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COMMUNICATIONS

Impact of impedance unbalance on the efficiency of electricity transmission and distribution - A case study

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This article is devoted to the analysis of the possible influence of impedance asymmetry on the efficiency of electricity transmission and distribution in the electricity system in Slovakia, at a voltage level of 110 kV - 400 kV, using synchronic phasor monitoring results. For simplicity of calculations, in practice, the impedance imbalance from mutual interfacial inductive capacitances bonds is neglected. In this way, the 3-phase network is interpreted as symmetrical in the calculations. In this case, it is possible to determine only some components of losses (ohmic losses, corona loss, leakages, *etc*). The influence of impedance asymmetry can be quantified by calculation using the results of the monitoring of the synchronous phasors of selected electricity system elements (OHL, transformer, choke) or by 3-phase modelling of real system elements. frequency to test the transformer for induced over voltage test, and its characteristics is analysed.

K e y w o r d s: efficincy of power transmission system; power transmission system; unbalance; losses reduction

1 Introduction

The issue of increasing energy efficiency is in all countries respecting the conclusions of the Paris Convention on Climate Conditions, closely linked to the reduction of electricity losses. Transmission and distribution of electricity are one of the areas where savings of non-renewable primary energy sources (coal, natural gas, oil) can be achieved within the SR the increase energy efficiency (e.g. by reducing losses in electricity transmission and distribution). The legislative of energy efficiency in the Slovak Republic is solved by the Act no. 321/2014 Col. and the Energy Efficiency Action Plan of the Slovak Republic, which brings together the requirements of Directive 2002/36/EC on energy services and the new requirements of Directive 2012/27/EU on energy efficiency. In line with the new Directive 2012/27/EU, the area of energy conversion, transmission and distribution (reducing the energy intensity of electricity transmission and distribution) is part of the Third Action Plan. The savings achieved in the transmission and distribution can be counted towards the fulfilment of the set goals related to SR energy savings.

Detailed quantification of the loss of electricity is an extensive and highly complicated task. The resulting loss value affects the variability of operating modes, the uncertainty of total energy transmission, and the methodology for calculating total losses, the magnitude of which can be affected by hidden (latent) losses. These include, for example, as well as power losses due to asymmetry of voltage and current phasor star [1]. How and where do these losses arise? What is their size? How can they be reduced or eliminated? Just advances in measuring and computing technology bring new possibilities for evaluating these power losses and allow answers to the above questions.

2 Unbalance in the transmission system

The loss balance for electricity transmission and distribution is usually evaluated in the calculations based on the simplistic assumption of an exactly symmetric 3-phase system replaced by a 1-phase scheme, thereby automatically neglecting the effects of unbalanced elements generating the zero and negative components of voltages and currents. The results of such calculations do not make possible to objectively examine all possibilities of increasing the efficiency of electricity transmission [1]. On the other hand, exact calculation of the size of asymmetry of phasor star of voltages and currents requires a new approach to calculations and measurements, as described below.

Losses in the electrical system (ES) can be quantified by a set of equations utilizing the results of measured time waveforms of active power and voltage on individual network parts. At present, the latest measurement technique allows to provide a time-synchronized vector recording of electrical quantities in selected ES nodes. With a high sampling rate (*eg* 100 kHz sampling, it is possible to obtain 2000 samples for the waveform of $u(t)$, $i(t)$ with a 50 Hz network frequency). This gives a comprehensive picture of monitored electrical quantities and enables detailed analysis and quantification of individual

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components of electricity loss on any individual part of the system. The total complex loss $\Delta \boldsymbol{S}$ on any piece of line can be calculated from the difference of the complex power at the beginning $\boldsymbol{S}^{(b)}$ and ending nodes $\boldsymbol{S}^{(e)}$ for each of A, B, C phases, respectively

$$\Delta \boldsymbol{S} = \boldsymbol{S}^{(b)} - \boldsymbol{S}^{(e)} = \\ = \begin{bmatrix} \Delta\mathcal{S}_A \\ \Delta\mathcal{S}_B \\ \Delta\mathcal{S}_C \end{bmatrix} = \begin{bmatrix} \mathcal{S}_A^{(b)} \\ \mathcal{S}_B^{(b)} \\ \mathcal{S}_C^{(b)} \end{bmatrix} - \begin{bmatrix} \mathcal{S}_A^{(e)} \\ \mathcal{S}_B^{(e)} \\ \mathcal{S}_C^{(e)} \end{bmatrix}, \tag{1}$$

where $\mathcal{S} = \mathcal{U}\mathcal{J}^*$ - is the so called complex power and where $\mathcal{U} = U_{\rm rms}\exp(j\phi)$ and $\mathcal{J}^* = I_{\rm rms}\exp(-j\psi)$.

One of the components of the total loss that is the subject of the analysis in this paper are losses in ES due to impedance unbalance arising on impedance-unbalanced electrical machines, apparatus, regulating and compensating devices located in electrical stations interconnected by unbalanced OHL and cable lines.

The total complex loss in case of asymmetric system (due to unbalanced impedances) in a branch or any other part can be expressed by decomposing the complex power at the beginning and ending nodes into zero (0), and tye two symmetrical: forward (1) and backward (2) components

$$\Delta \boldsymbol{S}_n = 3\left[\Delta \boldsymbol{S}_0 + \Delta \boldsymbol{S}_1 + \Delta \boldsymbol{S}_2\right] = \\ = 3\left[\boldsymbol{S}_0^{(b)} - \boldsymbol{S}_0^{(e)} + \boldsymbol{S}_1^{(b)} - \boldsymbol{S}_1^{(e)} + \boldsymbol{S}_2^{(b)} - \boldsymbol{S}_2^{(e)}\right] \tag{2}$$

the difference, to represent the loss, due to asymmetry of the system is therefore

$$\Delta \boldsymbol{S} = \Delta \boldsymbol{S}_n - \Delta \boldsymbol{S}_1 = \\ = 3\left[\boldsymbol{S}_0^{(b)} - \boldsymbol{S}_0^{(e)} + \boldsymbol{S}_2^{(b)} - \boldsymbol{S}_2^{(e)}\right] = \\ = \Delta \boldsymbol{P}_n + j\Delta \boldsymbol{Q}_n \tag{3}$$

where

$$\Delta \boldsymbol{P} = \begin{bmatrix} P_A \\ P_B \\ P_C \end{bmatrix}, \text{ and } \quad \Delta \boldsymbol{Q} = \begin{bmatrix} Q_A \\ Q_B \\ Q_C \end{bmatrix}.$$

Here P_A, P_B, P_C and Q_A, Q_B, Q_C are the active and reactive losses at a given branch or any other part of the transmission line.

2 Impedance asymmetry of chosen transmission system elements

Non-transposed EHV and HV OHL are a typical unbalanced element of the power system. The cause of the asymmetry is the longitudinal impedance inhomogeneities, caused by: changing the configuration of the masts (Portal, Single-web, Warren, Pratt, *etc*), phase sequence on the mast brackets, changing the phase conductors type and ground ropes in particular sections of the OHL, paralleling with other lines, etc. The magnitude of the impedance unbalance of the OHL can also be affected by its own unsymmetrical operating modes. They are forced by the asymmetry of the star phasors of nodal voltages and branch currents of the individual phases due to an asymmetric load.

Determining the effect of the impedance unbalance of the OHL on the efficiency of transmission or distribution of electric energy can be achieved by combining the vector record of electrical quantities at the input and output of the investigated line and the subsequent calculation of the operating impedance and admittance matrices. The calculation of the operating impedance and admittance matrices results from the 3-phase impedance $[\mathcal{Z}_{ABC}]$ and admittance $[\mathcal{Y}_{ABC}]$ matrix of the individual phases in generally $3n$-conductor system with grounding rods in matrix form, which have their own (phase-ground) and inter-phase inductive and capacitance bonds between all conductors. For the calculation of impedance and admittance matrices, the following input data are required: type, mast configuration, voltage level, conductor length, phase and ground conductor type, geometric distribution of phase conductors on masts, type and number of masts, amount of transmitted power by line [5].

The results of the project in the past confirmed the usability of the synchronous phasor monitoring to determine the size of the loss by asymmetry of the OHL. Vector records, operating variables u(t) and i(t) were recorded by PMU DEWE 571 (synchronous phasor measurement assemblies with 100 kHz sampling frequency). As an example, we present the results of monitoring on a simple 110 kV electric line with a length of 24,586 km, consisting of 103 pieces of Fi - narrow type masts. Three types of phase conductors (AlFe 150/25, AlFe 240/39 and AlFe 185/31) and KZL earth wire (F506-325-024) were installed on the line. At the time of monitoring, the average load of the single power line was 97 A, the average value of the associated voltage was 118.645 kV. Measurements took place in September between 9:00 and 14:00 in dry sunny weather and an average air temperature of 25 °C.

Based on the measured results, it was possible to quantify the operational impedance and admittance matrices by mentioned relations and to determine the size of the impedance inhomogeneity as well as the phasors asymmetry of stars of nodal voltages and branch currents, and thus the size of the losses due to the impedance asymmetry. On the analysed 110 kV line, the loss rate due to impedance imbalance ranged from 3.835 to 4.499 kW. This represented 6.01 to 7.67 % of total losses. An important parameter of the asymmetry evaluation according to STN EN 50160 is the voltage asymmetry coefficient. The value of this coefficient determined by the standard is 2%.

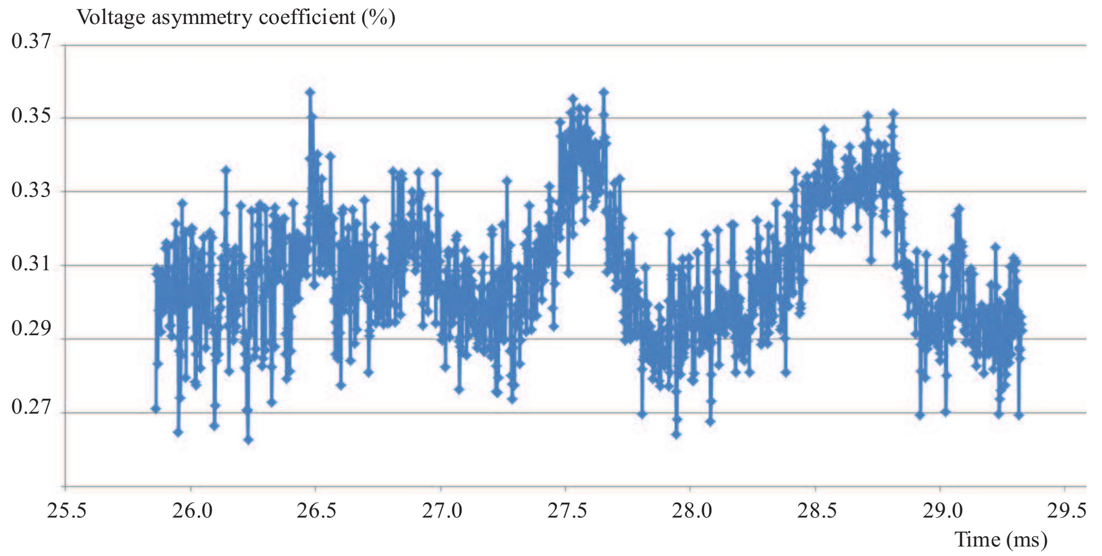

Fig. 1. Voltage asymmetry coefficient on single 110 kV OHL

The height of the voltage asymmetry coefficient value ranged from 0.26 to 0.36% (see Fig. 1).

Two-and three-winding HV an EHV power transformers are generally considered to be symmetrical in the calculations. However, the impedance imbalance of the transformers exists and depends on the design of the magnetic circuit of their core (core or shell construction), further on the asymmetry of the construction of the 3-phase primary and secondary windings, the clock angle and the corresponding internal current connections of the primary and secondary windings of the transformer. This fact is highlighted by the number of measurements and published publications on this issue [7, 8].

The magnitude of impedance unbalance also depends on the load of the transformer. For this reason, it is necessary, inter alia, to carry out the monitoring of the time courses, respectively phasors of phases values $(\mathcal{U}_A, \mathcal{U}_B, \mathcal{U}_C, \mathcal{J}_A, \mathcal{J}_B, \mathcal{J}_C)$ of the primary, secondary and tertiary voltages and currents of the transformers in real operation. Using these, the symmetric components of phasors of primary, secondary and tertiary voltages $(\mathcal{U}_0, \mathcal{U}_1, \mathcal{U}_2)$ and currents $\mathcal{J}_0, \mathcal{J}_1, \mathcal{J}_2$ by calculation is determined voltage and current asymmetry and imbalance of the 3-phase system on primary, secondary and tertiary at different transformer loads. Subsequently, it is possible to determine the impedance matrices of own and mutual impedances $[\mathcal{Z}_{ABC}]$ between primary/secondary, primary/tertiary and secondary/tertiary. For the calculation of impedance and admittance matrices, the input data on the transformer label (clock angel, transformer ratio, no-load current and short current), type and arrangement of the transformer core are necessary [7, 8].

The magnitude of the impedance imbalance of the compensating chokes is dependent on the design, the geometric arrangement, and their electrical connection to the transmission system.

Compensating chokes constructed as air coils can be connected separately for each phase as separate units arranged in a row (geometrically unsymmetrical arrangement) or into a triangle (geometrically symmetrical arrangement). In both cases, the presence of impedance asymmetry can be ascertained. The existence of this asymmetry is due to another magnitude of the electromagnetic field, which is generated by the transition of the electric current through the border coils to the coil located in the centre of the array of three separate coils of compensating coils.

Similarly, this applies even if the coils are installed in a metal container. The coil of the compensator choke installed in a common metal vessel placed in a row (in a triangle), or in the case that each coil of the compensating choke is installed separately in its own metal container, can be considered as impedance unsymmetrical. If the three coils of the compensator choke were arranged in a row in a common metal vessel, the impedance unbalance would be higher than the arrangement of these coils in a triangle. The cause is a higher magnetic bond than in a common metal container.

To determine the impedance and admittance matrices, input data such as the geometric arrangement, the design layout, and the compensation choke connection in the transmission system are required.

3 Conclusion

The size of loss by impedance asymmetry is dependent on the input design parameters (layout and placement of the conductors), but also the method of operation (load) of the ES elements. Applying the monitoring of the synchronic phasors on the individual elements of the ES and using the measured data for the calculation of the impedance and admittance matrices, it is possible to determine the effect of the impedance asymmetry on the efficiency of transmission and distribution of electric energy. The Slovakian TS operator for 2016 declared the efficiency of the transmission of electric energy with a value of 99.92 % [9]. Improvement in transmission efficiency due to reduction in impedance unbalance of OHL by 0.1 % leads to a reduction of total losses of 287 MWh. Designing appropriate measures to reduce the size of losses by reducing asymmetries have the potential to increase the overall efficiency of transmission and distribution of electricity in the ES SR.

One way to reduce the loss due to asymmetry on the OHL is to replace the position of the wires on the line by twisting. Twists can be complete (all wires change their position) or partial (only two wires change their position). For example, symmetrisation of the analysed 110 kV OHL at three locations in 1/3 of the length of the line can reduce asymmetry losses by 40 % to 60 % [10].

The issue of losses due to asymmetry on ES SR facilities will be further analysed in the APVV research project. Attention is paid to selected elements in which several measurements and calculations will be carried out in the next stages of the project. The aim of the project is to quantify the size of losses caused by asymmetry and to assess the possibilities for increasing transmission and distribution efficiency in 110 - 400 kV networks.

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