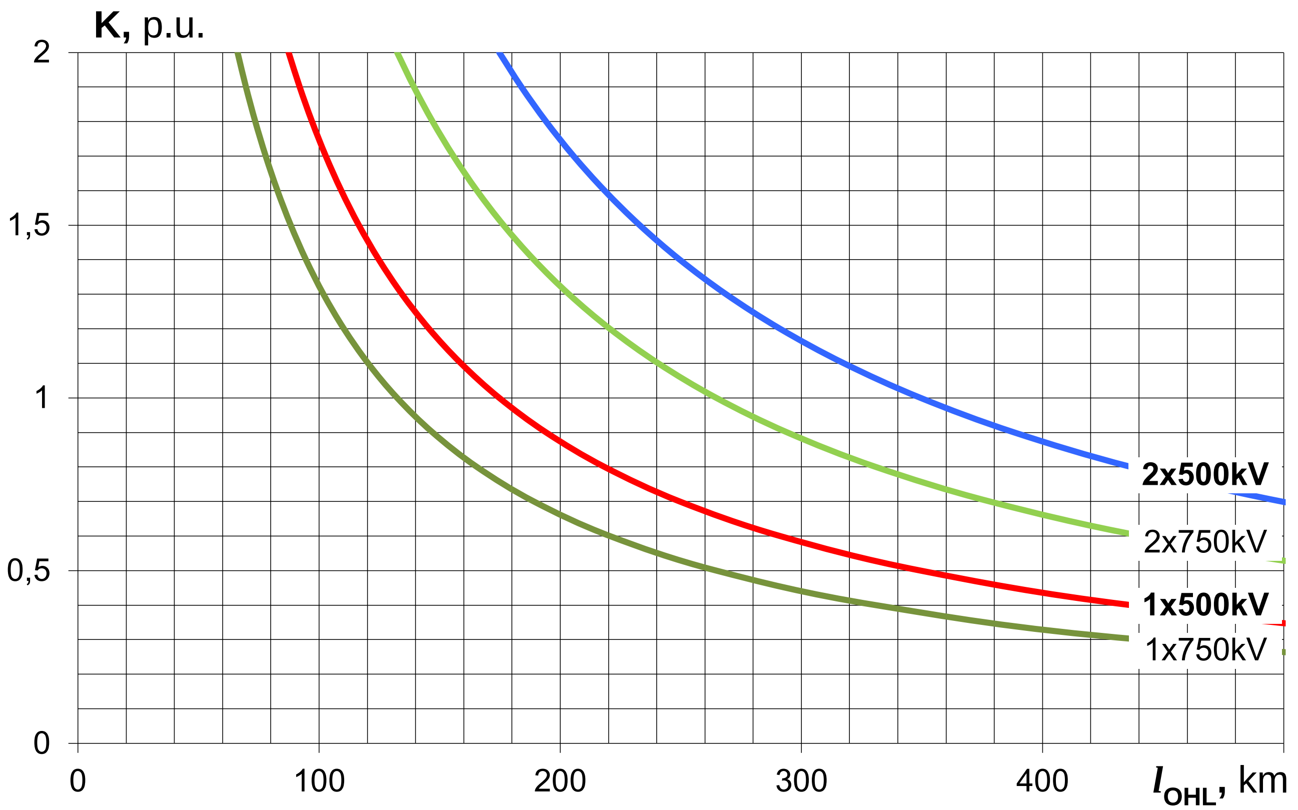

Fig.2. Compensation coefficient K depending on the length of the overhead line (500 kV, 750 kV) of the standard design and the total number (one, two) of connected shunt reactors:
– each reactor power is 180 MVAr for 500 kV;
– each reactor power is 330 MVAr for 750 kV.

II. LINE CHARGING POWER COMPENSATION

For power transmission lines equipped with SR (scheme Fig.1), an important characteristic is the compensation coefficient of the charging power of the line:

$$K = \frac{b_{SR.eqv}}{b_1} \tag{1}$$

where b_1 – is the capacitive conductivity of the line in a positive sequence;
$b_{SR.eqv} = 1/X_{SR.eqv}$ – equivalent inductive conductivity of all N reactors connected to the line,
$X_{SR.eqv} = X_{SR}/N$ – equivalent inductive impedance of reactors,
$X_{SR} = {U_{SR}}^2/Q_{SR}$ – the inductive impedance of one reactor, determined through its three-phase reactive power Q_{SR} and its highest operating voltage U_{SR} (525, 787 kV).

For a 500-750 kV overhead line of a typical design, the dependences K on the length of the line, the number and power of the reactors are shown in Fig.2. For example, 100% compensation of charging power ($K = 1$) for lines with one shunt reactor is achieved for the length:

– 175 km in case of a 500 kV overhead line with a 180 MVAr reactor;
– 130 km in case of a 750 kV overhead line with a 330 MVAr reactor.

III. CONTROLLED SWITCHING AND RESISTORS

Circuit breakers with controlled switching

The efficiency of equipping the overhead line breaker with controlled switching devices depends significantly on the accuracy of their operation. To solve the problem of aperiodic currents, overhead line switching (closing of the breaker contacts or breakdown of the gap between closing contacts) must occur at a time close to the amplitude of the 50 Hz sinusoidal voltage of the network. The possible deviation $\Delta\psi$ of the switching moment from the voltage amplitude is the main reason why the scope of the CS is limited.

In [2], the following expressions were obtained describing the range of OHL compensation coefficients at which the CS can be applied (Fig.3):

$$\begin{cases} 0 \le K \le \dfrac{1}{1 + 0.95 \cdot \sin\Delta\psi} \\ \dfrac{1}{1 - 0.95 \cdot \sin\Delta\psi} \le K < \infty \end{cases} \tag{2}$$

where the coefficient 0.95 takes into account the attenuation of the aperiodic current.

Based on the typical accuracy $\Delta\psi = 2$ ms of the CS devices currently offered on the market, according to Fig.3, we obtain that in a wide range of coefficients $0.65 < K < 2.25$, the use of CS is ineffective.

In other words, on 500-750 kV lines with close to 100% compensation of charging power, breakers with controlled switching devices will not be able to solve the problem of aperiodic currents.

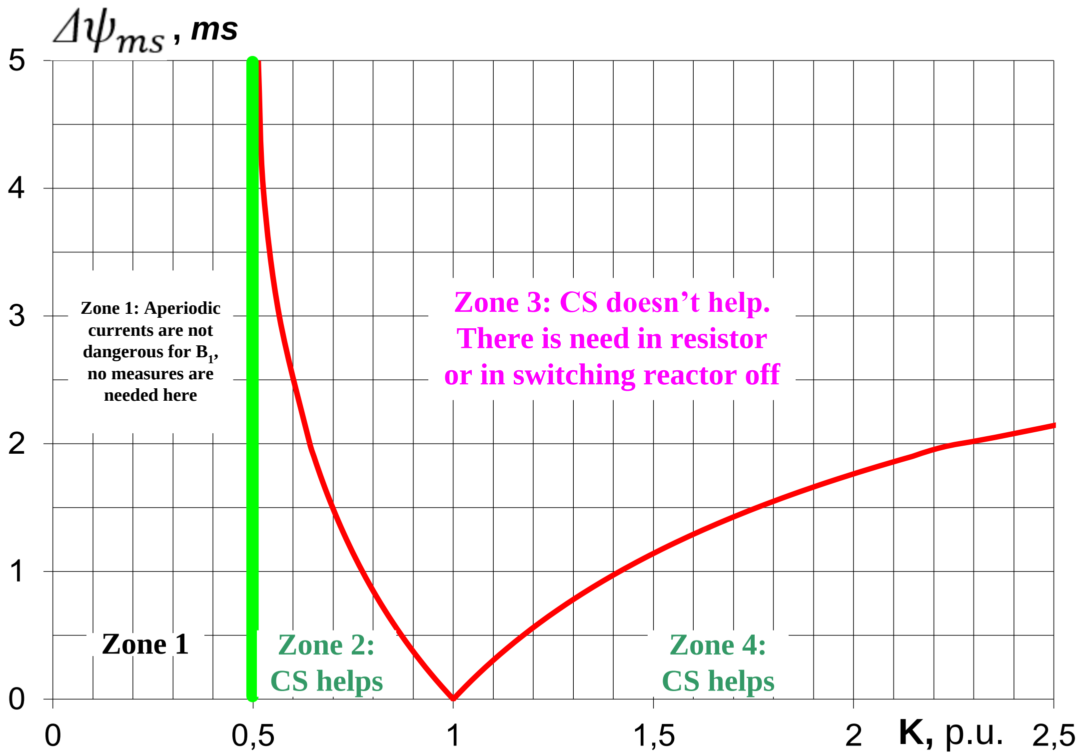

Fig.3. Requirements to the accuracy $\Delta\psi$ of controlled switching depending on the compensation coefficient K of the charging power of typical 500-750 kV overhead lines.

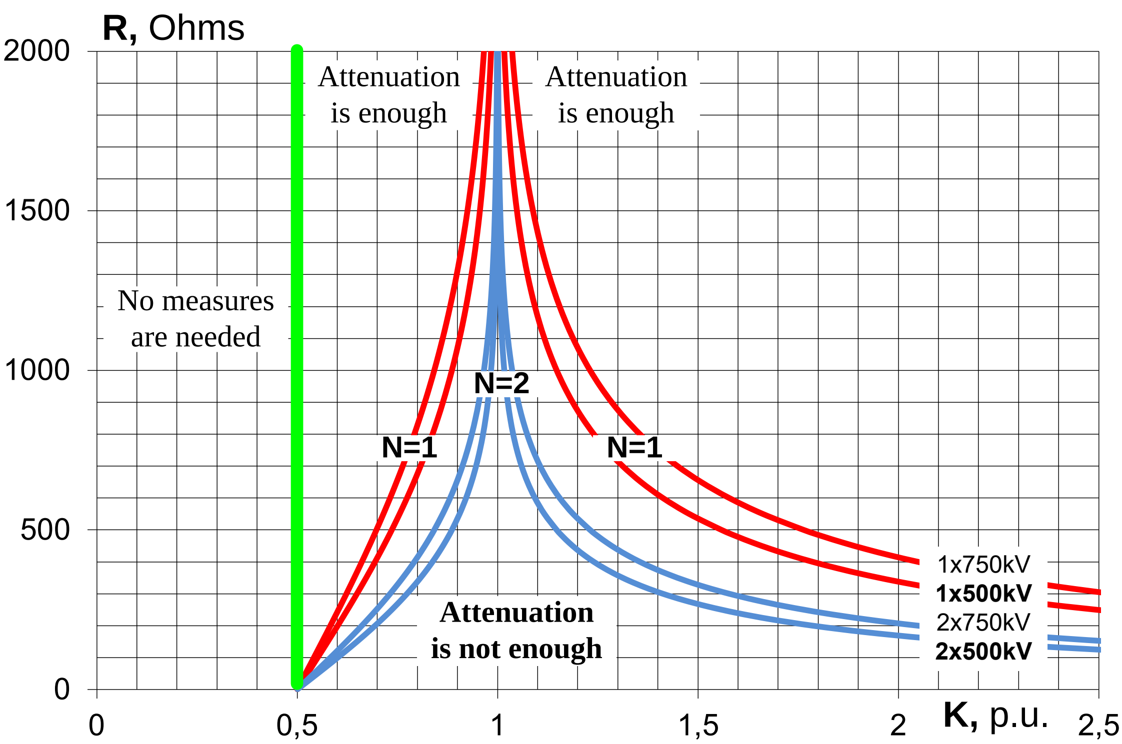

Fig.4. Requirements to the impedance of the pre-connected resistor depending on the compensation coefficient K of the charging power of typical 500-750 kV overhead line.

Circuit breakers with pre-connected resistors

Some experts suggest equipping linear circuit breakers with pre-connected resistors. In this case, the impedance of the resistor should be such that during its operation $\Delta T_R = 0.01$ sec, the aperiodic component fades [2].

The time constant of the "resistor-reactors" circuit can be found as

$$\tau_R = \frac{L_{SR.eqv}}{R}$$

where $L_{SR.eqv} = X_{SR.eqv}/\omega$ – is the equivalent inductance of all N line reactors;
$\omega = 314$ rad/s – is circular frequency.

To select the impedance of the resistor, you can use the formulas (2), where you need to substitute:

– the attenuation coefficient $\exp(-\Delta T_R/\tau_R)$ instead of 0.95;
– the error $\Delta\psi = 5$ ms, which, in fact, corresponds to the case of the absence of CS devices, i.e. $\sin\Delta\psi = 1$:

$$\begin{cases} 0 \le K \le \dfrac{1}{1 + \exp(-\Delta T_R/\tau_R)} \\ \dfrac{1}{1 - \exp(-\Delta T_R/\tau_R)} \le K < \infty \end{cases} \qquad (3)$$

These conditions can be used to find the dependence $R = f(K)$ of the required impedance of the resistor on the compensation coefficient K of the line charging power (Fig.4). For 500 kV and 750 kV overhead lines, the dependences differ little from each other due to the proximity of the inductive impedances of typical reactors:

– for 500 kV the reactor has 180 MVAr (it gives $X_{SR} = 1531$ Ω);
– for 750 kV the reactor has 330 MVAr (it gives $X_{SR} = 1877$ Ω).

In the area of compensation coefficients $K \approx 1$, it is inconvenient to determine the specific resistance value of a resistor using Fig.4. In such cases, it should be searched for differently: the complete attenuation of the aperiodic component occurs during $3\tau_R$ and should be no more than the time it is in operation ΔT_R (see [2]).

When operating line breakers (B1 and B2 on scheme Fig.1) equipped with pre-connected resistors, an aperiodic current can occur twice: when voltage is applied to the line through a resistor and when the resistor is shunted. Both components can be dangerous for the SF6 circuit breaker if, after switching on, it has to perform switching off.

If the resistor has an impedance of more than $R = 500$ Ω, then its shunting, as a rule, causes an intensive transient process and the appearance of a new aperiodic component. In other words, resistors with an impedance of more than 500 Ω are meaningless to deal with currents.

Using Fig.4, based on the limit value of 500 Ω, the following limits of inefficient operation of 500 kV breakers with resistors can be obtained:

– for 500 kV lines with one reactor $0.75 < K < 1.55$;
– for 500 kV lines with two reactors $0.9 < K < 1.15$.

For 750 kV switches, calculations give a slightly wider range:

– for 750 kV lines with a single reactor $0.7 < K < 1.8$;
– for 750 kV lines with two reactors $0.85 < K < 1.2$.

It can be seen that on 500-750 kV lines with charging power compensation close to 100%, switches with pre-connected resistors will not be able to solve the problem of aperiodic currents.

IV. "NEUTRAL" REACTORS

To limit resonant overvoltages in some non-three-phase overhead line modes (for example, with single-phase automatic reclosure, AR), reactors installed in the neutral of the SR [3,5] can be used. However, the main purpose of such reactors has always been not to combat overvoltages, but, during the AR pause, to reduce the feeding current (current that feeds arc on the disconnected phase of the line), on the magnitude of which the arc quenching and the success of the AR depends.

As experience has shown, for a number of reasons, "neutral" reactors did not take root in the networks: they were not in use or completely removed even on those lines where they were intended to fulfill their main purpose – compensation of the electrostatic component of the feeding current during the AR pause.

Based on the formulas [3], it is possible to find the multiplicity K_U of voltage increase U at the disconnected phase of the line (relative to the value of the network 50 Hz voltage E_{net}), which will be established at the AR after extinguishing the arc of the feeding current:

$$K_U = \left|\frac{U}{E_{net}}\right| = \left|\frac{\frac{X_N}{X_P+3X_N} - \frac{1}{n\cdot K}}{\frac{X_P+2X_N}{X_P+3X_N} - \frac{1}{m\cdot K}}\right| \qquad (4)$$

where X_N – is the inductive impedance of reactors that are installed in the neutral of linear reactors ($X_N = 0$ is the absence of a neutral reactor);
$n = b_1/b_M$ and $m = b_1/(b_1 - b_M)$ – are coefficients that depend on the design of the line;
b_1 – is the capacitive conductivity of the line in a positive sequence;
b_M – is the mutual (between phases) capacitive conductivity of the line.

Fig.5 shows the multiplicity K_U calculations according to the formula (4) for typical lines:
- of 500 kV voltage class ($n \approx 11.5$ and $m \approx 1.1$ are accepted);
- of 750 kV voltage class ($n \approx 10.4$ and $m \approx 1.1$ are accepted).

It follows from Fig.5 that for a 500-750 kV overhead line with close to 100% compensation and a neutral reactor in SR neutral, the steady-state voltage on the disconnected phase of the line at AR will be higher than 0.5 of the network voltage (that is $K_U > 0.5$ p.u.), which is big enough to cause repeated breakdowns in the place where the feeding arc has gone out. It means that chances to have successful AR are reduced in this case.

In fact, after extinguishing the arc of the feeding current, the voltage is restored in beats [5] and its maximum value in the transient process turns out to be noticeably higher than the steady state, which is shown in Fig.5. Such a voltage can not only cause repeated breakdowns in the place where the arc went out, but also damage the equipment of the line (if repeated breakdowns are not have arisen). In other words, neutral reactors in SR neutral for overhead lines with close to 100% reactive power compensation would be ineffective if they were used to limit resonant overvoltages in some non-three-phase overhead line modes (like single-phase AR).

V. DISCONNECTION OF THE LINEAR SHUNT REACTOR

To reduce line breaker aperiodic currents, controlled switching and pre-connected resistors are ineffective for overhead lines with 80-120% compensation. In addition, of course, they do not solve the problem of overvoltage in non-three-phase modes. The only universal solution for all overhead lines to combat both aperiodic currents and resonance overvoltages is, at first glance, the rejection of overhead line switching with a dangerous number of reactors. However, switching of 500-750 kV lines with a pre-disconnected reactor has a number of features and disadvantages.

Firstly, switching a 500-750 kV line with a pre-disconnected SR partially makes it pointless to install it on the overhead line, because the main purpose of a linear SR is to limit 50 Hz voltage increases on the end of the line (and to help surge arresterts in limiting switching overvoltages). In addition, frequent switching of reactors (much more often than required by operating conditions) reduces the life of reactor breakers and is undesirable for SR paper-oil insulation.

Secondly, in some cases there is a risk of damage of the SR breakers by aperiodic currents. Let's give an example.

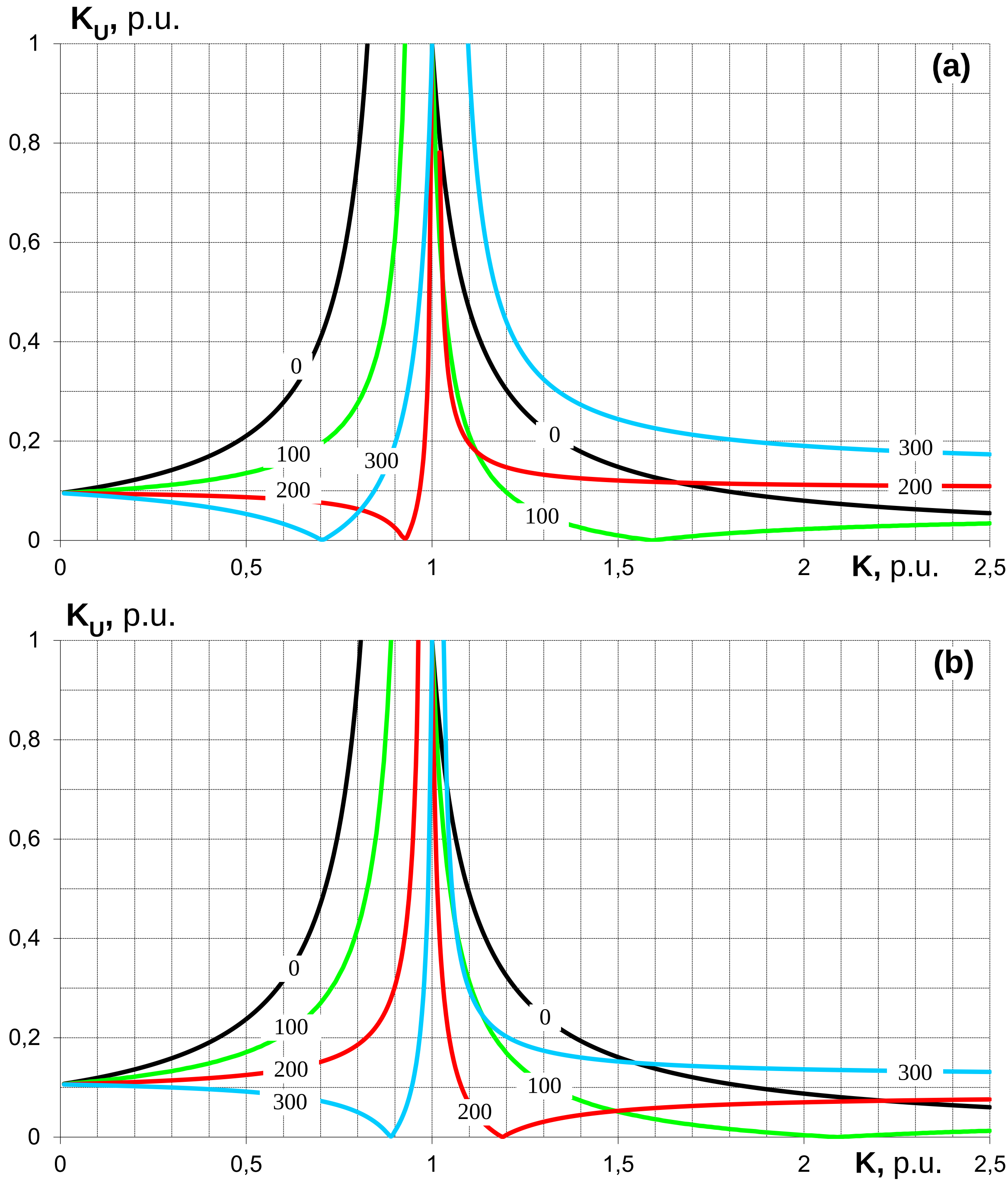

Fig.5. The multiplicity K_U of the steady-state 50 Hz voltage increase at the disconnected phase of the overhead line during no-current pause of the single-phase automatic reclosure, depending on the inductive impedance X_N of the neutral reactor (0, 100, 200, 300 Ω):
(a) – for 500 kV line;
(b) – for 750 kV line.

Let the normal operation mode take place in the scheme in Fig.1, but a single-phase short-circuit occurred on the line. If a short-circuit occurs near the zero value of the network sine voltage, then an aperiodic component appears in the short-circuit current (Fig.6a) and in the reactor current (Fig.6b). In this case, the periodic component of the current in the overhead line breaker, flowing under the action of network voltage, is present (Fig.6a), whereas in the current of the breaker of the SR phase, the same with the damaged phase of the line, it is absent (Fig.6b). Moreover, there is no compensation coefficient K regardless of the length of the overhead line, since the reactor phase turned out to be shunted by the short-circuit location (network voltage and line capacity no longer affect the reactor current).

The resulting single-phase short-circuit will trigger the automatic reclosure (AR) cycle, the breakers at the ends of the overhead line will turn off the emergency phase. However, if for this overhead line the project provides shutdown of the SR for the time of the AR, then the breaker of the SR will have difficulties, since an aperiodic current passes through it, which closes along the contour "line – place of the short circuit – ground – SR" (see Fig.1), and the periodic component of the current is completely absent (Fig.6b). With a high probability, the SR circuit breaker will be damaged by analogy with the breakers at the ends of the overhead line [2].

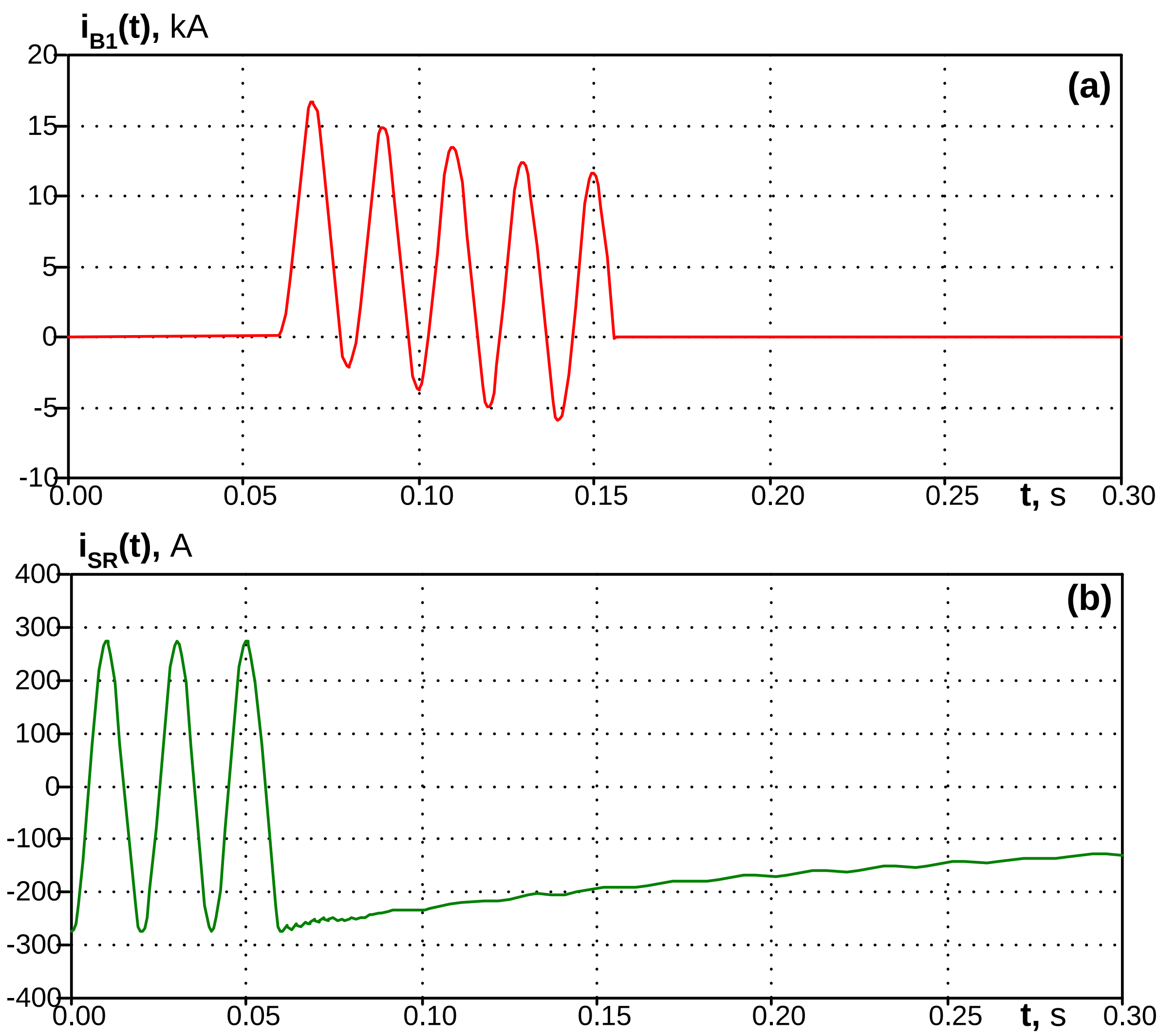

Fig.6. The phase currents in case of a short-circuit on the overhead line in the scheme Fig.1:
(a) – current of the breaker of the line;
(b) – current of the breaker of the reactor.

Transfer of linear reactors from the line to busbars

If reactors installed on overhead lines and providing close to 100% compensation cause such serious problems, the only universal solution of which is to turn off one reactor for the duration of overhead line switching (and even with the risk of damage to the reactor breaker), then the question arises: is it necessary to strive for 100% compensation of overhead line charging power by linear shunt reactors or is it advisable to connect some of these reactors not to the line, but to the busbars of switchgear?

In 500-750 kV networks, the main purposes of the SR are:

- ensuring acceptable 50 Hz voltages in low-load modes (for example, limiting the 50 Hz voltage at the open end of one-side energized overhead line);
- ensuring the balance of reactive power.

The placement of reactors on the line (instead of busbars) is necessary first of all to ensure an acceptable 50 Hz voltage level on the overhead line in its one-side power supply modes [1,6].

If this voltage does not pose a danger to the equipment (for example, due to the short length of the line), then the main purpose of the reactors is the balance of reactive power, and any SR – both linear and busbar – are suitable for performing such functions. However, as it has been shown, connecting shunt reactors to switchgear busbars is preferable, since this will reduce the degree of compensation of the overhead line charging power by the inductance of linear reactors, and relieve overhead lines from problems with aperiodic currents and overvoltages in non-three-phase modes.

According to paragraph 5.37 of the Recommendations [1], the choice of reactor installation sites should be based on calculations of voltage modes. In order to determine the possibility of placing reactors not on a 500-750 kV line, but on switchgear busbars, we will perform calculations of the 50 Hz voltage in the most unfavorable case – with its one-side energizing from a low-power network (network with increased internal inductive impedance X_{net}).

VI. CALCULATION OF THE 50 Hz VOLTAGE ON THE OPEN END OF THE ONE-SIDE ENERGIZED OVERHEAD LINE

The calculated case for checking the effects on the equipment and making a decision on the need to have a reactor at the end of the overhead line is the case of overhead line which is one-side energized from the network (for the time of synchronization after which another breaker turns on).

The multiplicity of voltage increases at the end of a one-side energized overhead line can be defined [6] as:

$$K_U = \left|\frac{U}{E_{net}}\right| = \frac{sin(\alpha_{SR}) \cdot cos(\alpha_{net})}{sin(\lambda + \alpha_{SR} + \alpha_{net})} \quad (5)$$

where E_{net} – is the phase value of the network voltage;

$\lambda = 1.047 \cdot 10^{-3} \cdot l_{OHL}$ – the wave length of the overhead line in a positive sequence (in radians);

l_{OHL} – is the length of the line (km);

Z_w – is the surge impedance of the line in a positive sequence (can be taken 280 Ω for 500 kV line, 260 Ω for 750 kV line), used to determine angles (in radians):

$$\alpha_{net} = arctg(X_{net}/Z_w)$$
$$\alpha_{SR} = arctg(X_{SR.end}/Z_w)$$

where X_{net} – is the equivalent inductive impedance of the system (at 50 Hz) in a positive sequence;

$X_{SR.end} = X_{SR}/N_{end}$ – equivalent inductive impedance (at 50 Hz) of all N_{end} shunt reactors connected at the end of the overhead line (scheme Fig.1).

The greatest overvoltages in (5) are obtained with an increased inductive impedance X_{net} of the network, i.e. for a low-power supply network. Fig.7 shows the results of calculations for (5) with impedance $X_{net} = 50\ \Omega$. Such calculations make it possible to make undervalued estimates of voltage increases, since for 500-750 kV networks, X_{net} is usually $X_{net} < 50\ \Omega$.

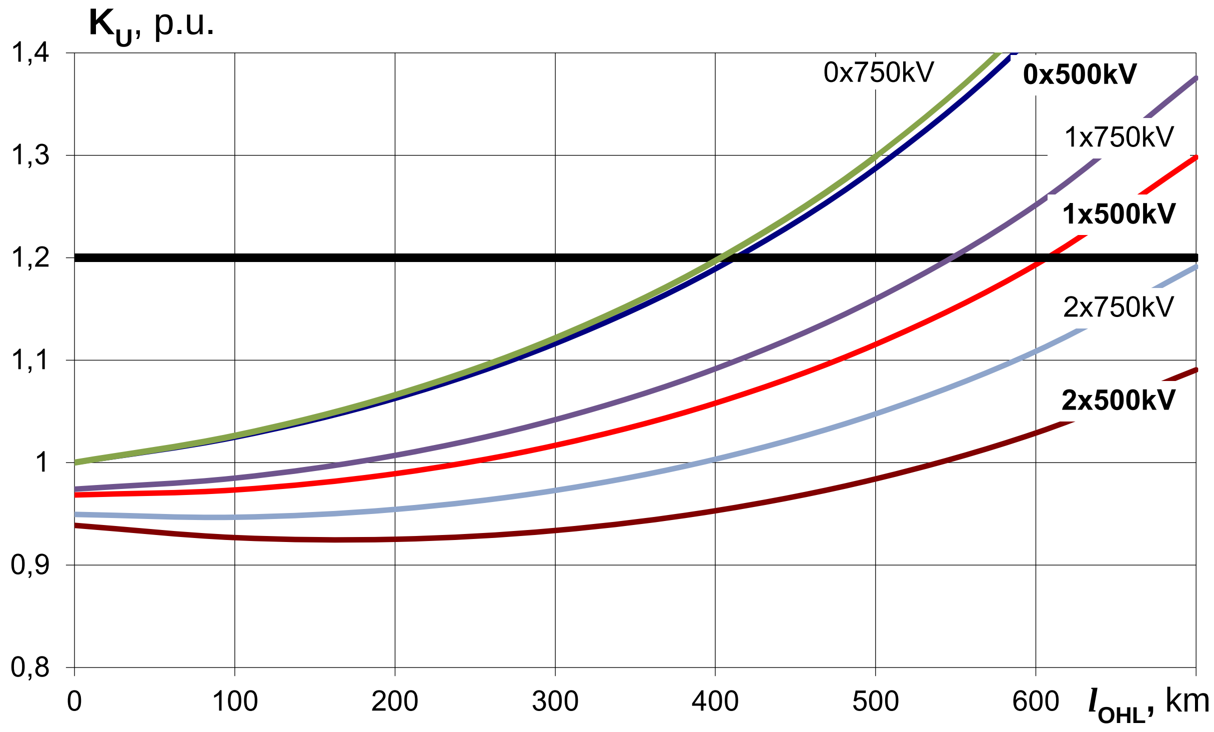

Fig.7. Voltage increase at the open end of 500-750 kV overhead lines of a typical design, depending on the number (zero, one, two) of shunt reactors connected at the line open end:
– for 500 kV each reactor power has 180 MVAr;
– for 750 kV each reactor power has 330 MVAr.

Table 1. The permissible increase in the 50 Hz voltage for 500-750 kV equipment according to [7].

Equipment	Rated voltage	Permissible increase (p.u.) and the duration of exposure			
		20 min	20 s	1 s	0.1 s
Shunt reactors and electromagnetic voltage transformers	500 kV	1.15	1.35	2	2.08
	750 kV	1.10	1.30	1.88	1.98
Circuit breakers, capacitive voltage transformers, current transformers, communication capacitors	500 kV	1.15	1.60	2.20	2.40
	750 kV	1.10	1.30	1.88	1.98
Surge arresters	500, 750 kV	1.26	1.35	1.52	–

For the equipment, the permissible increase in the voltage of the industrial frequency 50 Hz, depending on the duration of exposure, is indicated in the PTE [7] – see Table. 1. Even if the time of one-side energizing of the line was 20 minutes, then a voltage with a multiplicity of 1.10 would be acceptable for all equipment connected to the line at its open end. Based on this multiplicity, using Fig.7, we obtain that for a 500-750 kV overhead line with a length of up to 250-300 km, the installation of a shunt reactor on the line is not required!

The one-side energizing mode for 500-750 kV lines occurs primarily for the synchronization time (angles of EMF of networks at the beginning and the end of the line have to be close to each other before switching the line from one-side mode to power transit). Synchronization, when using modern automatic synchronizers, does not exceed tens of seconds. At this short time, the allowable multiplicity will be at least 1.20-1.30. With an acceptable multiplicity of 1.20, the installation of reactors on lines is not required for lengths up to 400 km (see Fig.7). For lines longer than 400 km, 1-2 reactors are already required, but only at the open end of the overhead line (next to the breaker on which synchronization is performed, that is next to B2 for the scheme Fig.1).

VII. CONCLUSIONS

1. There is a practice according to which on many 500-750 kV overhead lines there is a high, close to 100%, compensation of charging power by inductance of linear shunt reactors. This leads to the appearance of:
- aperiodic currents dangerous to overhead line breakers;
- resonant overvoltages dangerous for all overhead line equipment in non-three-phase modes (for example, with single-phase automatic reclosure).
2. To limit the aperiodic currents, 500-750 kV overhead line circuit breakers can be equipped with controlled switching devices or pre-connected resistors. The purchase and operation of such equipment is burdensome. At the same time, such devices affect only aperiodic currents and, in principle, are not able to limit overvoltages in non-three-phase modes, and for lines with compensation of about 80-120% they are ineffective even to combat aperiodic currents.
3. To limit resonant overvoltages in non-three-phase modes, "neutral" reactors can be installed in the neutral of linear shunt reactors, but such a solution is not used for a number of reasons. At the same time, for lines with compensation of about 80-120%, it is completely ineffective.
4. The only measure that allows even for the most problematic lines with 80-120% compensation to limit both currents and voltages to safe values is to turn off any of the linear shunt reactors before switching 500-750 kV overhead lines. Such a solution is "free", but has a number of disadvantages, the main one of which is the risk of damage of shunt reactor breaker by aperiodic currents arising from a short-circuit on the overhead line.
5. The main reason for placing reactors on the line, and not on the busbars, is the need to limit the voltage increase at the end of the overhead line in its one-side power supply mode. According to calculations for 500-750 kV overhead lines without linear reactors, as a rule, an increase in voltage is still acceptable even with a length of overhead lines up to 400 km. Linear reactors are needed primarily for longer overhead lines.
6. The above considerations speak in favor of, as far as possible, abandoning the high (80-120%) degree of compensation for the charging power of 500-750 kV overhead lines by linear reactors. The number of linear reactors should be selected to compensate for no more than 60-70% of the line charging capacity (the rest of the power should be compensated by busbar shunt reactors). With compensation of no more than 50% of the line charging power, there are no problems with aperiodic currents and no problems overvoltages in non-three-phase modes.

REFERENCES

1. Company standard SO 153-34.20.118-2003 "Methodological recommendations for the design of the development of power systems", Moscow, 2003.
2. Dmitriev M.V. " Methodology for selecting measures to combat aperiodic currents on lines with shunt reactors" // "News of Electrical engineering" magazine, No.4(77), 2012.
3. Dmitriev M.V., Evdokunin G.A. and others "Single-phase automatic reclosure on lines with a controlled shunt reactor" // "The Energetik" magazine, No.4, 2012.
4. "Handbook on the design of electric power systems" // edited by S.S. Rokotyan and I.M. Shapiro –3rd edition. –Moscow: Energoatomizdat, 1985.
5. Belyakov N.N., Kadomskaya K.P. and others. "Processes during single–phase reconnection of high voltage lines" // edited by M.L. Levenshtein. –Moscow: Energoatomizdat, 1991.
6. Evdokunin G.A. "Electrical systems and networks" // "Sintez Book" publishing house, Saint Petersburg, 2011.
7. "Rules of technical operation of power plants and networks of the Russian Federation" // "Energoservice" publishing house, Moscow, 2003.