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METHOD FOR INCREASING SENSITIVITY OF THE DISTANCE PROTECTION ON A 330 KV DOUBLE-CIRCUIT TRANSMISSION LINE

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Possibilities of increasing the distance protection (DP) sensitivity are considered for a double-circuit transmission line connected to a substation busbar only with one circuit-breaker in each phase. The DP sensitivity can be increased on such a line using mutual connections of the phase wires along its whole length. The minimal (optimal) number of the connections is found by the proposed calculation method.

Key words: *distance protection, tripping zone sensitivity, mutual coupling, wire connections.*

1. INTRODUCTION

One of the problems at the use of distance protection (DP) as the primary protection for all types of fault is its insufficient sensitivity for the first tripping zones of a double-circuit transmission line (TL) whose both ends are joined together and connected to a substation busbar with one circuit-breaker only [1, 2].

For the case of a double-circuit 330 kV TL mutually connected by phases and having the network connection to the substation busbar only through one circuit-breaker per phase the short-circuit (SC) current calculations have been carried out with a 10% step along the TL with and without fault resistance at the SC location, taking into account the maximum allowable power flow in both directions.

2. PROBLEM FORMULATION

The problem is illustrated by Fig. 1. It is seen there that when the first DP zone covers only 40% of the TL length, the second zone does not cover its part from 60% to 80%, and only in the third DP zone the necessary sensitivity for the whole TL length can be ensured, although with a considerably higher tripping time setting.

The above mentioned conditions take place when the SC current, depending on its location, is flowing by paths of different length, especially when there are SCs to earth.

It is known that in such a case the total voltage induced in one circuit can approximately be written as

$$U_1 = U_{1L} + U_{1M} \tag{1}$$

for the first circuit, and

$$U_2 = U_{2L} + U_{2M} \tag{2}$$

for the second circuit.

The mutual coupling voltage is, respectively:

$$\begin{aligned} U_{1M} &= \pm M \frac{di_2}{dt}; \\ U_{2M} &= \pm M \frac{di_1}{dt}, \end{aligned} \tag{3}$$

where: i_1 – current flowing first in Circuit 1;
i_2 – current flowing first in Circuit 2.

The minus sign in these equations corresponds to the coincident directions of self-inductivity and mutual coupling currents, whereas the plus sign – to their opposite directions.

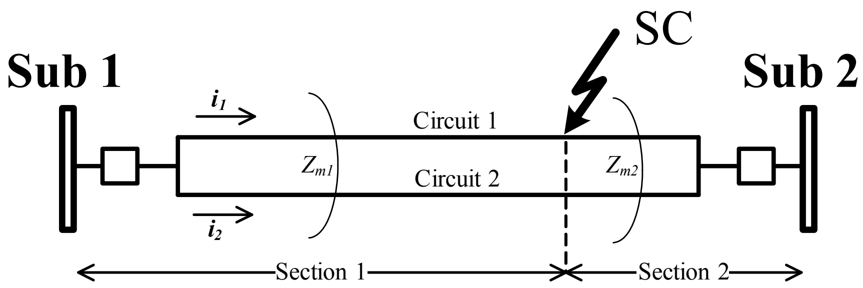

Fig. 1. Short circuit on a double-circuit TL.

Therefore, the single-phase or two-phase SCs to earth on one of the two 330 kV TL circuits significantly increase the resistance values, for example, if the SC is located approx. at a 75% distance from Substation 1 (see Fig. 1).

3. DP SENSITIVITY INCREASE ON A DOUBLE-CIRCUIT TL USING MUTUAL CONNECTIONS OF ITS PHASE WIRES ALONG THE WHOLE TL LENGTH

Phase-to-phase faults

One of the ways to increase the DP first zone sensitivity on a double-circuit TL is to use additional mutual connections of phase wires along the whole line. Such a solution is neither simple nor economically beneficial. To realize it, every particular case should be thoroughly analyzed (TL sizes, topology, mutual inductivity with other TLs, etc.).

From the above it follows that the number of connections must be as small as possible; at the same time, it should be sufficient to ensure at least 20% overlapping of the DP first sensitivity zones from both TL sides.

The correct solution starts from determination of the impedance characteristics when the SC location is shifting along the whole line length from the busbar of Substation 1 to that of Substation 2.

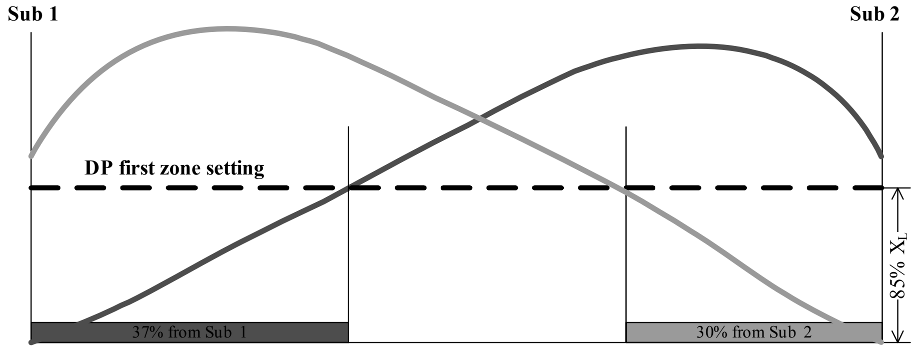

Fig. 2. Double-circuit TL characteristics (from both line ends) if the mutual phase wire connections are only at the line ends (the case of three-phase SC).

In Fig. 2 it is seen that at SC occurring in the shown interval the overlapping of the DP first zones is not provided if its setting is selected with the coordination factor of 0.85.

To find a methodical approach to this scientifically-technical problem it is necessary:

- to determine the DP first zones' mutual overlapping for at least 20% from both line ends; e.g., if at one line end the first zone coverage is about 40%, at the other TL end this should be about 80% of the line length;
- to consider the places of mutual connections of TL phase wires taking into account the sensitivity of the DP first stages from both line ends;
- for calculations, to take into account the maximum allowable power flows and the specified fault resistances, which not always would ensure the mentioned 20% overlapping (in some cases this overlapping can be as small as 10%).

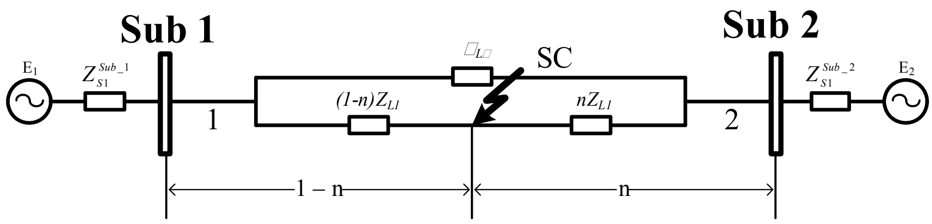

Fig. 3. Equivalent circuit diagram of positive and negative SC sequences.

Positive and negative sequence equivalent circuit impedances according to Fig. 3 are as follows.

*Sub*_1*-circuit:*

$$Z_{Sub\_1} = \frac{Z_{L1} \cdot (1-n) \cdot Z_{L1}}{Z_{L1} + n \cdot Z_{L1} + (1-n) \cdot Z_{L1}} = \frac{(1-n) \cdot Z_{L1}}{2}; \tag{4}$$

Sub_2-circuit:

$$Z_{Sub\_2} = \frac{Z_{L1} \cdot n \cdot Z_{L1}}{Z_{L1} \cdot 2} = \frac{n \cdot Z_{L1}}{2}; \tag{5}$$

SC- circuit:

$$Z_{SC} = \frac{n \cdot Z_{L1} \cdot (1-n) \cdot Z_{L1}}{Z_{L1} \cdot 2} = \frac{n \cdot (1-n) \cdot Z_{L1}}{2}. \tag{6}$$

The number of mutual connections of a double-circuit TL phase wires can be found analytically, using the delta-star transformation of the end scheme (Fig. 4) and the loop current method, as well as dividing the damaged TL impedances into Z_N and $(Z_L - Z_N)$.

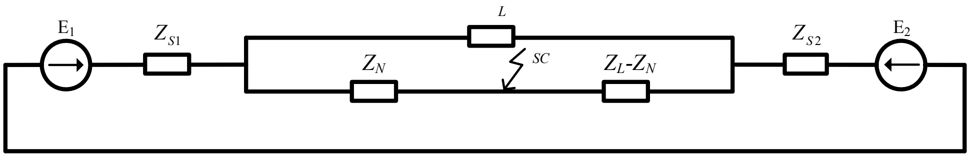

Fig. 4. Equivalent circuit diagram of positive sequence SC impedances.

After the delta-star transformation the circuit diagram will appear as displayed in Fig. 5, where $Z_1 = \frac{Z_N}{2}$, $Z_2 = \frac{Z_L - Z_N}{2}$ and $Z_3 = \frac{Z_N \cdot (Z_L - Z_N)}{2 \cdot Z_L}$.

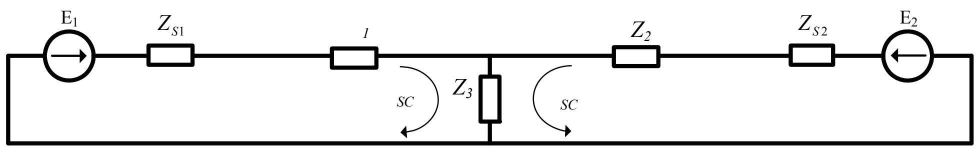

Fig. 5. Equivalent circuit diagram of positive sequence SC impedances after delta-star transformation

Using the loop current method for both circuits we will have:

$$\begin{cases} (Z_{S1} + Z_1 + Z_3) \cdot I_{SC1} + Z_3 \cdot I_{SC2} = E_1 & (7) \\ Z_3 \cdot I_{SC1} + (Z_{S2} + Z_2 + Z_3) \cdot I_{SC2} = E_2. & (8) \end{cases}$$

After the transformation we obtain:

$$Z_{Sub\_1} = \frac{Z_N}{2} + \frac{Z_N \cdot (Z_L - Z_N)}{2 \cdot Z_L} \times \left(1 + \frac{E_2 \cdot \left(Z_{S1} \cdot 2 \cdot Z_L + 2 \cdot Z_L \cdot Z_N - Z_N^2\right) - E_1 \cdot (Z_N \cdot (Z_L - Z_N))}{E_1 \cdot \left(Z_{S2} \cdot 2 \cdot Z_L + Z_L^2 - Z_N^2\right) - E_2 \cdot (Z_N \cdot (Z_L - Z_N))}\right) \tag{9}$$

and

$$Z_{Sub\_2} = \frac{Z_L - Z_N}{2} + \frac{Z_N \cdot (Z_L - Z_N)}{2 \cdot Z_L} \times \left(1 + \frac{E_1 \cdot \left(Z_{S2} \cdot 2 \cdot Z_L + Z_L^2 - Z_N^2\right) - E_2 \cdot (Z_N \cdot (Z_L - Z_N))}{E_2 \cdot \left(Z_{S1} \cdot 2 \cdot Z_L + 2 \cdot Z_L \cdot Z_N - Z_N^2\right) - E_1 \cdot (Z_N \cdot (Z_L - Z_N))}\right). \tag{10}$$

The Z_N value is not constant and depends on the SC location on one of the two TL circuits.

Using the impedance data derived from Eqs. (9) and (10) for the phase-to-phase SCs we can fit the impedance curves from Substation 1 and Substation 2 sides by moving the short-circuit location. The impedance curve of Fig. 6 will determine whether additional phase connections are required [2].

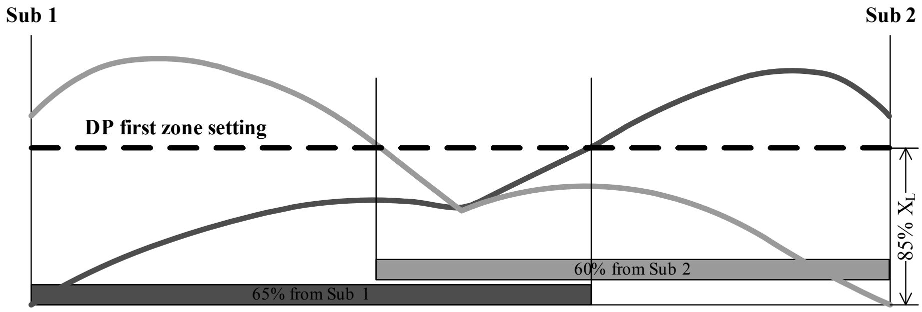

Fig. 6. Double-circuit TL impedance characteristics (for both line ends) with one mutual connection of phase wires (in the middle of the line) for three-phase SC.

Phase-to-earth faults

In the zero-sequence equivalent circuit (see Fig. 7) it is necessary to take into account the mutual coupling impedance Z_{m0}, and recalculate the scheme.

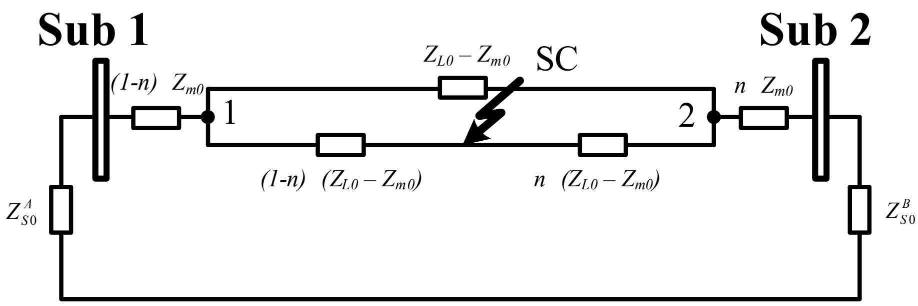

Fig. 7. Equivalent circuit of the SC zero-sequence.

Transforming "delta" to "star" connection we obtain the following circuit impedances:

*Circuit*_1

$$Z_{Circuit\_1} = \frac{(Z_{L0} - Z_{m0}) \cdot [(1-n) \cdot (Z_{L0} - Z_{m0})]}{(Z_{L0} - Z_{m0}) + (1-n) \cdot (Z_{L0} - Z_{m0}) + n \cdot (Z_{L0} - Z_{m0})} =$$

$$= \frac{(1-n) \cdot (Z_{L0} - Z_{m0})}{2}; \quad (11)$$

*Circuit*_2

$$Z_{Circuit\_2} = \frac{(Z_{L0} - Z_{m0}) \cdot [n \cdot (Z_{L0} - Z_{m0})]}{2 \cdot (Z_{L0} - Z_{m0})} = \frac{n \cdot (Z_{L0} - Z_{m0})}{2}; \quad (12)$$

Circuit_SC

$$Z_{Circuit\_SC} = \frac{[n\cdot(Z_{L0}-Z_{m0})]\cdot[(1-n)\cdot(Z_{L0}-Z_{m0})]}{2\cdot(Z_{L0}-Z_{m0})} =$$

$$= \frac{n\cdot(1-n)\cdot(Z_{L0}-Z_{m0})}{2}. \qquad (13)$$

To calculate the impedance to Substation 1 for *Circuit*_1 the zero-sequence equivalent impedance $(1-n)\cdot Z_{m0}$ has to be added:

$$\Sigma Z_{Circuit\_1} = (1-n)\cdot Z_{m0} + \frac{(1-n)\cdot(Z_{L0}-Z_{m0})}{2} =$$

$$= \frac{(1-n)\cdot(Z_{L0}+Z_{m0})}{2}. \qquad (14)$$

Similarly, to calculate the impedance to Substation 2 for *Circuit*_2 the zero-sequence equivalent impedance $n\cdot Z_{m0}$ is added:

$$\Sigma Z_{Circuit\_2} = n\cdot Z_{m0} + \frac{n\cdot(Z_{L0}-Z_{m0})}{2} = \frac{n\cdot(Z_{L0}+Z_{m0})}{2}. \qquad (15)$$

To perform calculation of the optimal length for a double-circuit transmission line it is necessary to determine the TL length at which mutual connections are provided only at the ends. In the case when a double-circuit line is longer by the DP first stage sensitivity criteria, it is recommended that some extra connections are made between the double-circuit line phases, which can increase the DP first zones' mutual coverage at least by 20% on both line ends.

For the single-phase SCs, when it is necessary to determine the sensitivity level all line long, both alternating (source impedance) and non-alternating (line impedance) power network parameters should be taken into account.

Another changeable parameter – the compensation factor for the zero-sequence equivalent impedance − has to be calculated for the SC at the opposite TL end.

To determine the DP sensitivity for single-phase SC it is necessary to choose the starting conditions with the appropriate network parameters (the source impedance and the compensation factor).

Figure 8 shows that the DP sensitivity level for the first tripping zone in the case of single-phase SCs increases by 7% (for the considered double-circuit TL with the length 3ZL the calculated compensation factor is 0.85).

For the single-phase short-circuit in the middle of a TL (at the same EMF and source impedances at the TL ends) the mutual coupling impedance Z_m almost does not affect the DP calculated impedance under the condition that the zero-sequence current is equal to the phase current.

It can be inferred that the sensitivity of the DP first tripping zone increases at the single-phase SC occurrence (the mutual overlapping of DP first zones will extend).

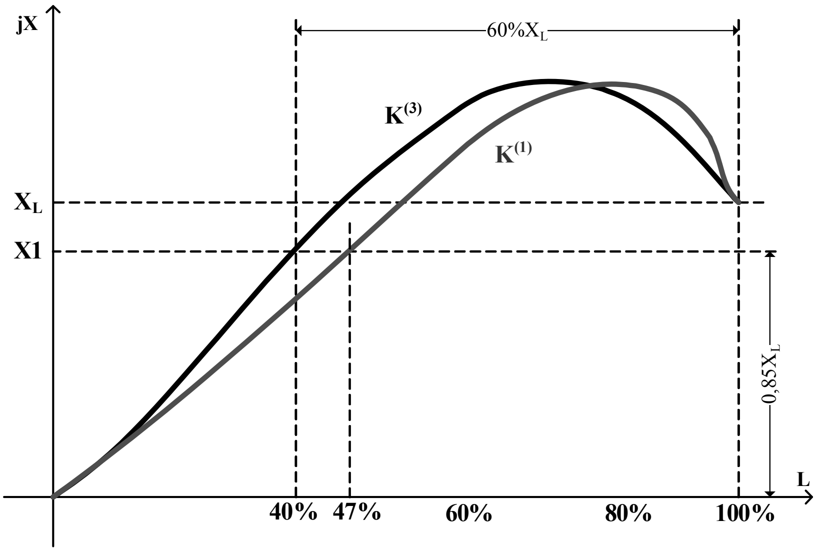

Fig. 8. Double-circuit TL impedance characteristics (for one line end) without mutual connections of phase wires for single-phase SC.

To calculate the impedances at single-phase faults it is necessary to use the following algorithm:

- to calculate the total short-circuit current at the SC location;
- to calculate the current and voltage distributions for the circuits;
- to calculate the faulty phase impedances for both the TL ends depending on the SC location.

To calculate the faulty phase impedance a symmetrical component method for a single-phase fault could be employed, with the following equations to be used: for calculation of positive and negative sequence impedances − Eqs. (4)–(6), and for calculation of the zero-sequence impedance – Eqs. (11)–(15), while for the faulty phase currents ($I_{Circuit\_1}, I_{Circuit\_2}$), voltages ($U_{Circuit\_1}, U_{Circuit\_2}$) and zero-sequence currents ($3I_{0\_Circuit\_1}, 3I_{0\_Circuit\_2}$) special SC calculation programs should be used.

Combining all the above equations, the faulty phase impedances for both TL ends, depending on the SC location, will be:

$$Z^{(1)}_{Sub\_1} = \frac{U_{Circuit\_1}}{I_{Circuit\_1} + K_k \cdot 3I_{0\_Circuit\_1}}; \tag{16}$$

$$Z^{(1)}_{Sub\_2} = \frac{U_{Circuit\_2}}{I_{Circuit\_2} + K_k \cdot 3I_{0\_Circuit\_2}}, \tag{17}$$

where $I_{Circuit\_1}, I_{Circuit\_2}$ – faulty phase currents from Substations 1 and 2 sides;

$U_{Circuit\_1}, U_{Circuit\_2}$ – faulty phase voltages from Substations 1 and 2 sides;

$3I_{0\_Circuit\_1}, 3I_{0\_Circuit\_2}$ – zero-sequence currents from Substations 1 and 2 sides;

$K_k = \frac{(Z_{0\Sigma} + Z_{\mu\Sigma}) - Z_{1\Sigma}}{3Z_{1\Sigma}}$ – compensation factor.

In turn, if the EMF values and the source impedances for the TL ends are not the same, the mutual overlapping of the DP first tripping zones will extend to 12%, which does not ensure sufficient sensitivity.

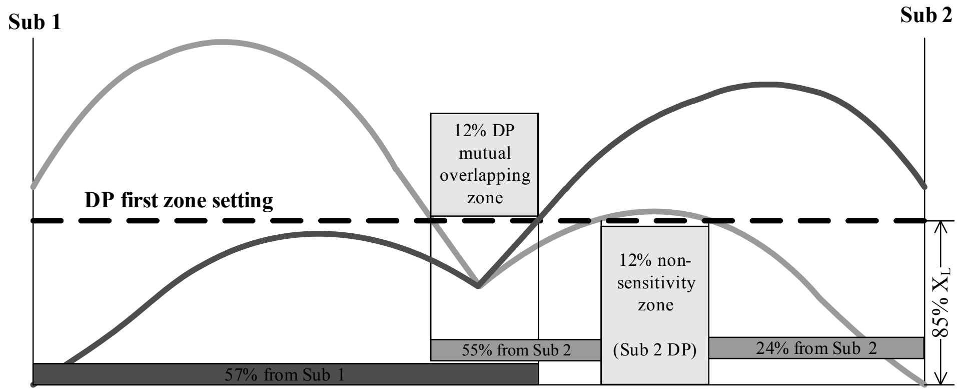

Fig. 9. Double-circuit TL impedance characteristics (for both line ends) with one mutual connection of phase wires (in the middle of the line) for single-phase SC (without power flow and fault resistance).

Figure 9 shows that from the Substation 1 side a 12% non-sensitivity zone appears (from 24% to 36% of the distance from the Substation 2 side).

The compensation factor for the zero-sequence current of the DP first tripping zone is calculated for the short circuit on the opposite substation busbar (without power flow and fault resistance, see Fig. 9).

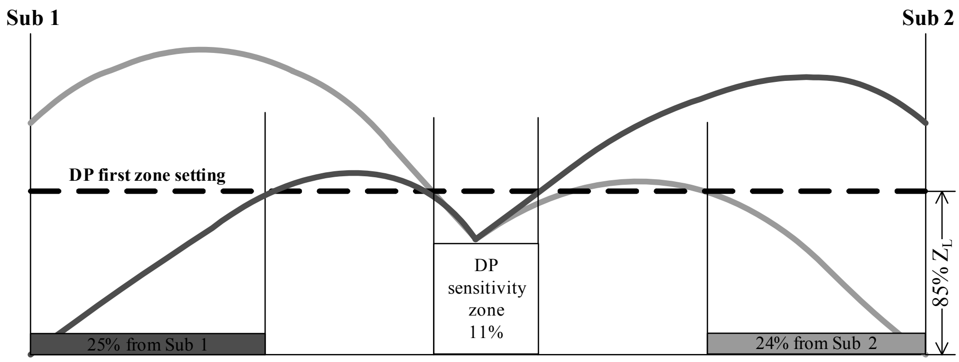

Fig. 10. Double-circuit TL impedance characteristics (for both line ends) with one mutual connection of phase wires (in the middle of the line) for single-phase SC with maximum power flow and fault resistance).

If only one parameter (e.g., the fault resistance) or both the fault resistance at the SC location and the maximum power flow are taken into consideration, no overlapping of the DP first tripping zones occurs from both TL ends (Fig. 10).

Obviously, analytical calculations of the faulty phase impedance values should have several stages. These values depend on the distance to the SC location; also, some other factors should be taken into account − the power flow direction, fault resistance, equivalent source impedances at the TL ends (the circuit impedance components) and the TL positive and zero-sequence impedances.

To ensure mutual overlapping of the DP first zones from both ends of a double-circuit TL it is necessary to make at least one mutual wire connection in the middle of the line.

For more precise calculations of the place for wire connection it is necessary to determine the non-sensitivity zone for all possible operating conditions of a power network (Fig. 11).

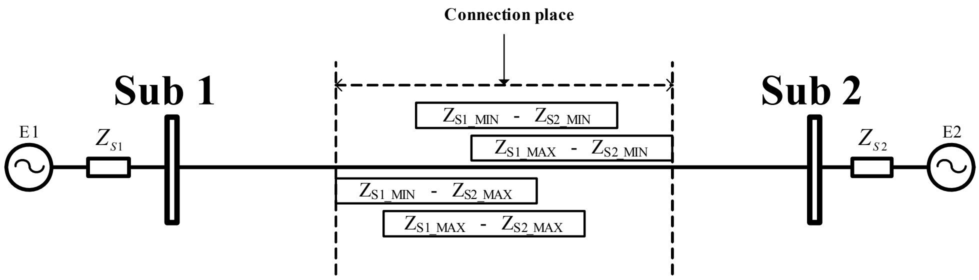

Fig. 11. DP non-sensitivity zone for all operating conditions of a power network.

After the DP non-sensitivity zone determination, it is necessary to find the mutual connection point of TL phases – in the middle of the non-sensitivity zone.

4. CONCLUSIONS

- The proposed calculation methods allow determination of the minimal (optimal) number of connections for the double-circuit transmission lines mutually coupled at both ends using only one circuit-breaker in each phase.
- To determine the number of double-circuit TL connections at a single-phase short-circuit we should, in addition, take into account the mutual coupling effects and the fault resistance at the SC location.

REFERENCES

1. Briņķis, K., & Drozds, D. (2008). Distantaizsardzību iestatījumu izvēles īpatnības atkarībā no elektriskajiem režīmiem un iekārtu parametriem. *Enerģija un Pasaule*, *48* (1), 80–85 (in Latvian).
2. Briņķis, K., Drozds, D., & Vanzovičs, E. (2009). Distantaizsardzības jutības palielināšanas iespējas divķēžu 330 kV PEL. *Enerģija un Pasaule, 58* (5), 82–83 (in Latvian).

DISTANTAIZSARDZĪBAS JUTĪBAS PALIELINĀŠANAS METODES
330 kV DIVĶĒŽU PĀRVADES ELEKTROLĪNIJĀM

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K o p s a v i l k u m s

Rakstā aplūkota divķēžu 330 kV PEL, kuras savstarpēji savienotas pa fāzēm un pieslēgtas pie kopnēm katrā galā caur vienu jaudas slēdzi katrai fāzei. Bija jāveic divķēžu PEL optimāla garuma noteikšanas analīze, lai noteiktu pie kādiem PEL garumiem ir pieļaujama to savstarpēja savienošana tikai pa galiem. Par vienu no DA pirmās pakāpes jutības paaugstināšanas iespējam uz divķēžu PEL, kuras savstarpēji savienotas abos galos pie viena jaudas slēdža katrā fāzē no kopņu puses, var apskatīt savstarpēju savienojumu izveidi visā PEL garumā. Piedāvātā aplēses metodika dod iespēju noteikt minimālo (optimālo) savienojumu skaitu uz divķēžu PEL.

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