Placement of phase shifting transformer in the Albanian Power System

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***Abstract*— Today power systems are shifting towards more complex systems, and it is becoming increasingly complex to operate the power systems. One of the direct challenges faced today by transmission system operators in managing the power system is congestion management due to high loading of transmission elements. Photovoltaic and Wind generation is increasing also in the recent years which leads to increase in unscheduled flows between transmission systems. This paper explores possible alternatives for applying advanced technologies for introducing control methods in the power system, i.e., Phase Shifting Transformers. The analysis will use as a case study the Albanian Transmission System, which at the current stage does not have phase shift transformers, but there are visible parts of the network which are heavily congested. The study uses simulation tools to analyze congested area, and comparative analysis to analyze the impact of phase shifting transformer in critical nodes of the transmission system to alleviate congestion and minimize network losses. The results show that implementation of PST's will provide an improved situation in the power system. The study clearly shows the important role of PST on enhancing security of supply and improve flexibility in the system.**

Keywords—Power System; Phase Shift Transformer; Transmission; PSS/E; Losses;

I. INTRODUCTION

The Albanian Transmission System includes 400 kV, 220 kV, and 110 kV voltage levels[1]. The Albanian Transmission Network plays an important regional role in energy transmission, especially in recent years where injections from renewable sources have significantly increased, particularly in the southeast of the Balkans. In the recent years it has been observed a notable increase in transit flows especially in direction south to north within the Albanian system. Additionally, the expansion of the regional network with new DC interconnection lines (such as Greece-Italy, Montenegro-Italy) is making the Albanian transmission system increasingly important in the regional energy transmission and market.

The transmission network extends vertically from the south to the north of the country, with the largest generators connected to the Transmission Network and most private hydropower plants, which are partially connected to the distribution system, are in northern region of the country. The largest hydro-generating plants are HPP Koman, HPP Fierza, and HPP Vau i Deja, which are owned by KESH, a public company.

In the south, we have concentrated photovoltaic plants built in the last two years. The positioning of photovoltaic plants in this area is due to the high solar irradiation in the southwest of Albania. Some of the largest photovoltaic plants are Karavasta Solar, SPV Blue 1 and Nova Solar.

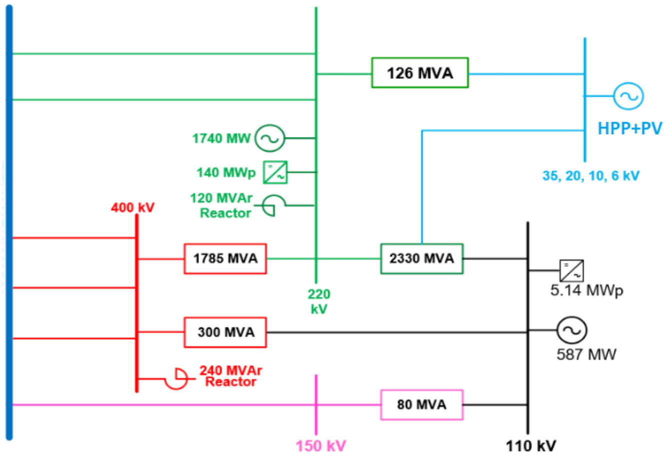

Figure 1 Simplified diagram of Albanian Power System

Regarding the load center, it is concentrated in the center and south of the country. The Albanian Transmission Network Expansion Plan aims to increase transmission capacities with neighboring countries such as Greece, Montenegro, Kosovo, North

Macedonia, and Italy (HVDC Cable). This plan will transform Albania into an important energy hub in the Southeast Europe for electricity transmission.

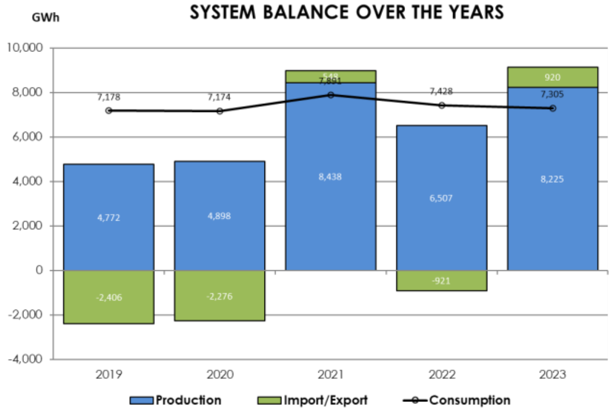

Figure 2. Albanian system balance year 2019 to 2023

In the recent years a due to strong support schemes from government in the Southeast of Europe, it has been observed an increase in renewable energy sources (RES) production, especially from Photovoltaic plants, which leads to huge transit flows. The most representative example is the case of transit flow in direction south to north, from Greece to Albania and further to Montenegro. The high transit flow clearly demands for further expansion of the transmission grid or added control feature in operating the power system[2]. Another important aspect the analysis and identification of contingencies, which have a significant role in assessing the safe conditions of operation and verify if the power system meets the security criterions. In certain situation controllable devices are needed to ensure N-1 criterion[3] for the overall power system security.

II. PHASE SHIFTING TRANSFORMER BACKGROUND

Transmission[4] of electric power between node *i* and node *j*, is represented in the figure 1:

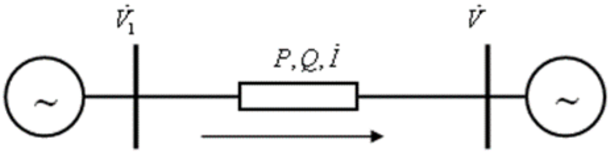

Figure 3 Power transfer between 2 nodes

Supposing that voltages in nodes i and j are:

$$\dot{V_i} = V_i * e^{j\delta_i}; \dot{V_j} = V_j * e^{j\delta_j} \quad (1)$$

A phase-shift transformer (PST) is a specialized type of transformer[5], commonly used to control active power flows in three-phase electrical transmission networks. It does this by adjusting the voltage phase angle difference between the two nodes of the system[6].

$$P_{PST} = \frac{|\dot{V_i}| * |\dot{V_j}|}{X_l} * \sin(\delta_i - \delta_j) = \frac{V_i * V_j}{X_l} sin\Delta\delta_{ij} \quad (2)$$

$$Q_{PST} = \frac{|\dot{V_i}| * |\dot{V_j}|}{X_l} * \cos(\delta_i - \delta_j) - \frac{V_i^2}{X_l} \quad (3)$$

where V1 and V2 are the voltage magnitudes of the node 1 and node 2. X_l represents the line reactance. δ represents phase angles between for nodes 1 and node 2 of V1 and V2. The PST takes part of the voltage of two neighbouring phases and combines them as an additional voltage, which is then injected into the third phase.

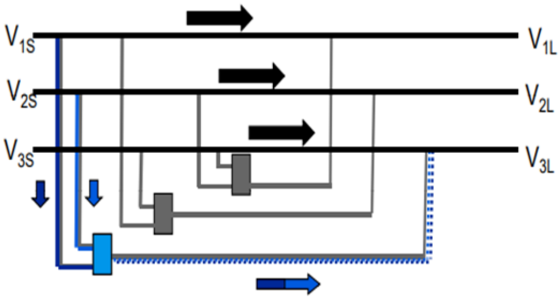

Figure 4 Voltage representation of PST addition

It can be deduced that the active power flow transmitted from bus 1 to bus 2 can be changed by the voltage V1 and V2, reactance XL, and power angle δ. Thus, PST is capable of the change of power flow value and direction through the line by controlling the power angle δ [7]. The phase angle is shifted by the angle α with the tap control of PST due to the change of its reactance. According to their construction phase shift transformers can be classified:

a) Symmetrical Phase Shift Transformer

Symmetrical phase-shift transformers are designed to change the phase angle between the input and output voltages without affecting the voltage amplitude. This type of Phase shifting transformer (PST) is used in load flow control in power system, and to maintain nominal values of voltage.

b) Asymmetrical Phase Shift Transformer

Asymmetrical PSTs also known as half tap PSTs change the phase angle and voltage magnitude. This property is desirable in cases whereas both angle and voltage magnitude adjustments are required.

c) Quadratic Phase Shift Transformer (PST)

Quadratic PSTs achieve phase angle shifts and voltage magnitude changes based on a quadratic function relationship. This feature allows for more precise adjustments, required in complex systems with stricter requirements for controlling power flows.

Practically phase shifting transformer can used to transfer in a controlled manner active power flow within the power system between the nodes it is connected.

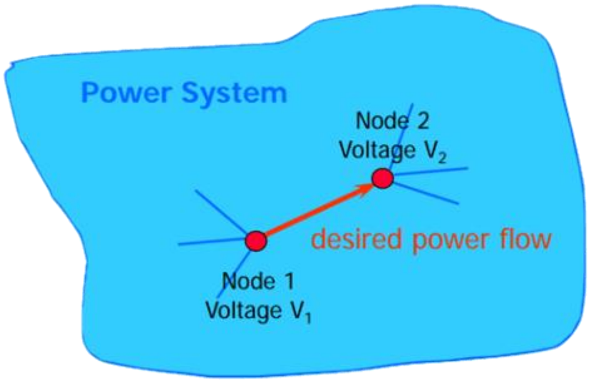

Figure 5 Phase Shifter Application in Power System

III. CALCULATION OF POWER FLOW

Transmission networks have a meshed structure and there are a very large number of possible parallel routes between generators and loads. The actual flow of power through each network element is determined by Kirchhoff's and Ohm's laws and given by Equations

$$P_i = V_i^2 Y_{ii} cos\theta_{ii} + \sum_{j=1;j\neq i}^{N} V_i V_j Y_{ij} \cos(\delta_i - \delta_j - \theta_{ij})$$

$$Q_i = -V_i^2 Y_{ii} sin\theta_{ii} + \sum_{j=1;j\neq i}^{N} V_i V_j Y_{ij} \sin(\delta_i - \delta_j - \theta_{ij}) \quad (4)$$

Generally, the flow in each line and transformer cannot be directly controlled as it is a function of generations and demands in all network nodes. Predicting future power flows plays a major role in planning the future expansion system as well as in helping to run the existing system in the best possible way. Real and reactive power flows in a network can be modified to some extent by using controllable network elements without changing the overall generation and demand pattern. Figure 3 and the simplified power flow equations, Equations (1) and (2), show that the flow of real and reactive power through a network element (i.e., a line or a transformer) is mainly a function of:

a) voltage magnitudes at both ends of the element.
b) the load (or power) angle, that is the difference between the terminal voltage angles.
c) the series reactance of the element.

These individual models are combined to model the whole network by forming the nodal network equation:

$$\begin{bmatrix} \dot{I}_1 \\ \vdots \\ \dot{I}_i \\ \vdots \\ \dot{I}_N \end{bmatrix} = \begin{bmatrix} \dot{Y}_{11} & \cdots & \dot{Y}_{1\imath} & \dot{Y}_{1N} \\ \vdots & \ddots & \vdots & \vdots \\ \dot{Y}_{i1} & \cdots & \dot{Y}_{ii} & \dot{Y}_{iN} \\ \vdots & & \vdots & \vdots \\ \dot{Y}_{N1} & \cdots & \dot{Y}_{Ni} & \dot{Y}_{NN} \end{bmatrix} \begin{bmatrix} \dot{V}_{11} \\ \vdots \\ \dot{V}_{i1} \\ \vdots \\ \dot{V}_{N1} \end{bmatrix} \text{ or } \dot{\boldsymbol{I}} = \boldsymbol{Y}\dot{\boldsymbol{V}} \quad (5)$$

Where all the elements are now real sub matrices of the form

$$\dot{\boldsymbol{I}}_\imath = \begin{bmatrix} \boldsymbol{I}_{ai} \\ \boldsymbol{I}_{bi} \end{bmatrix}, \dot{\boldsymbol{V}}_\imath = \begin{bmatrix} \boldsymbol{V}_{ai} \\ \boldsymbol{V}_{bi} \end{bmatrix}, \dot{\boldsymbol{Y}}_{\imath\jmath} = \begin{bmatrix} \boldsymbol{G}_{ij} & -\boldsymbol{B}_{ij} \\ \boldsymbol{B}_{ij} & \boldsymbol{G}_{ij} \end{bmatrix} \quad (6)$$

Quite often it is convenient to 'mix' the coordinate systems so that the voltages are expressed in polar coordinates as in equations (2) and (3) while the admittances are expressed in rectangular coordinates as;

$$Y_{ij} = G_{ij} + jB_{ij}$$

Equations (2) and (3) then take the form

$$P_i = V_i^2 G_{ii} + \sum_{j=1;j\neq i}^{N} V_i V_j [B_{ij} \sin(\delta_i - \delta_j)] + G_{ij} \cos(\delta_i - \delta_j) \quad (6)$$

$$Q_i = -V_i^2 B_{ii} + \sum_{j=1;j\neq i}^{N} V_i V_j [G_{ij} \sin(\delta_i - \delta_j)] B_{ij} \cos(\delta_i - \delta_j) \quad (7)$$

Basically, a power flow solution predicts what the electrical state of the network will be when it is subject to a specified loading condition. The result of the power flow is the voltage magnitude and angle at each of the system nodes. These bus voltage magnitudes and angles are defined as the system state variables (or independent variables) as they allow all the other system quantities, such as the real and reactive power flows, current flows, voltage drops, power losses and so on, to be computed.

The starting point for any power flow study is the set of generation and load data with the electrical network being described by the nodal admittance matrix Y of Equation (5). Usually, the generation and load data are given in terms of the scheduled real and reactive power generation at the generator nodes and the predicted real and reactive power demand at the load nodes, rather than in terms of current injections. This means that the relationship between the data inputs (real and reactive power nodal injections) and the state variables (nodal voltage magnitudes and angles) is nonlinear, as indicated in Equations (4) or (6) and (7).

The power flow problem described by Equations (4) or (6) and (7) is nonlinear and therefore must be solved iteratively. The first load flow computer programs used the Gauss–Seidel method because this required little computer memory. Nowadays, with increased computer speed and on-chip memory, the Newton–Raphson method is used almost exclusively.

IV. CASE STUDY

To study the application of PST transformers in the Albanian system, the authors have identified 2 potential locations to achieve the objective of reducing overloads in 220kV network and reducing overall transmission losses in the system. The chosen locations are:

a) Substation Koman, where a 600MW hydro power plant is located, 4X220kV lines and 2 X 400kV lines is nearby.
b) Substation Fierze, where 500MW hydro power plant is located, 4 X 220kV overhead lines, and 2 X 400kV line is nearby.

The locations have been chosen to increase the flow between 220kV network where major part of generation is located and 400kV transmission lines.

Phase shifting Transformers linking 400kV and 220kV, will be used with the objective of reducing the loading in 220kV network and increasing the loading of 400kV transmission lines. The 400kV transmission lines are underloaded compared to their nominal capacity of 1.3 GW, operating also in higher voltage than nominal due to low load.

PSS/E version 33 from Siemens is used with a complete power flow working model will be used to perform the simulations. Figure 6, shows single line diagram from PSS/E simulation tool representing PST in Koman without changing the tap positions.

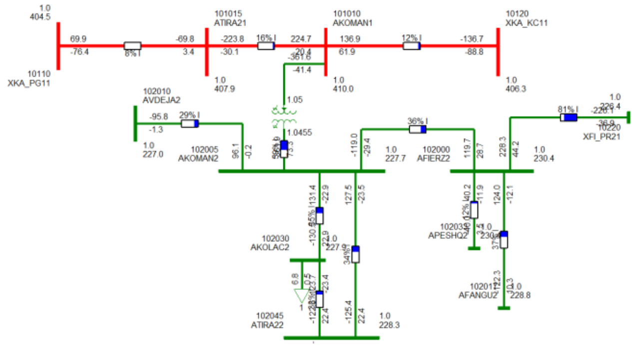

Figure 6 Single line diagram of area of interest

The lines to be monitored and used for comparative analysis are represented in Table I.

TABLE I. MONITORED TRANSMISSION LINES

ID	Voltage	Node1	Node2
1	400	Koman	KosovaB
2	400	Koman	Tirana2
3	220	Koman	Fierze
4	220	Koman	Vau Dejes
5	220	Koman	Kolacem
6	220	Koman	Tirana2
7	220	Fierze	Prizren
8	220	Fierze	Peshqesh
9	220	Fierze	Titan

One Phase Shift Power Transformer has been modelled in Koman substation, with the following parameters:

TABLE II. PHASE SHIFT TRANSFORMER DATA

Nameplate data	Value	Unit
S	600	MVA
U1	410	kV
U2	230	kV
Uk	13.5	%
I0	0.1	%
Load losses	570	kW
No Load losses	105	kW
Taps	+/- 10	degree

The same phase shift transformer data have been used for modelling the PST in Fierze substation for connecting 400kV and 220kV voltages. The main difference is that for the second case a PST will be added to Fierze substation, in Koman, the existing Power Transformer 400/220kV 345MVA, will be kept in operation. In doing so we will be looking at the current situation of the transmission network and analyze the potential impact of only adding one phase shift transformer, hence reducing initial investment costs. It is known from literature that phase shift power transformer has at least a ratio 1:10 in terms of costs compared to standard Power Transformers.

V. RESULTS AND DISCUSSION

Error! Reference source not found., shows results of installation of PST in Koman substation, between 400kV and 220kV busbars. The change in tap positions of PST in Koman, for different angles shows a steep decrease in total active power losses from 60.2MW for angle -7 Degree and a flow of 150MW in the PST, to 49.3MW losses, for a 600MW flow in the PST.

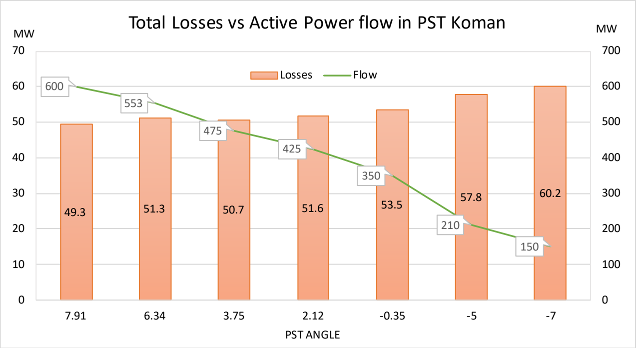

Figure 7 PST Koman active power flow vs total active losses in the system

Figure 8, shows the comparison of flows for the monitored transmission lines in the area of interest. As it can be observed the Phase shift transformer is highly effective in decreasing the power flow for most loaded transmission lines.

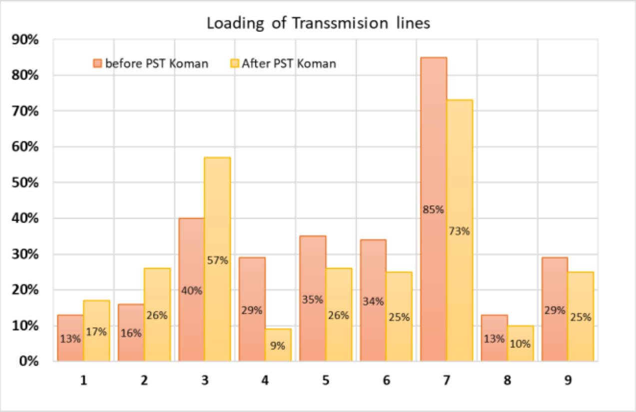

Figure 8 Comparison of Overhead lines loading with and without PST in Koman

Figure 9, shows results of installation of PST in Fierze substation, between 400kV and 220kV busbars. The change in tap positions of PST in Fierze, for different angles shows a steep decrease in total active power losses from 54.4 MW for angle -7 Degree and a flow of 35MW in the PST, to 46.9MW losses, for a flow 505MW in the PST in Fierze.

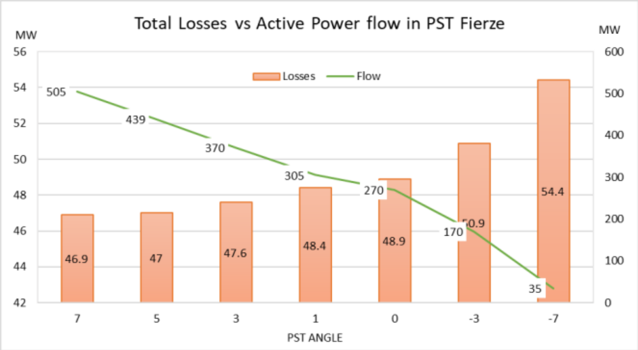

Figure 9 PST Fierze active power flow vs total active losses in the system

Figure 10, shows the comparison of flows for the monitored transmission lines. As it can be observed the Phase shift transformer will reduce the loading of transmission lines in 220kV, thus reducing congestion in the area.

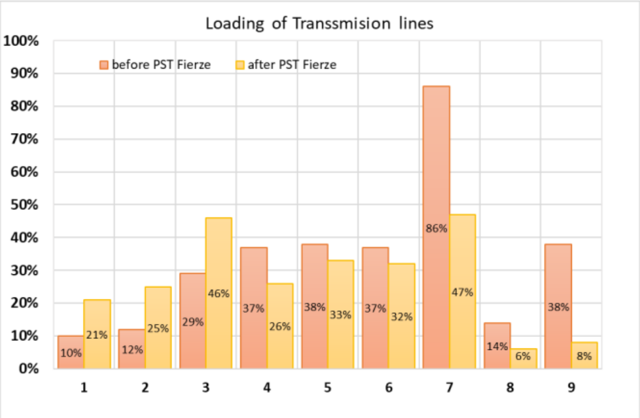

Figure 10 Comparison of Overhead lines loading with and without PST in Fierze

Beside power flows and active power losses, another indicator has been used to compare the cases for analyzing the benefits of phase shifting transformer in Albanian Power System. Bothe cases have been compared in terms of voltage improvement.

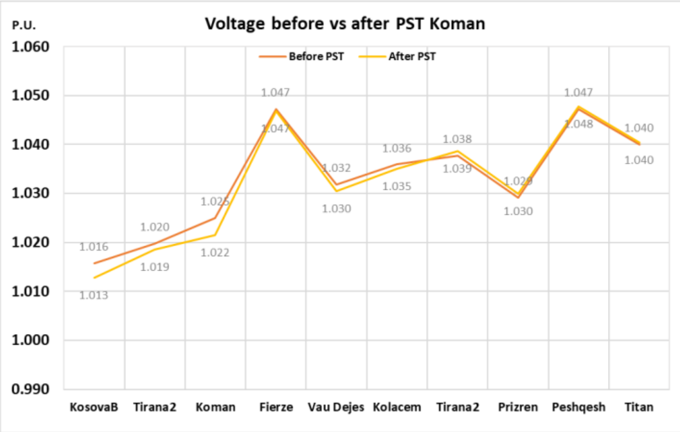

Figure 11 Voltage profile before and after PST in Koman

Figure 11 shows voltage before and PST modelling in Albanian Power System. As it can be noticed in the graphs, the improvement in voltage is minimal, with very few kV change in nodes voltage. The biggest change can be observed in Koman substation where the PST is connected.

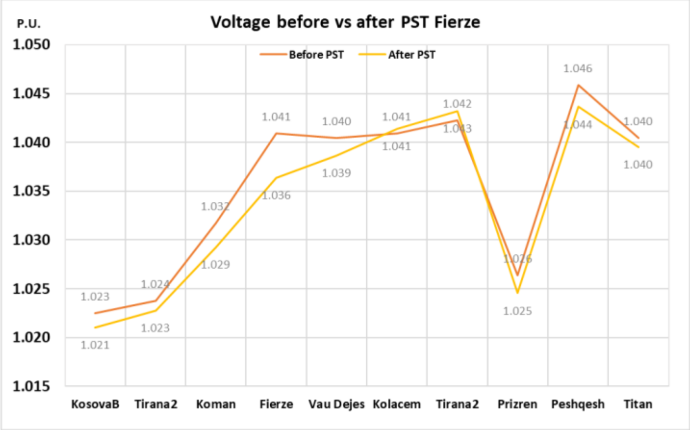

Figure 12 Voltage profile before and after PST in Fierze

Figure 12, on the contrary show's larger changes in voltages in the nodes. The major change can be observed in Fierze 400kV node, but also in Koman 400kV node.

VI. CONCLUSIONS

The paper conducts a power flow analysis in the Albanian Power System identifying possible locations for the installation of phase shifting transformers.

The installation of Phase shifting power transformers in critical nodes of the system, will reduce congestion especially in heavily loaded networks. The simulations showed a decrease in power flows for the 220kV Fierze-Prizren, which is a line that was highly loaded prior to PST installation.

The second case of installing a standard Power transformer in Koman 345MVA, and 600MVA PST in Fierze, showed better results, in terms of balancing the loading of transmission lines and reducing active power losses.

Active Power losses were calculating using PSS/E simulation tool before PST and after PST installation. In case of Koman PST, the losses were reduced from 60.2MW to 49.3, which is optimal result. Similar reduction in active power losses from 54.4MW to 46.9MW in the case of Fierze PST.

Using Phase shift transformer providers increased flexibility in the system, by changing tap positions, the active power flows can be adjusted, without creating new topological reconfigurations, which sometimes pose great risk to the power system security.

By retaining the existing 400/220 kV transformer in Koman and adding a PST, initial investment costs are minimized while achieving notable system improvements.

Inconclusion Phase shift transformers provide an improved method for controlling power flows and maximizing utilization transmission infrastructure in a safe way.

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