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Assessment of the phase-by-phase transmission line effect asymmetry on power transfer capability in open phase mode

***Abstract**. During the operation of EHV lines, the overwhelming proportions of single-phase short circuits can be eliminated in the cycle of a short-term no-current pause, followed by the restoration of the normal circuit. Thus, SPAR refers to the most important measure that increases the reliability of EHV power transmission. The success of elimination of arc short circuits in the SPAR cycle on the one hand, are determined by the characteristics of the secondary arc arising in long air gaps, and on the other hand - the effectiveness of used on lines of methods for reducing secondary arc currents and recovering stresses in the place of arc burning after its extinction. Implementation of SPAR is difficult the presence of recharge of the short circuit from the side of the non-disconnected phases. The paper shows how by proper adjustment of the operating parameters that determine the conditions for extinguishing the secondary arc we get an additional reduction in losses in the transmission line due to more accurate compensation of charging power.*

***Streszczenie.** Podczas eksploatacji linii najwyższych napięć, przeważająca część zwarć jednofazowych może być wyeliminowana w cyklu krótkotrwałej przerwy bezprądowej, po której następuje przywrócenie normalnej pracy. JSPZ jest więc najważniejszym środkiem zwiększającym niezawodność przesyłu energii elektrycznej w sieci najwyższych napięć. O powodzeniu likwidacji zwarć łukowych w cyklu JSPZ z jednej strony decydują charakterystyki łuku wtórnego powstającego w długich przerwach powietrznych, a z drugiej strony skuteczność stosowanych na liniach metod ograniczania prądów łuku wtórnego i odtwarzania napięć w miejscu wystąpienia łuku po jego zgaśnięciu. Realizację JSPZ utrudnia obecność wyładowań zwarciowych od strony faz nie rozłączonych. W artykule pokazano jak poprzez odpowiednie dobranie parametrów pracy określających warunki gaszenia łuku wtórnego uzyskujemy dodatkowe zmniejszenie strat w linii przesyłowej dzięki dokładniejszej kompensacji mocy obciążającej. (**Ocena wpływu asymetrii międzyfazowej linii przesyłowej na zdolność przesyłu mocy przy braku jednej fazy**).*

Keywords: electromagnetic transients, power transfer capability, single-phase automatic reclose, phase-by-phase asymmetry
Słowa kluczowe: stany przejściowe, zdolność przesyłu mocy, jednofazowe automatyczne ponowne załączenie, asymetria międzyfazowa.

Introduction

The main source of asymmetry of currents and voltages in normal operating modes of electrical systems is the phase-by-phase difference in the electrical parameters of the line. The asymmetry of the parameters of overhead lines is due to their design features. Particular attention is paid to asymmetry issues when creating extra high voltage (EHV) lines, since their lengths in some sections can reach 500 km [1-4]. The support on which the transposition is performed is the weak point of the overhead line [2-6]. In long-distance power transmission lines, the flow of failures is almost completely determined by accidents on the line due to its long length. At the same time, as already noted, in lines with a voltage of 750 kV, the overwhelming share of outages is caused by single-phase short circuits (SPS). This is due to the increase in interphase insulation distances on the supports and in the spans. From the point of view of disturbing effects on adjoining systems, the method of eliminating short circuits in the line is essential. Unstable SPS arising on the line are accompanied by minimal disturbances to adjacent systems if they are eliminated in a single-phase automatic reclosing cycle (SPAR) [1-5].

Extra high voltage transmission line transposition schemes

There are many works devoted to the problem of eliminating unstable SPS [1-3]. As a rule EHV long lines use a phase transposition consisting of three transposition steps. When assessing secondary arc current and resonance overvoltages, such lines are usually assumed to be ideally transposed, that is, having symmetry of phase and interface parameters. However, as studies have shown [5-9], such modeling of the line gives results that are far from the true results obtained when taking into account the real transposition, when at a separate step of the transposition the line is characterized by asymmetry of parameters [5-13].

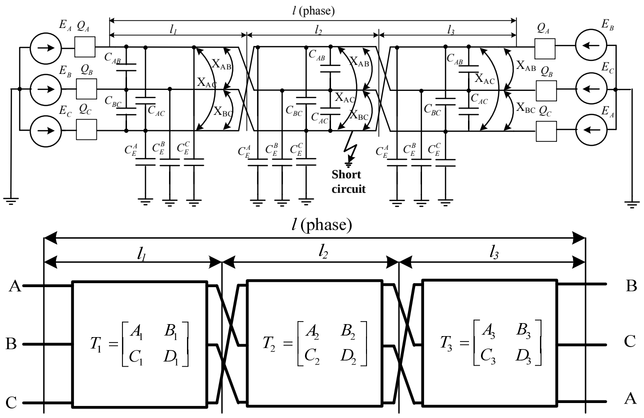

Fig. 1. The scheme of whole traditional transposition

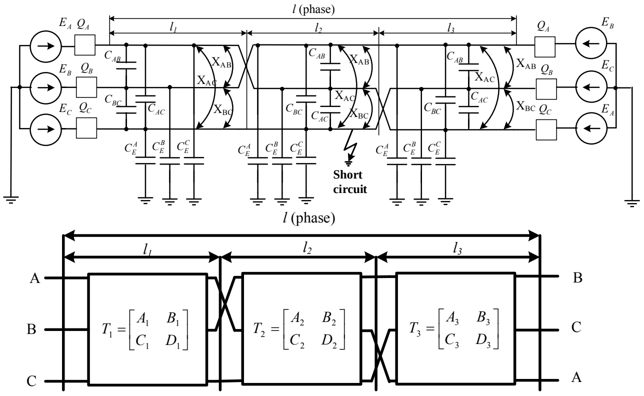

Fig. 2. Simplified transposition scheme

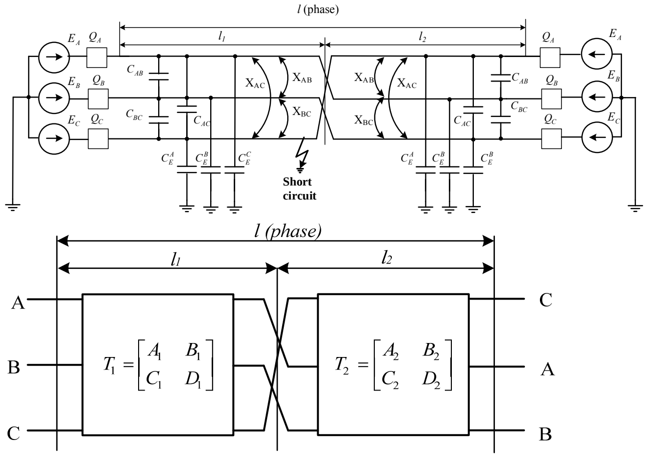

Figure 3 Equivalent Incomplete scheme of transposition

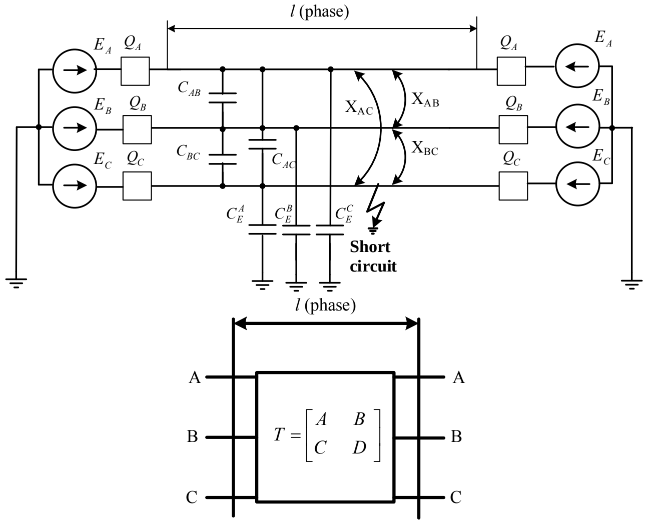

Fig. 4 An untransposed line

Figure 1 shows a diagram of the traditional classical transposition of wires with real line lengths of steps. Figure 2 shows a simplified diagram of the complete scheme of wire transposition. Figure 3 shows a diagram of the incomplete transposition cycle. Figure 4 shows an untransposed line.

Analysis of asymmetry coefficients for pre-existing schemes of transposition of EHV line based on the advanced parameters: *U*=750 kV - nominal voltage of the line. Phase design for 4xAC-400/93 wire, characterized by the following parameters r_0=0.071 Ω/km, x_0=0.248 Ω/km, g_0=22.35·10^{-9} S/km, g_0=4.10·10^{-6} S/km.

Method for determining power transfer capability reduction in open-phase mode

To assess the effect of phase-by-phase unbalance from a real transposition circuit on a decrease power transfer capability in an open-phase mode, consider the equivalent circuit, which is shown in Fig. 2. In Fig. 2 indicates the disconnected phase and the two phases remaining in operation.

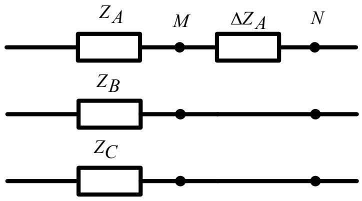

Fig. 2 Power line section asymmetry

An additional resistance is switched into the phase A ΔZ_A fig. 2 at consideration the open phase mode the power transmission line. Obviously, the voltage drop between the points M and N in the phase coordinate system can be represented by the following column vector

$$\Delta U = \begin{bmatrix}\Delta U_A\\ 0\\ 0\end{bmatrix} = \begin{bmatrix}I_A\Delta Z_A\\ 0\\ 0\end{bmatrix} \tag{1}$$

Changing the resistance ΔZ_A in the range 0 to ∞ will correspond to the symmetric mode $\Delta Z_A = 0$, the open-phase mode $\Delta Z_A = \infty$ and the phase-wise asymmetry of the line parameters (intermediate values of ΔZ_A.

As a result of the transformation of the mathematical model of power transmission from the phase to the coordinate system of symmetrical components of the vector-column of voltage drops in the section M and N, it will look like

$$\begin{bmatrix}\Delta U_1\\ \Delta U_2\\ \Delta U_3\end{bmatrix} = \frac{1}{3}\begin{bmatrix}1 & a & a^2\\ 1 & a^2 & a\\ 1 & 1 & 1\end{bmatrix}\begin{bmatrix}I_A\Delta Z_A\\ 0\\ 0\end{bmatrix} = \frac{1}{3}\begin{bmatrix}I_A\Delta Z_A\\ I_A\Delta Z_A\\ I_A\Delta Z_A\end{bmatrix} \tag{2}$$

The additional resistance introduced into the phase A of the power transmission is taken into account by including in the dissection of the equivalent circuit of each of the symmetrical components an additional EMF directed counter to the current and numerically equal to the voltage drop at the additional resistance in the coordinate system of the symmetric components $1/3\Delta U_A$.

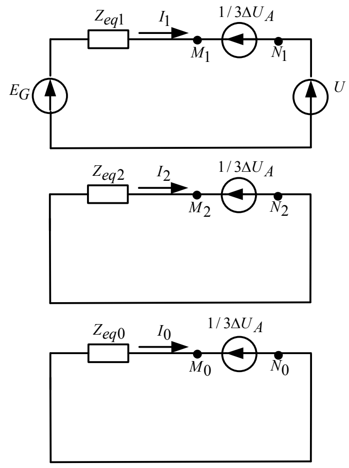

Fig.3 Equivalent circuits of direct, reverse and zero sequence

The mode of each of the symmetrical components can be calculated independently. However, the complexity of such an independent calculation is that at the preliminary stage the magnitude of the EMF introduced into the circuit of each of the symmetrical components is unknown. This leads to the need for joint calculation of independent schemes of symmetrical components, taking into account additional restrictions. As such an additional limitation, the equation can be used

$$\Delta U_A = I_A\Delta Z_A = (I_1 + I_2 + I_3)\Delta Z_A \tag{3}$$

Then the equations of the second Kirchhoff law for each of the schemes of symmetrical components, solved together with equation (1), uniquely determines the operating parameters of the power transmission in the coordinate system of symmetrical components

However, in practice this approach is usually not applied, since it is more convenient to use a complex equivalent circuit of Fig.4. The latter can be obtained by combining points $M_{1,}M_{2,}M_{0,}$ and $N_{1,}N_{2,}N_{0,}$ characterized by equal potentials in equivalent circuits of symmetrical components. In this case, the equation is taken into account in the complex equivalent circuit with the help of resistance $\Delta Z_A / 3$ included between the points $M_{1,}$ and $N_{1,}$ of the complex equivalent circuit.

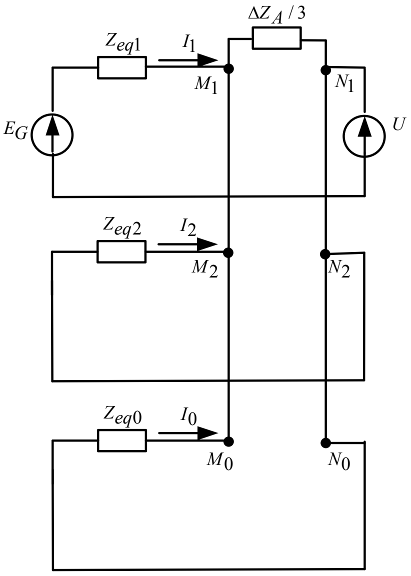

Fig.4 Complex single-ended equivalent circuit

The analysis of the complex equivalent circuit shows that to determine the direct sequence current it is necessary to add additional resistance to the circuit ΔZ_1 Fig. 8. The latter is defined as the equivalent resistance of parallel connected resistances $\Delta Z_{A/3,}\Delta Z_{eq2,}\Delta Z_{eq0,}$

(4) $$\Delta Z_1 = \frac{\Delta Z_A Z_{eq2} + \Delta Z_A Z_{eq0} + 3\Delta Z_{eq2} Z_{eq0}}{\Delta Z_A Z_{eq2} Z_{eq0}}$$

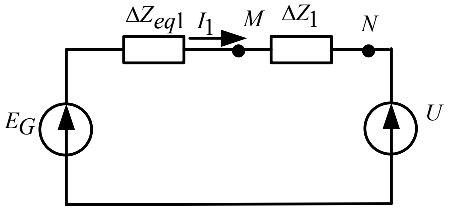

Fig.8 Equivalent complex equivalent circuit

Negative and zero sequence currents can be determined by expressions

(5) $$I_2 = -I_1 (1 + \frac{\Delta Z_A Z_{eq2} + 3\Delta Z_{eq2} Z_{eq0}}{\Delta Z_A Z_{eq0}})$$

(6) $$I_1 = -I_1 (1 + \frac{\Delta Z_A Z_{eq0} + 3\Delta Z_{eq2} Z_{eq0}}{\Delta Z_A Z_{eq2}})$$

As noted above, the out-of-phase mode, characterized by the disconnection of phase A, will correspond to the value of the added resistance $\Delta Z_A = \infty$

In the general case, a complex equivalent circuit not related to a specific power transmission configuration is shown in Fig. 10 such an integrated circuit will satisfy the additional limiting condition of the non-safe mode.

(7) $$I_A = I_1 + I_2 + I_0 = 0$$

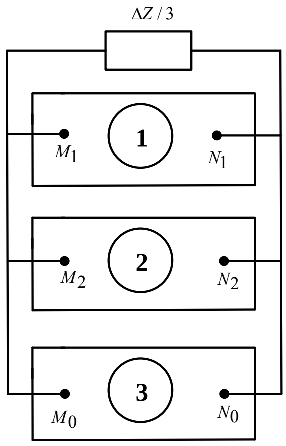

Fig.9 Generalized complex equivalent circuit of the line operation mode with asymmetry of the parameters of one phase

For the mode under consideration, the additional resistance introduced into the direct sequence circuit to obtain the direct sequence current value is

(8) $$\Delta Z_1 = \frac{Z_{eq2} Z_{eq0}}{Z_{eq2} + Z_{eq0}}$$

The reducing of transmission capacity of an extra high voltage transmission in an open-phase mode is determined by the expression:

(9) $$\delta P = \frac{Z_{eq1}}{Z_{eq1} + \Delta Z_1}$$

where Z_{eq1} – direct sequence equivalent resistance

Expression 9 is used to analyze the capacity in the open-phase mode of a power line.

The transmission capacity is inversely proportional to its equivalent inductive reactance. Therefore, the relative decrease in the transmission power transfer capability in the repair mode will be numerically equal to the relative increase in the equivalent transmission resistance, which is determined according to the complex equivalent circuit shown in Fig. 10

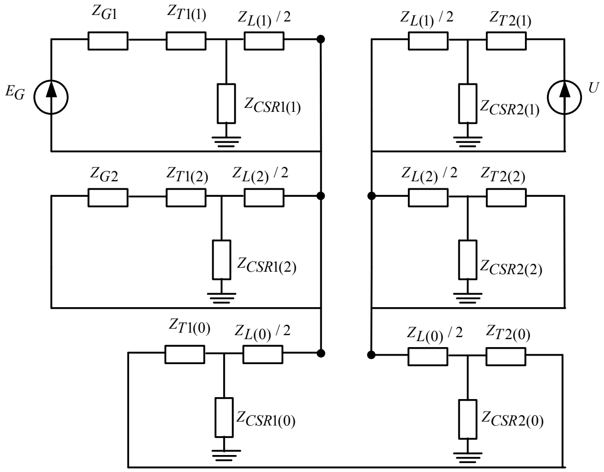

Fig.10 Complex equivalent circuit of EHV Power Line

At Fig. 10 Z_{G1}, Z_{G2} denote the resistances of generator; $Z_{T1(1)}, Z_{T1(2)}, Z_{T1(0)}, Z_{T2(1)}, Z_{T2(2)}, Z_{T2(0)}$ are the resistances of transformers; $Z_{L(1)}, Z_{L(2)}, Z_{L(0)}$ the resistances of overhead line, and $Z_{T1(1)}, Z_{T1(2)}, Z_{T1(0)}, Z_{T2(1)}, Z_{T2(2)}, Z_{T2(0)}$ are the resistances of controlled shunt reactors (CSR).

On Figure 11 the reduction of power transfer capability in the open-phase mode with influence of the phase-by-phase line asymmetry have been shown. As can be seen from the Figure 11, there is a significant difference in the values for a line with an idealized transposition compared to a really transposed line according to scheme 1 or 2. This difference is due to phase-by-phase unbalance, which must be taken into account when determining the decrease in line capacity in non-phase mode.

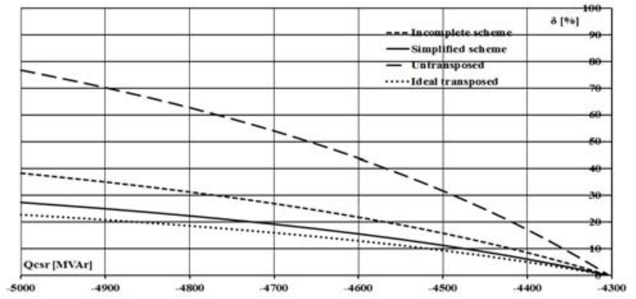

Fig. 11. Reduction of power transfer capability

Conclusions

The presented method allows taking into account the real transposition of the extra high voltage power transmission line. The paper also presents alternative transposition schemes: a simplified and transposition scheme and an incomplete cycle of wire transposition. The above method also makes it possible to take into account lateral compensation devices, in particular, controlled bypass reactors. As can be seen from Figure 11, by controlling the power of controlled shunt reactors, it is possible to achieve a decrease in the power transfer capability in an incomplete phase mode.

The increase in capital costs in the installation of CSR, instead of traditional SR, should be offset by a reduction in electricity losses in the transition from the normal steady state of the power system to the economic, which is realized through CSR. The paper shows that we get an additional reduction in losses in the transmission line due to more accurate compensation of charging power. It should also be noted that CSR is a multifunctional device and with the appropriate settings allows you to adjust not only the established normal modes of electrical networks, but also their abnormal modes and transients.

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