Untransposed HV Transmission Line Influence on the Degree of Unbalance in Power Systems

Ljupčo D. Trpezanovski[1] and Metodija B. Atanasovski[2]

***Abstract* – In this paper, the untransposed HV transmission line influence on the degree of unbalance in power systems is presented. The model of untransposed HV line with ground wires is given in phase and sequence domain. The proposed model is used for asymmetrical load-flow solution by Newton-Raphson procedure, incorporated in the Neplan 5.0 software. All 400 and 220 kV unbalanced transmission lines in the power system of the Republic of Macedonia are taken with real parameters and asymmetrical state is analyzed. The unbalance factors for negative- and zero-sequence voltages for 400 and 220 kV buses are calculated. Positive-sequence voltages from asymmetrical state are compared with phase voltages from symmetrical state for the same power system, when the transmission lines are treated as balanced.**

***Keywords* – Untransposed HV transmission lines, unbalance factors, asymmetrical load-flow.**

I. INTRODUCTION

The three-phase power system consists of several networks with different rated voltages, connected with two or three-winding interconective transformers. The elements in the power system can be balanced (with equal phase parameters) or unbalanced (with different phase parameters). Practically, all generators, transformers, transposed lines and symmetrical loads can be treated as balanced elements. The untransposed and asymmetrical loads are treated as unbalanced elements. If there is even only one unbalanced element, asymmetrical state in power system is occurred and sequence voltages and currents are present in the power system buses and elements.

The presence of sequence components causes negative influence on the elements correct function. For example: negative-sequence currents at generator terminals rise heating in their rotors; malfunctions of protective relays; zero-sequence currents increase greatly the effect of inductive coupling between parallel transmission lines; higher power system losses; zero-sequence currents in the ground wires and through the ground, etc.

The degree of deviation from the symmetrical state can be valued with the unbalance factors for negative- and zero-sequence voltages or currents. When a system has adverse unbalanced factors, the transposition on phase conductors at substations or all through the lines should be applied.

[1]Ljupco D. Trpezanovski is with the Faculty of Technical Sciences, University St. Kliment Ohridski, I. L. Ribar bb, 7000 Bitola, Macedonia, E-mail: ljupco.trpezanovski@uklo.edu.mk

[2]Metodija B. Atanasovski is with the Faculty of Technical Sciences, University St. Kliment Ohridski, I. L. Ribar bb, 7000 Bitola, Macedonia, E-mail: metodija.atanasovski@uklo.edu.mk

It should be noted, that in this research all loads are treated as balanced elements.

The unbalance factors can be calculated from the sequence components (for voltages or currents). If these components are not on disposal, they are obtaining by transformation of the corresponding phase values. Values of phase nodes voltages or elements phase currents for the three-phase power system states, which deviate more or less from symmetrical states, are obtaining with asymmetrical load-flow (ALF) calculations. The solution of ALF problem was successfully performed using methods in phase domain (Newton-Raphson and Fast decoupled procedures) [1] and faster methods in sequence domain [2], [3].

II. UNTRANSPOSED HV TRANSMISSION LINE MODEL IN PHASE AND SEQUENCE DOMAIN

If the HV transmission line has a considerable length, and phase conductors are not transposed, it can causes a significant negative- and zero-sequence components. Usually, because of the great costs for the transposition towers and insulators, line transposition is avoided. Practically, the transposition is recommended if inequality (1) is satisfied:

$$U_n\,(\mathrm{kV}) \cdot L_V\,(\mathrm{km}) \geq 5000\,(\mathrm{kV} \cdot \mathrm{km})\,, \qquad (1)$$

where U_n is rated voltage in kV and L_V total line length in km [4]. It is shown that inequality (1) is satisfied for 220 and 400 kV lines, but should be checked for 110 kV lines. For exact unbalance factors calculation, a proper mathematical model of three-phase HV transmission line should be defined. In steady state problems, three-phase transmission line is represented by lumped-π circuit. The series reactance and inductance are lumped between line ends and shunt capacitance of the transmission line is divided into two halves and lumped at line ends [1], [2] and [5].

Let us consider a three-phase unbalanced transmission line with one ground wire.

A. Series Impedance of a Transmission Line

The series impedances of phase conductors and ground wire with earth influence, which are mutually inductive coupled, are illustrated in Fig. 1.

The following equation for the line ends voltage difference can be written for phase *a*:

$$\underline{V}_a - \underline{V}_{a'} = \underline{I}_a \cdot (R_a + j\omega L_a) + \underline{I}_b \cdot j\omega L_{ab} + \underline{I}_c \cdot j\omega L_{ac} + j\omega L_{ag} \cdot \underline{I}_g - j\omega L_{an} \cdot \underline{I}_n + \underline{V}_n\,. \qquad (2)$$

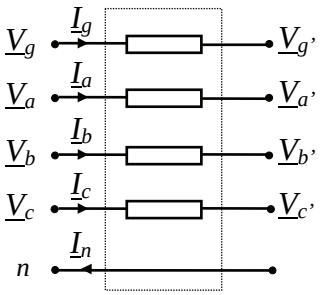

Fig. 1. Series mutually inductive coupled line impedances.

The voltage and current of the fictive earth conductor, signed as *n*, are given with next equations:

$$\underline{V}_n = \underline{I}_n \cdot (R_n + j\omega L_n) - \underline{I}_a \cdot j\omega L_{na} - \underline{I}_b \cdot j\omega L_{nb} - \underline{I}_c \cdot j\omega L_{nc} - \underline{I}_g \cdot j\omega L_{ng}\,, \tag{3}$$

$$\underline{I}_n = \underline{I}_a + \underline{I}_b + \underline{I}_c + \underline{I}_g\,. \tag{4}$$

Substituting Eqs. (3) and (4) in Eq. (2) gives:

$$\Delta V_a = \underline{Z}_{aa-n} \cdot \underline{I}_a + \underline{Z}_{ab-n} \cdot \underline{I}_b + \underline{Z}_{ac-n} \cdot \underline{I}_c + \underline{Z}_{ag-n} \cdot \underline{I}_g \tag{5}$$

Writing similar equations for the other phases and ground wire, the following matrix equation results:

$$\begin{bmatrix} \Delta\underline{V}_a \\ \Delta\underline{V}_b \\ \Delta\underline{V}_c \\ \hdashline \Delta\underline{V}_g \end{bmatrix} = \left[\begin{array}{ccc:c} \underline{Z}_{aa-n} & \underline{Z}_{ab-n} & \underline{Z}_{ac-n} & \underline{Z}_{ag-n} \\ \underline{Z}_{ba-n} & \underline{Z}_{bb-n} & \underline{Z}_{bc-n} & \underline{Z}_{bg-n} \\ \underline{Z}_{ca-n} & \underline{Z}_{cb-n} & \underline{Z}_{cc-n} & \underline{Z}_{cg-n} \\ \hdashline \underline{Z}_{ga-n} & \underline{Z}_{gb-n} & \underline{Z}_{gc-n} & \underline{Z}_{gg-n} \end{array}\right] \begin{bmatrix} \underline{I}_a \\ \underline{I}_b \\ \underline{I}_c \\ \hdashline \underline{I}_g \end{bmatrix}. \tag{6}$$

The series impedances line model with only three phase conductors is more convenient and it can be established in few steps. At first, matrix Eq. (6) should be presented in partitioned matrix form as follows:

$$\begin{bmatrix} \Delta\mathbf{V}_{abc} \\ \hdashline \Delta\mathbf{V}_g \end{bmatrix} = \left[\begin{array}{c:c} \mathbf{Z}_A & \mathbf{Z}_B \\ \hdashline \mathbf{Z}_C & \mathbf{Z}_D \end{array}\right] \begin{bmatrix} \mathbf{I}_{abc} \\ \hdashline \mathbf{I}_g \end{bmatrix} \tag{7}$$

Multiplying the partitioned matrices results with equations:

$$\Delta\mathbf{V}_{abc} = \mathbf{Z}_A\mathbf{I}_{abc} + \mathbf{Z}_B\mathbf{I}_g\,, \tag{8}$$

$$\Delta\mathbf{V}_g = \mathbf{Z}_C\mathbf{I}_{abc} + \mathbf{Z}_D\mathbf{I}_g\,. \tag{9}$$

Assuming that the ground wire is at zero potential ($\Delta\mathbf{V}_g = 0$), from Eq. (8) and (9) can be obtained the final three phase conductors model for the transmission line in matrix form:

$$\Delta\mathbf{V}_{abc} = \mathbf{Z}_{abc}\mathbf{I}_{abc}\,. \tag{10}$$

The $\mathbf{Z}_{abc}$ impedance matrix includes phase self-impedances and mutual inductive couplings with influence of earth and ground wire(s). All elements of this matrix can be calculated from the matrix equation:

$$\mathbf{Z}_{abc} = \mathbf{Z}_A - \mathbf{Z}_B\mathbf{Z}_D^{-1}\mathbf{Z}_C = \begin{bmatrix} \underline{Z}_{aa} & \underline{Z}_{ab} & \underline{Z}_{ac} \\ \underline{Z}_{ba} & \underline{Z}_{bb} & \underline{Z}_{bc} \\ \underline{Z}_{ca} & \underline{Z}_{cb} & \underline{Z}_{cc} \end{bmatrix}. \tag{11}$$

Usually, instead of impedance matrix, the series admittance matrix $\mathbf{Y}_{abc}^{z} = \mathbf{Z}_{abc}^{-1}$ is applying for the line model.

B. Shunt Capacitance of a Transmission Line

Shunt mutual capacitive couplings for the three phase conductors, ground wire and earth are illustrated in Fig. 2.

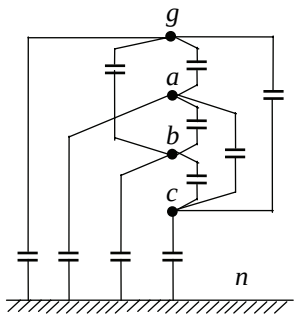

Fig. 2. Shunt mutually coupled line capacitances.

The potentials of the line phase conductors and ground wire are related to the conductor charges by the matrix equation:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \\ \hdashline V_g \end{bmatrix} = \left[\begin{array}{ccc:c} p'_{aa} & p'_{ab} & p'_{ac} & p'_{ag} \\ p'_{ba} & p'_{bb} & p'_{bc} & p'_{bg} \\ p'_{ca} & p'_{cb} & p'_{cc} & p'_{cg} \\ \hdashline p'_{ga} & p'_{gb} & p'_{gc} & p'_{gg} \end{array}\right] \begin{bmatrix} Q_a \\ Q_b \\ Q_c \\ \hdashline Q_g \end{bmatrix}, \tag{12}$$

where p'_{aa}, p'_{ab}, …, p'_{gg} are potential coefficients. On the same way, as it was conducted for the series impedances, the only three phase conductors line model for the shunt capacitances could be established. Taking into account the zero potential of the ground wire(s) and Eq. (12), potentials of the line phase conductors with included influences of earth and ground wire(s) in matrix form are:

$$\mathbf{V}_{abc} = \mathbf{P}_{abc}\mathbf{Q}_{abc}\,. \tag{13}$$

The capacitance matrix can be easy calculated as:

$$\mathbf{C}_{abc} = \mathbf{P}_{abc}^{-1} = \begin{bmatrix} C_{aa} & -C_{ab} & -C_{ac} \\ -C_{ba} & C_{bb} & -C_{bc} \\ -C_{ca} & -C_{cb} & C_{cc} \end{bmatrix}. \tag{14}$$

Usually, the shunt admittance matrices Eq. (15) corresponding to the line ends are applying instead of capacitance matrix.

$$\mathbf{Y}^{s}_{abc} = \frac{1}{2}\, j\omega \mathbf{C}_{abc}\,. \tag{15}$$

Finally, the series and shunt admittance lumped-π model of an untransposed transmission line (connected between buses *k* and *j*) represented with three-phase compound admittances is shown in Fig. 3.

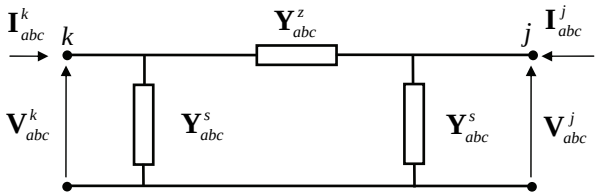

Fig. 3. Lumped-π model of an untransposed transmission line in phase domain.

Following the rules developed for the formation of the admittance matrix using the compound concept [1], the bus *k* and bus *j* injected currents can be related to the nodal voltages by the equation:

$$\begin{bmatrix} \mathbf{I}^{k}_{abc} \\ \mathbf{I}^{j}_{abc} \end{bmatrix}_{(6,1)} = \begin{bmatrix} \mathbf{Y}^{z}_{abc} + \mathbf{Y}^{s}_{abc} & -\mathbf{Y}^{z}_{abc} \\ -\mathbf{Y}^{z}_{abc} & \mathbf{Y}^{z}_{abc} + \mathbf{Y}^{s}_{abc} \end{bmatrix}_{(6,6)} \begin{bmatrix} \mathbf{V}^{k}_{abc} \\ \mathbf{V}^{j}_{abc} \end{bmatrix}_{(6,1)} \tag{16}$$

Above explained procedure can be used for formation the lumped-π model of an untransposed transmission line with more than one ground wire.

Series and shunt admittances can be converted in sequence domain using transformation matrix $\mathbf{T}_s$ and equations:

$$\mathbf{Y}^{z}_{dio} = \mathbf{T}_s^{-1} \cdot \mathbf{Y}^{z}_{abc} \cdot \mathbf{T}_s \tag{17}$$

$$\mathbf{Y}^{s}_{dio} = \mathbf{T}_s^{-1} \cdot \mathbf{Y}^{s}_{abc} \cdot \mathbf{T}_s\,. \tag{18}$$

Now, the lumped-π model of an untransposed transmission line in sequence domain can be presented as in Fig. 4.

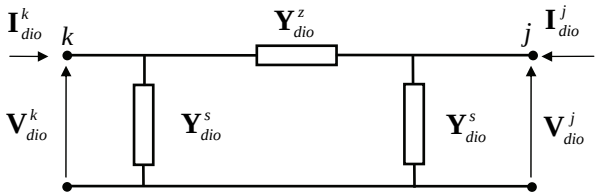

Fig. 4. Lumped-π model of an untransposed transmission line in sequence domain.

Finally, the mathematical model in sequence domain can be presented in matrix form with Eq. (19), similar as it was presented for the phase domain.

$$\begin{bmatrix} \mathbf{I}^{k}_{dio} \\ \mathbf{I}^{j}_{dio} \end{bmatrix}_{(6,1)} = \begin{bmatrix} \mathbf{Y}^{z}_{dio} + \mathbf{Y}^{s}_{dio} & -\mathbf{Y}^{z}_{dio} \\ -\mathbf{Y}^{z}_{dio} & \mathbf{Y}^{z}_{dio} + \mathbf{Y}^{s}_{dio} \end{bmatrix}_{(6,6)} \begin{bmatrix} \mathbf{V}^{k}_{dio} \\ \mathbf{V}^{j}_{dio} \end{bmatrix}_{(6,1)} \tag{19}$$

Inductive and capacitive mutual couplings among positive-, negative- and zero-sequence circuits are expressed with nonzero off-diagonal elements in matrices $\mathbf{Y}^{z}_{dio}$ and $\mathbf{Y}^{s}_{dio}$.

Instead of mutually admittances, the couplings can be expressed by compensation current sources. Thus, the unbalanced line model can be presented with three decoupled sequence circuits. The mutual couplings are replaced by corresponding controlled sources – current sources. More detailed explanation for the untransposed transmission lines modeling in phase and sequence domain is given in [1, 2], [5].

III. Asymmetrical load-flow solution

The phase voltages for all buses of the entire power system can be obtained performing the ALF solution. Because the sequence voltages are of interest for unbalanced factors definition, it is appropriate to use the ALF methods established in sequence domain. Presented results in this paper are obtained by Newton-Raphson method in sequence domain [2], incorporated in the Neplan 5.0 software [6]. This method is based on the system of three matrix equations each one related to the decoupled positive-, negative- and zero-sequence equivalent circuit of the power system (Eqs. (20), (21) and (22) respectively).

$$\begin{bmatrix} \mathbf{H}_d & \mathbf{N}_d \\ \mathbf{M}_d & \mathbf{L}_d \end{bmatrix} \begin{bmatrix} \Delta\theta_d \\ \Delta \mathbf{V}_d / \mathbf{V}_d \end{bmatrix} = \begin{bmatrix} \Delta \mathbf{P}_d \\ \Delta \mathbf{Q}_d \end{bmatrix}. \tag{20}$$

$$\mathbf{Y}_i \cdot \mathbf{V}_i = \mathbf{I}_i\,, \tag{21}$$

$$\mathbf{Y}_o \cdot \mathbf{V}_o = \mathbf{I}_o\,. \tag{22}$$

Actually, the matrix Eq. (20) has the same form as the equations that represent the symmetrical Newton-Raphson load-flow model. The other two supplementary systems given by Eqs. (21) and (22) are systems of linear equations.

IV. Study cases – calculation of unbalance factors

The influence of untransposed HV transmission lines on the degree of unbalance was studied on the entire power system of the Republic of Macedonia. In the performed analyze are included 50 buses of 400, 220 and 110 kV voltage level, 53 lines, 5 interconnective transformers and 9 equivalent generators with step-up transformers. All 400 and 220 kV lines are untransposed, and real phase arrangements shown in Fig. 5 are taken into account.

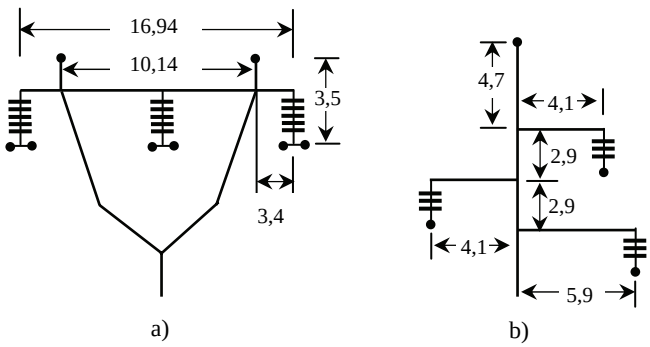

Fig. 5. Phase conductors and ground wire arangement for untransposed a) 400 kV line and b) 220 kV line (*produced by EMO-Ohrid).

The mentioned power system is shown in Fig. 6, only with buses in which the unbalance factors are calculated. The rest parts of Macedonian power system and connections with neighborhood's power systems are presented with blocks.

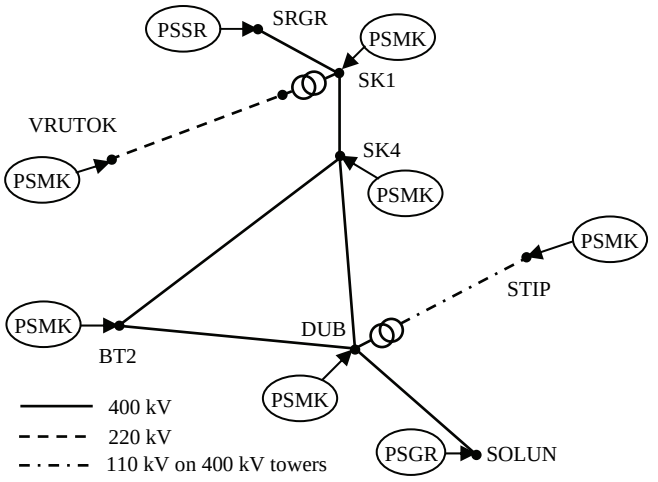

Fig. 6. Untransposed lines and their connections in power system of the Republic of Macedonia - PSMK.

Two cases with all balanced loads were studied. In the first case, all transmission lines are treated as balanced. The solution for voltages in each node of the system buses shows that only positive-sequence voltages exist and they are equal with phase voltages. For this case the voltage in phase (node) *a* for the bus *j* is denoted as $\underline{V}_{abal}^{j}$ and it is equal with positive-sequence voltage $\underline{V}_{d}^{j}$. This notation is necessary for definition an unbalanced factor for positive-sequence voltages, when asymmetrical state of the system is compared with the symmetrical state for the same system. In this case total active power loss is $\Delta P_{bal} = 31{,}22$ MW .

In the second study case, all 400 and 220 kV lines are taken with their real parameters. Presence of six 400 kV lines with total length of 376,7 km, one 220 kV line with 65,2 km and one 110 kV line with length of 40 km (build on 400 kV towers), cause asymmetrical state and appearance of sequence voltages and currents. Because the sequence components have unwanted effects on the power system elements it is desirable to measure the degree of system unbalance. For this purpose the unbalance factors (usually in %) are introduced. Unbalanced factors for positive-, negative- and zero-sequence voltages are given with Eq. (23) respectively.

$$F_d = \frac{V_d}{V_{abal}} \cdot 100\,; \quad F_i = \frac{V_i}{V_d} \cdot 100\,; \quad F_o = \frac{V_o}{V_d} \cdot 100\,. \qquad (23)$$

If $F_d = 100\%$ and $F_i = F_o = 0\%$ power system is in symmetrical state. Asymmetrical power system states, which deviate more or less from symmetrical state have greater or smaller unbalanced factors F_i and F_o. Results from study cases are shown in Table I. Although, the unbalanced factors for negative- and zero-sequence voltages are small, the total active power loss in second case is $\Delta P_{unbal} = 37{,}28$ MW .

TABLE I
RESULTS FOR UNBALANCED FACTORS

bus	V_{abal} (kV)	V_{L1} (kV) V_{L2} (kV) V_{L3} (kV)	F_d (%)	F_i (%)	F_o (%)
BT2 400	226.328	226.507 225.760 226.697	100.003	0.0977	0.1263
DUB 400	224.525	225.039 224.363 225.192	100.1512	0.1224	0.1363
SK4 400	221.696	222.552 221.671 222.567	100.2556	0.1481	0.2047
SK1 400	221.446	222.382 221.434 222.394	100.2816	0.2023	0.1858
STIP 110	59.577	59.829 59.570 59.816	100.2699	0.2133	0.2371
SK1 220	117.196	117.568 117.090 117.638	100.2045	0.1942	0.1973
VRU 220	117.604	117.896 117.477 118.084	100.1659	0.3446	0.5628

V. CONCLUSION

The presence of untransposed HV transmission lines causes asymmetrical states in the power system. These states have unwanted effects on the power system elements and there is a need for their quantification. For evaluation of the unbalance degree, the unbalanced voltage factors are introduced. In this paper, the procedure for untransposed line modeling in phase and sequence domain is presented. Decoupled-sequence line model is applied in the Newton-Raphson method for asymmetrical load flow calculation incorporated in Neplan 5.0 software. Two real state cases of the Macedonian power system are studied. Results from the studies show that in the case with untransposed lines, although the unbalance factors are small, total active power loss growth for 6 MW, against the case when lines are treated as transposed.

REFERENCES

[1] J. Arrillaga, C.P. Arnold, B.J. Harker, *Computer Modelling of Electrical Power Systems*, John Wiley & Sons Ltd, 1983.
[2] X.-P. Zhang, "Fast Three Phase Load Flow Methods", IEEE Trans. on PS, Vol. 11, No. 3, pp. 1547-1554, August 1996.
[3] V. Strezoski, Lj. Trpezanovski, "Three–phase asymmetrical load–flow", International Journal of Electrical Power and Energy Systems, Vol. 22, No. 7, pp. 511-520, October 2000.
[4] N. Rajakovič, *Analiza elektroenergetskih sistema I*, Elektrotehnički fakultet, Akademska misao, Beograd, 2002.
[5] M.S. Chen, W.E. Dillon, "Power System Modeling", Proc. IEEE, Vol. 62, No. 7, pp. 901-915, July 1974.
[6] Neplan 5.0 software, BCP Switzerland (Educational version for Faculty of Technical sciences - Bitola).