Reducing the Active Power Losses in Transmission Network by Using Phase Shifting Transformer

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Abstract—**This paper analyses the possibility of decreasing the active power losses in 110 kV transmission network in BiH/RS by using phase shifting transformer. The network before and after connection of phase shifting transformer on the line with the largest power flow is simulated by a commercially available software package. The optimal phase shift required to minimize the overall losses in the transmission network is determined by a search through simulation results.**

Keywords - phase shifting transformer, power flows, power losses.

I. INTRODUCTION

The main role of Phase Shifting Transformer (PST) is to control active power flows in a steady state in transmission networks with many line loops and parallel lines [1].

The PSTs are devices of a great significance in current tendency for increasing transmitted power through existing lines and improving the efficiency of the network. Modern transmission networks are usually loaded close to their transmission limits. The PST is proposed as one of the most cost-effective solution that efficiently controls the flows of active power through network, and therefore optimizes network operation, improves system stability and thus reduces the active power losses.

Apart from avoiding overloading and instability problems in transmission networks, PSTs can help to decrease operational costs by performing optimized delivery of energy to consumers in post-failure state (state after damage). Furthermore, by using PSTs, investments in electrical power system (EPS) can be postponed by using the existing transmission lines operating on the limits of their thermal capabilities without overloading.

Phase shifting transformers are used for [2]:

- controlling active power flows in parallel lines,
- increasing of transmission capacities without violation of n-1 safety criterion,
- increassing the system reliability,
- decreasing the post-failure line overloads,
- eliminating unwanted power flows,
- removing bottlenecks in the network caused by concentrated power injection.

This paper describes the importance of using PSTs in the regulation of active power flows through lines of 110kV network in the part of electric power system of Bosnia and Herzegovina, with the aim of decreasing overall active power losses.

The paper is organized in two parts. The first part gives the basic principles of PSTs, while in the second part a computer model of 110kV network in program package PowerWorld Simulator (PWS) [3] is developed, in order to calculate power flows and active power losses in an EPS for the case with and without using the PST. Results of the calculation are given at the end of the paper.

II. PHASE SHIFTING TRANSFORMER

Due to mainly inductive character of transmission lines of the EPS, the active power flow between the source and consumer is defined by phase difference between voltages on the input and output of the line. In order to control active power flows, the phase shifting transformer can be used. The voltage phase shift is based on proper connection of the primary and secondary phase windings of the PST.

The active power P that is transmitted by transmission line from the sending node k to the receiving node m, (Figure 1a), is calculated by [4]:

$$P = \frac{U_k \cdot U_m}{X_L} \cdot sin(\theta_k - \theta_m). \quad (1)$$

From (1) it can be seen that active power P is proportional to the modules of voltage at the beginning and the end of transmission line, the sine of the phase angles difference between the beginning and the end of the line, and also inversely proportional to the reactance of the line X_L.

Relation (1) gives the basics for possible techniques of the active power flow control through a network branch. As voltage modules do not change significantly in normal operation (values are defined by standards), and reactance of transmission line X_L is constant in normal operation modes, the difference of phase voltage angles θ_k - θ_m remains a possibility for controlling the active power flows.

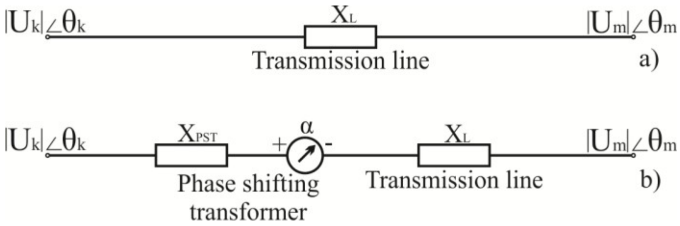

Figure 1. Transmission line with and without PST [4]

If the PST is placed between the nodes k and m on a transmission line (Figure 1b), the equation (1) is modified to:

$$P = \frac{U_k \cdot U_m}{X_L + X_{PST}} \cdot sin(\theta_k - \theta_m + \alpha), \tag{2}$$

where X_{PST} is the reactance of PST, and α is the phase angle of PST.

Figure 2 gives a comparison of the transmission of active power through the line with and without PST. The line parameters are $\underline{U}_k = 1.050\angle 0°$ [p.u.], $\underline{U}_m = 0.997\angle 0.475°$ [p.u.], and $X_L = 0.205$[p.u.], while the parameters of PST are $X_{RFT} = 0.125$ [p.u.] and $\alpha = 20°$.

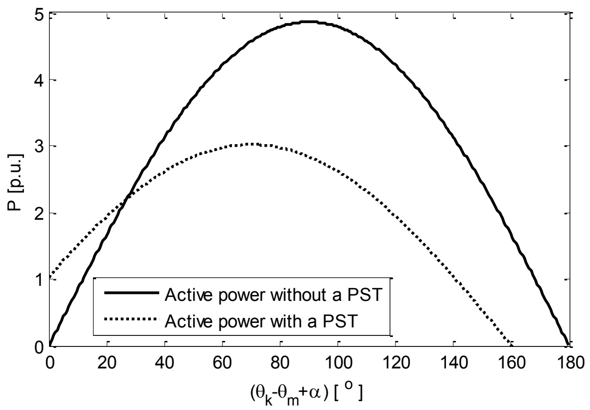

Figure 2. Active power flows without and with a PST

From the Figure 2 it can be seen that by using PST the transmitted active power can be increased if the angle $\theta_k - \theta_m + \alpha$ ranges between 0° and 26.93°.

A. Principles of Operation of Phase Shifting Transformer

The general principle of operation of PST is based on the connection of a part of one phase winding to the winding of another phase. In order to obtain a quadrature voltage ΔU for the phase shift regulation, the simplest solution is to use delta-connected winding on the secondary side [5]. Figure 3 shows connection of the secondary phase windings of phase L_2 and L_3. The secondary windings are split into two halves and connected in series with phase winding L_1. The regulating winding is connected by using on-load tap changer which provides regulation voltage ΔU and the phase-shift angle [5].

The phase diagram (Figure 4) shows the change of phase angle between input and output voltages for no load conditions, i.e., without considering the voltage drops in the transformer. It also should be noted that the currents in the two halves of the series winding I_{L1} and I_{L2} are not in phase. This is different from normal power transformers and has consequences with respect to the internal flux distribution [5].

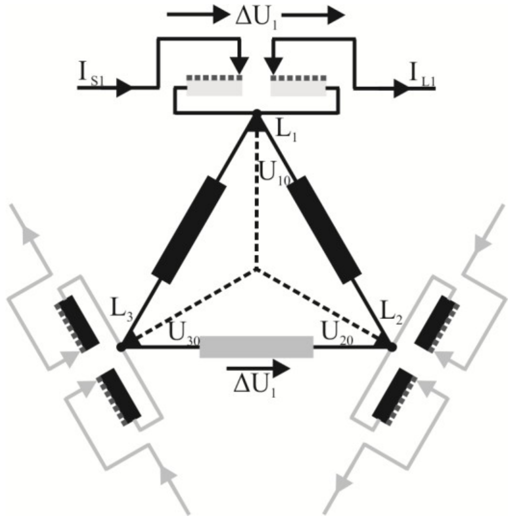

Figure 3. PST in delta-connection [5]

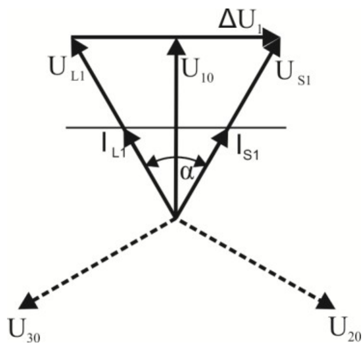

Figure 4. Phase diagram [5]

III. Minimization of Active power Loss by Application of Phase Shifting Transformers

In order to minimize the losses of active power in 110 kV transmission network of Bosnia and Herzegovina (Figure 5), a computer simulation of power flows before and after inserting PST is made in PWS.

The considered 110kV network is supplied from substation Banja Luka 6 and hydropower plants HPP Bocac and HPP Jajce, and has both single and dual lines.

The powerful 400kV network that supplies the substation Banja Luka 6 is modeled as a slack generator. Dual lines of 110kV network are modeled by the single line equivalents. The line parameters are given in the Table I.

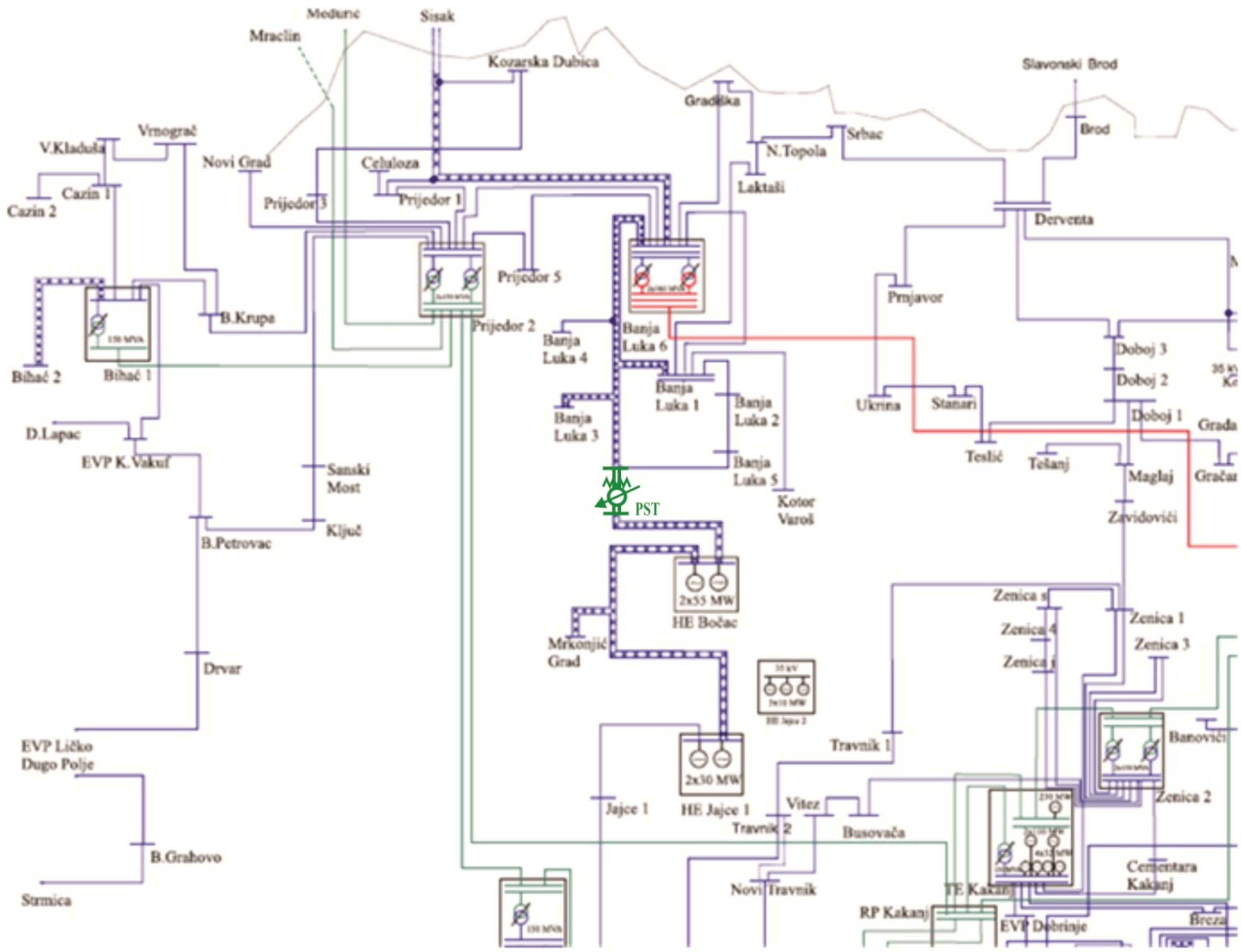

Figure 5. Part of 110kV network in BiH/RS [6]

The active power flows and losses for 110kV network from Figure 5 are at first calculated without the PST and this is considered as the base state. After that, the PST is placed on the line with the largest active power flows, in order to control active power flows through it and to decrease overall losses in the network.

By placing a PST to a series with the line with the highest active power flow, it is expected that active power flows are changed in both the observed line and the surrounding lines. Due to active power flows change, the losses also change and they are calculated by:

$$P_{loss} = R \cdot \frac{P^2 + Q^2}{U^2}, \tag{3}$$

where R is the line resistance, P and Q are the active and reactive power flows at the sending (receiving) node of the line, and U is the voltage at the sending (receiving) node of the line.

The model of the observed part of 110kV network in PWS is shown in Figure 6.

TABLE I. PARAMETERS OF TRANSMISSION LINES

Transmission line	Length [km]	x [p.u.]	r [p.u.]	Note
BL6 - Gradiška	38.2	0.12660	0.06330	Single line
BL 6 – Prijedor 1	62.6	0.10373	0.05187	Dual line
BL 6 – Prijedor 2	42.5	0.14085	0.07043	Single line
BL 6 – BL 3	15.1	0.02502	0.01251	Dual line
BL 6 – BL 1	12.7	0.02104	0.01052	Dual line
BL 3 – HE Bočac	33.1	0.05485	0.02743	Dual line
BL 1 – HE Bočac	37.2	0.06164	0.03082	Dual line
BL 1 – BL 2	4.50	0.01491	0.00746	Single line
BL 2 – BL 5	10.4	0.03447	0.01724	Single line
BL 5 – Grbići	1.80	0.00597	0.00300	Single line
HE Bočac – MG	15.4	0.02552	0.01276	Dual line
HE Bočac – Jajce 1	23.3	0.03861	0.01931	Dual line
MG – HE Jajce 1	19.3	0.03198	0.01599	Dual line
Prijedor 1 – Prijedor 2	3.70	0.01226	0.00613	Single line

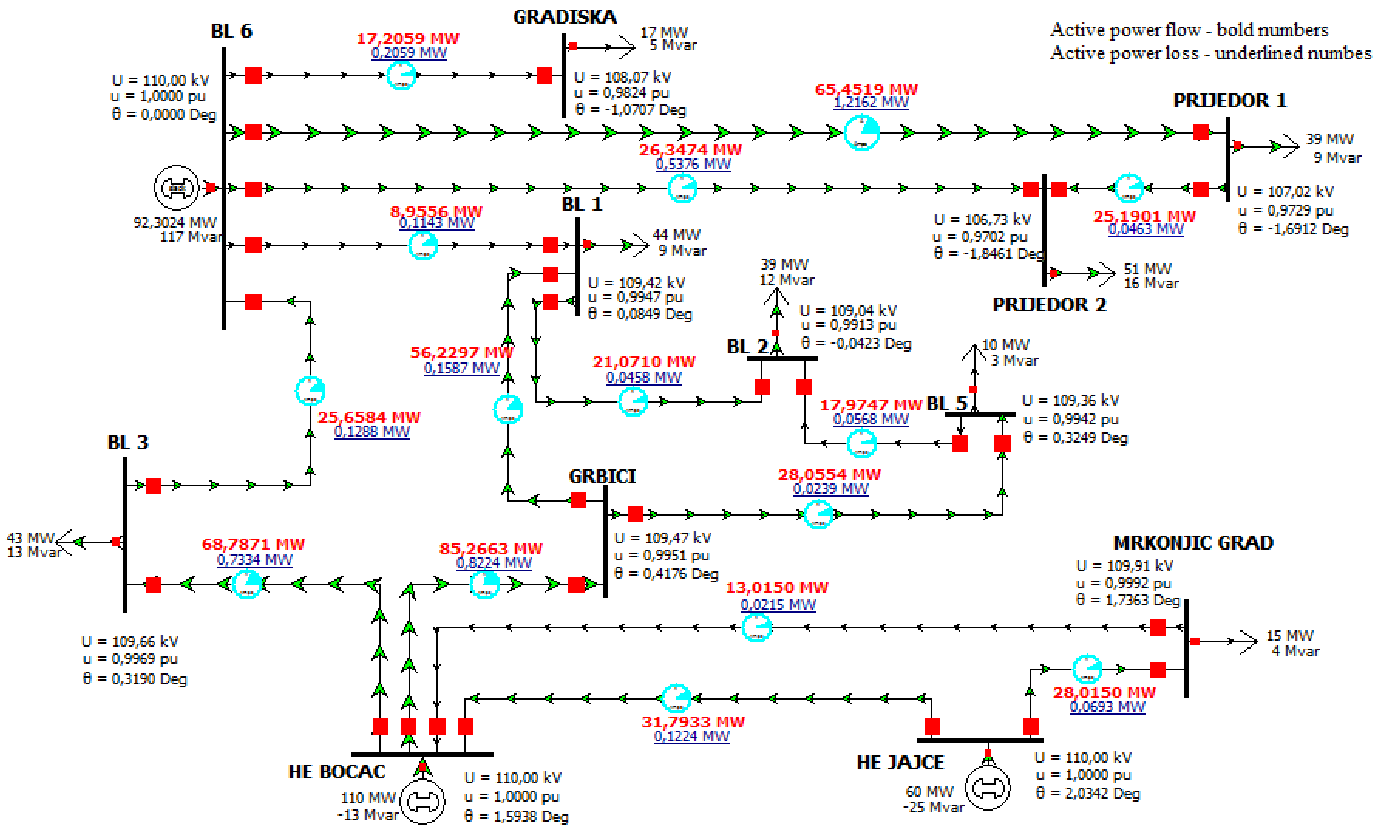

Figure 6. The PWS model of the system under consideration

The overall active power losses for the base case (without PST) for the observed network are 4.3033 MW.

In order to reduce the active power losses, the PST is placed in series with a line with the highest active power flow (Hydropower plant Bočac - Grbići, Figure 5). The phase angle of PST is changed from -20° to 20° in steps of 1° and for each phase shift the overall active power losses in the network are calculated (Figure 7).

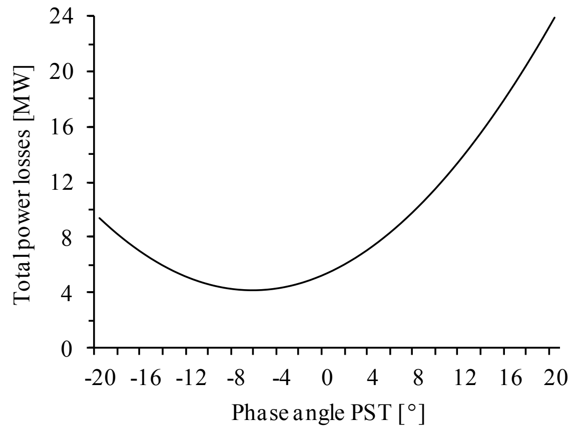

Figure 7. Overall active power losses as a function of the PST phase angle shift

The minimum overall active power losses are obtained for the PST shift angle equaling approximately -6°. The losses are reduced down to 4.1965MW, which is 2.48% lower than in the base case.

If the phase angle is further changed within the range of -6° to -7° (Figure 8) in steps of -0.1°, the minimum active power losses are obtained for the phase angle of -6.5° and they equal to 4.1878MW, or 2.68%. Relative decrease of overall active power losses in network as function of the PST phase angle shift is given in the Figure 8. Certainly, the resolution of the optimization search should be in a compliance with the resolution of the PST shift angle change.

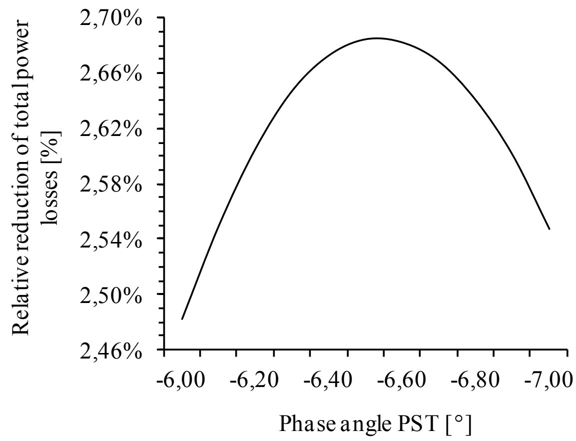

Figure 8. Relative reduction of overall active power losses as function of the PST phase angle shift

The resulting change of the active power flows does not cause overload of any line in the observed network. The voltage conditions in the network upon installing the PST with set phase angle of -6.5° are also within their permissible limits.

IV. Simplified Cost-Benefit Analysis

A simplified cost-benefit analysis for the proposed solution for minimizing power losses can be conducted by comparing the investment costs of PST and savings obtained through decreasing of the losses. Since the active power flow through the branch in which the PST is located equals 89.6434 MW, the PST with rated power of 100 MVA power can be used. A rough estimation of PST price is based on unit price of 20 BAM/kW, which estimate the costs of PST at 2 millions BAM. The average price of electric power in EPS on 110kV voltage level is 0,035 BAM/kWh, resulting in the savings on losses of approx. 100 BAM per day, which implies that the simple period of return is as high as 55 years. Based on the given analysis it can be concluded that savings of 2.68% in the active power losses are not enough for the investment to be profitable.

V. Conclusion

In this paper a possibility of decreasing overall active power losses in transmission network by using PST is analyzed. The PST is placed on the line with the largest active power flow with the aim of obtaining optimal power flows that shall result in minimum power losses. The results of the simulation of a part of EPS of BiH/RS show that by controlling phase angle by PST, the overall active power losses can be reduced by 2.68%. For this particular situation, the proposed use of PST is not an economically acceptable solution. In further work, a methodology for optimal selection of location for the PST, which will include both technical and economical aspects, should be developed.

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