

ANALYSIS OF PHASE–SHIFTING TRANSFORMER (PST) APPLICATION VARIANTS IN A REAL–WORLD TRANSMISSION NETWORK

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Abstract: The contemporary energy landscape, characterized by the intensive integration of renewable energy sources and rising electricity demand, has introduced significant volatility and capacity constraints into power transmission systems. As existing infrastructure increasingly operates near its stability limits, unscheduled power flows—often referred to as loop flows—exacerbate network congestion and jeopardize operational security. In this context, Phase–Shifting Transformers (PSTs) have emerged as a critical technical solution for active power flow management, offering a flexible and cost–effective alternative to traditional grid expansion. This paper provides a comprehensive analysis of various PST installation strategies within a real–world transmission network model. The study examines the technical principles of PST operation, focusing on the device's ability to adjust the voltage phase angle to redistribute active power flows without requiring major infrastructural changes. Utilizing specialized simulation tools, the research evaluates system performance under both normal (N) operating conditions and N–1 contingency scenarios, using data from a specific high–transit regime recorded in the Croatian transmission grid. The analysis focuses on three primary installation variants: a South–North configuration at the 400 kV K substation, an East–West configuration at the 400 kV Z substation, and a combined dual–PST approach. The simulation results demonstrate that a strategically placed PST can significantly alleviate congestion on critical 400 kV corridors, with one variant achieving a transit reduction of approximately 800 MW. However, the study also highlights the "side effects" of such interventions, including the redirection of power into lower–voltage networks (220 kV and 110 kV), which can lead to new bottlenecks and increased total network losses. In conclusion, the research underscores that while PSTs are highly effective tools for enhancing grid flexibility and deferring expensive investments, their implementation requires precise coordination and site selection. The findings suggest that the optimal application of PSTs must balance the relief of high–voltage corridors with the potential strain on adjacent network segments to ensure overall system reliability and efficiency

Keywords: phase–shifting transformer, PST, power flow control, transmission network, congestion, simulation, N–1 criterion

1. INTRODUCTION

The increasing integration of renewable energy sources has brought significant changes to power systems. These changes are mainly driven by the growth in generation, the inherent variability of renewable output, and rising electricity consumption [1]. As a result, transmission systems are experiencing capacity constraints on existing lines and network transformers, often worsened by unscheduled power flows (loop flows) [2]. In this context, Phase–Shifting Transformers (PSTs) offer a viable technical solution for managing power flows within the transmission grid. Their ability to relieve loading on critical corridors enables better utilisation of network capacity, improved operational security, and relatively low investment costs [2]. This paper analyses various PST installation options for power flow management within a real–world transmission network, considering technical principles, mathematical models, simulation methods, and the associated operational consequences. Special emphasis is placed on examining the impact of PSTs on power flow distribution and line loading within the selected transmission network model.

The growing number of interconnections, the increasing share of renewable energy in the generation mix, and the rise in cross–border power flows lead to congestion issues and threats to system security. These challenges are particularly evident through unscheduled power flows, network congestion, and security risks during both normal and N–1 operating states. Traditional approaches to addressing these problems typically involve the construction of new transmission lines or generation redispatching; however, these options are often limited by technical, economic, and regulatory factors.

As a result, PSTs have emerged as an effective and flexible tool for active power flow management in transmission networks. Their application enables active control of power distribution by adjusting the voltage phase angle without requiring significant infrastructural changes. PSTs are becoming increasingly vital in meshed networks and interconnected systems, where they can mitigate congestion, improve operational reliability, and optimize the use of existing transmission infrastructure.

In the analytical section of this study, various transmission network operating scenarios are examined with and without the application of PSTs, covering normal operating states and the N–

1 reliability criterion. The analysis includes power flow redistribution, the emergence of new bottlenecks, the impact of PSTs on line loading, and changes in total network losses. The paper emphasizes the importance of optimal site selection and the coordination of PST operation with other power system elements. Examples of existing PST installations demonstrate their effectiveness in increasing transfer capacities, enhancing system security, and reducing unscheduled power flows.

■ The problem of Power Flows in the Power System

Over the last decade, power system (PS) security issues have become one of the primary challenges in both planning and operation. System security [2,3] is defined by the constraints on power transfer between different systems or system components. Within this framework, the electrical grid is expected to be capable of transmitting the maximum possible amount of power under various constraints. A fundamental driver of the interest in transfer capacity limitations lies in the fact that systems are operating dangerously close to their stability margins; this is due to increased system loading that has not been matched by a corresponding increase in transmission capacity. The problem of transmission in power systems where large changes in power magnitude and direction are expected represents a serious challenge during both the infrastructure development and operational phases. Consequently, significant attention is devoted to understanding transfer capacity limitations under conditions of increased uncertainty, as well as to the application of various methods for mitigating security threats during both normal and contingency (disturbed) operations [3].

■ Problems in the Transmission Network and Line Loading

In modern power systems, issues arising within the transmission network and line overloads have become increasingly significant. The problem stems from rising electricity demand, which the existing grid is often unable to meet while maintaining reliability and security. This results in congested or maximum line loading, thereby reducing system flexibility. Furthermore, the risk of voltage issues increases, ultimately leading to security incidents and faults [4].

Line overloading carries a range of security and technical risks. If thermal loading approaches or exceeds permissible limits, it increases the risk of conductor overheating, reduced equipment lifespan, insulation degradation, or conductor damage especially if peak loading is sustained over long periods. Similarly, high line utilization reduces security margins, which is particularly critical during contingencies; in such cases, system reliability is jeopardized due to a lack of flexibility required to reroute power flows.

Beyond thermal and mechanical constraints, high utilization of the transmission network causes disturbances in overall power system stability and the voltage profile. When loading reaches threshold values, voltage stability issues become prominent, particularly during sudden changes in consumption or the switching of large generating units. Such situations can lead to significant instability, voltage drops, and challenges in maintaining system balance or frequency [5]. An additional challenge is the increasing integration of renewable energy sources, such as solar and wind power plants, whose generation is variable and unpredictable over short time intervals. Figure 1 provides an illustrative overview of congestion, voltage instability, and the variability of renewable sources within the transmission network.

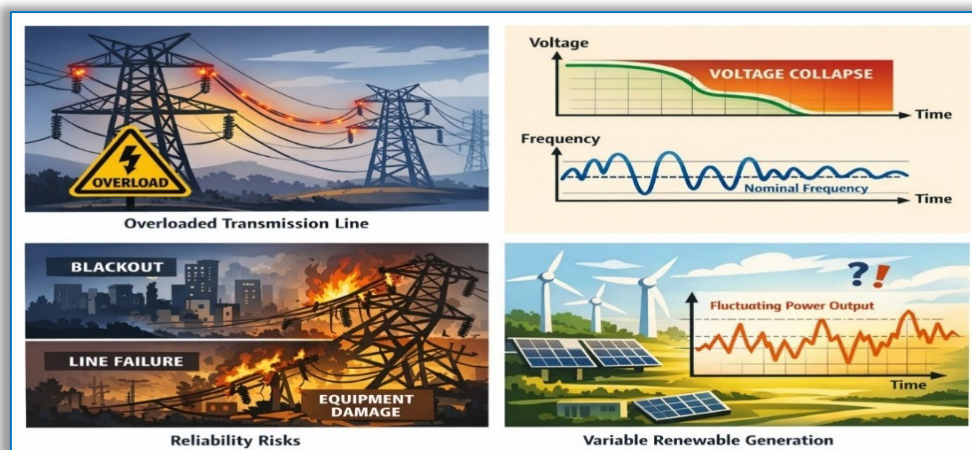


Figure 1. Representation of congestion, voltage instability, and renewable energy source variability

Such changes cause fluctuations in power flows across the transmission grid, which further strain the lines and increase the need for more flexible grid management. A particularly critical situation arises when the grid is already operating near its maximum capacity; as shown in Figure 2, such variations can lead to the violation of limit values, energy losses, an increased risk of oscillations, and general system instability [6].

Due to all the aforementioned factors, approaches such as constructing new transmission lines and transformers are becoming more time-consuming, expensive, and often impractical—especially in regions with challenging geographical conditions or high population density. Furthermore, the implementation of new infrastructure is slowed down by regulatory, financial, and administrative hurdles [7].

Consequently, modern approaches focus on increasing the flexibility and efficiency of the existing grid. One of the most effective methods is the implementation of transformers for voltage and power flow regulation, which allow for better capacity utilization without exceeding thermal and stability limits. This approach makes the system more flexible in accommodating variable generation and addresses overloading issues, which is crucial in an era of energy transition and growing demand [8].

2. PHASE-SHIFTING TRANSFORMERS (PST)

Phase-shifting transformers (PSTs) are installed in networks to adjust the voltage angle on transmission lines, thereby enabling the control of power flow in accordance with power system requirements [9] [10]. PSTs are most commonly used in high-voltage (HV) and extra-high-voltage (EHV) grids to provide significant power flow control capabilities within the power system [11] [12]. They serve as an effective tool for power flow management, where their application can reduce or minimize unscheduled (loop) flows [13][14]. In a meshed network, multiple PSTs can be deployed, but their coordination must be carefully analyzed to achieve an optimal network configuration or optimal system control [15] [16].

■ PST Operating Principle

When two areas are connected by multiple transmission lines, it is sometimes necessary to manage the active power flow through the transmission network. Phase-shifting transformers are installed to create a phase angle shift between the ends of a transmission line, thereby initiating or altering the active power flow. A phase shift of only a few degrees is sufficient to significantly change the magnitude of power flowing through the system, while the PST itself only needs to transform a very small fraction of the total power flowing through the system. The following equation describes the active power flow between two buses, which can be approximated as:

$$P = \frac{V_S \cdot V_R \cdot \sin \theta}{X} \quad (2-1)$$

where: P – active power flow in the per-unit system

V_S – per-unit voltage at the receiving-end (secondary) bus

V_R – per-unit voltage at the sending-end (primary) bus

θ – phase angle difference between voltages V_S and V_R

X – per-unit reactance between the secondary and primary buses

The situation is analogous to a voltage regulating transformer, which can induce reactive power flow through a small change in voltage. In a very similar manner, a phase-shifting transformer controls active power flow. In this case, an autotransformer design is a logical choice, utilizing a special phase-regulating configuration as shown in Figure 3.

The common series windings with regulating taps are identical to those in a voltage regulating transformer,

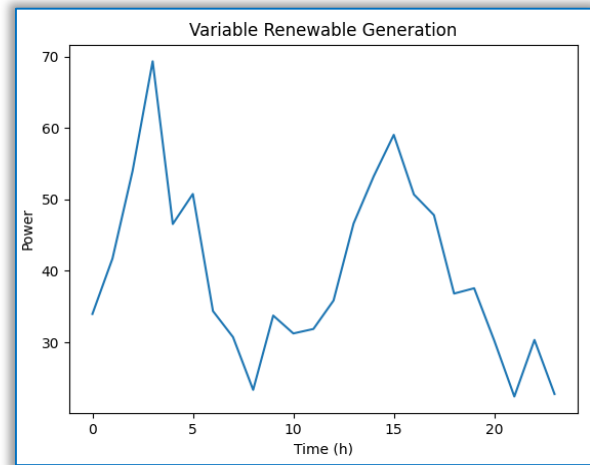


Figure 2. Variability of renewable energy production over time

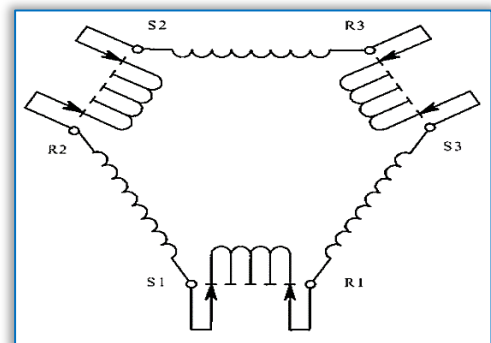


Figure 3. Winding configuration of a variable phase-shifting transformer

although in this case, they are interconnected differently to produce a phase shift rather than a voltage magnitude change. This configuration employs six on-load tap changers (OLTC), although some designs use three tap changers along with an additional advance-retard switch for direction changes. If it is necessary to regulate reactive power flow independently of active power, voltage and phase angle control can be combined within a single regulating transformer using two independent sets of tap changers. One set regulates in-phase voltages, while the other regulates quadrature voltages; their output components are then vectorially summed.

A PST is a device used for power flow control to alleviate congestion and minimize power losses in electrical grids. Figure 4 shows a schematic diagram of a PST installed on a transmission link between buses i and j . The input and output ends of the transmission link are represented by voltage phasors V_S and V_R , and their corresponding impedances Z_S and Z_R . A conventional PST is typically designed as a three-phase unit with a total of twelve windings on six magnetic cores.

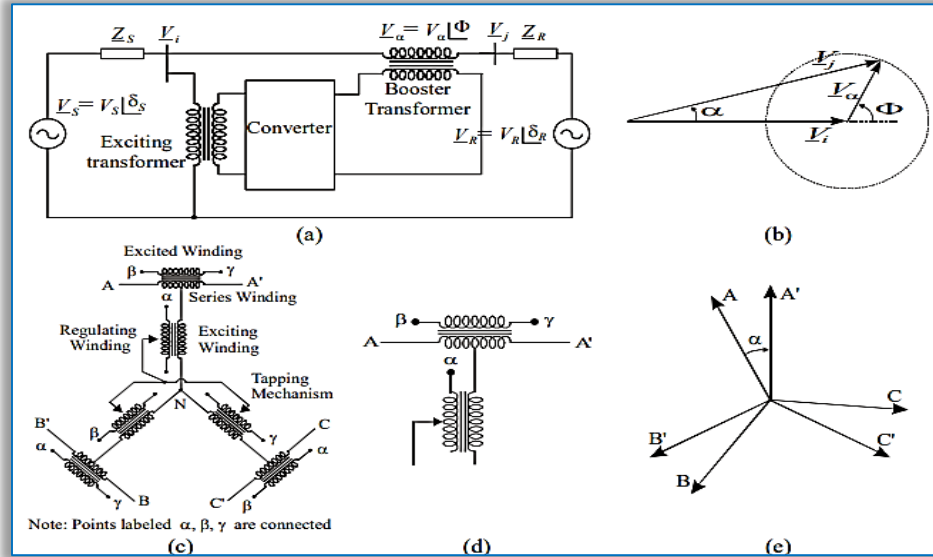


Figure 4. PST Diagram: (a) schematic (b) phasor (c) windings (d) quadrature booster (e) phase shift

Figure 4.a illustrates the winding arrangement of a typical device. The exciting and series windings, which are directly connected to the transmission link, do not have tap-changing devices (Figure 4.d). All tap changes are performed via the regulating winding, which operates at a lower voltage. As the turn ratio between the regulating and exciting windings is increased by the regulator through tap changes, a voltage is induced in the series winding that is in quadrature (displaced by 90°) relative to the phase voltage. This effectively leads to a phase shift in voltage between the two transformer terminals. Figure 4.e shows the phasor diagram of the angle increase for nodes A and A'. An angle reduction is achieved by adjusting the regulator in the opposite direction, i.e., by reducing the number of turns between the regulating and exciting windings.

Depending on the magnitude and phase angle of the injected voltage V_a , V_j the magnitude and/or phase angle of the system voltage (Figure 4.b). In a flexible PST, the resulting regulation voltage forms a circle centered at the tip of the phasor V_i with a radius equal to the amplitude of V_a . The output voltage of the PST is controlled by varying the amplitude and angle of the phasor V_a i.e. V_a and Φ . The active power on the transmission line that includes the PST is given by the expression:

$$P = \frac{V_S V_R}{X_{eq}} \sin(\delta_S - \delta_R \pm \alpha) \quad (2-2)$$

where X_{eq} is the total equivalent reactance of the line and source, and δ_R and δ_S are the phase angles V_R and V_S . For a given system operating state, the converter characteristics define the range within which the phase angle and amplitude of the injected voltage are controllable. The converter section of a conventional PST consists of mechanical tap changers usually installed within the exciting transformer.

A conventional PST can vary the angle α within approximately ± 40 degrees, in discrete steps of about 1 to 2 degrees. Rapid phase angle regulation can be achieved by replacing the tap changer with a thyristor-based switching circuit.

■ Impact of PST on Power Flows

To demonstrate the fundamental concept of power flow control via angle regulation, let us consider a simple case of two equivalent machines interconnected by a transmission line (Figure 4). A phase angle regulator (PAR) is inserted between the generator at the injection side and the transmission line [17].

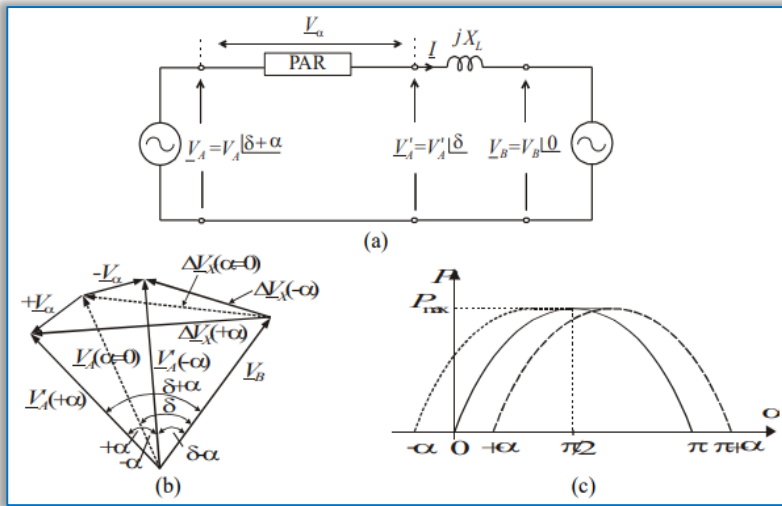


Figure 4. (a) Two-machine power system with a PAR; (b) voltage phasor diagram; (c) transmitted power characteristic as a function of angle

α , while their amplitudes remain unchanged, namely:

$$V_A' = V_A = V \quad (2-4)$$

The primary purpose of a phase angle regulator is to maintain the power flow through a transmission line at a desired value, regardless of the existing phase difference δ between the voltages at both ends of the line. According to the regulation characteristic given by equation (2-4) and the effective phase angle $(\delta - \alpha)$ between the secondary and primary end voltages, the active and reactive power flows are as follows:

$$P_L = \frac{V^2}{X} \sin(\delta \pm \alpha) \quad (2-5)$$

$$Q_L = \frac{V^2}{X} [1 - \cos(\delta \pm \alpha)] \quad (2-6)$$

The steady-state active power flow characteristic as a function of angles δ and α , derived from equation (2-6), is shown in Figure 4.c. Naturally, for an uncompensated line, from a stability perspective, the maximum transmissible power is achieved at a phase difference of $\delta = \pi/2$. When a phase angle regulator is used, the active power flow can theoretically be maintained at its peak value even for angles $\delta = \pi/2$, potentially within the range $\frac{\pi}{2} < \delta < \frac{\pi}{2} + \alpha$. This is made possible by controlling the amplitude of the injected quadrature voltage V_a such that the effective phase difference $(\delta - \alpha)$ between the secondary and primary end voltages does not exceed $\pi/2$.

The power flow characteristic can be shifted to the left or right depending on the direction/polarity of the injected voltage. PAR equipment does not increase the theoretical maximum transmissible power, but it can increase or decrease the actual transmitted power flow for the same phase angle δ as shown in Figure 5.

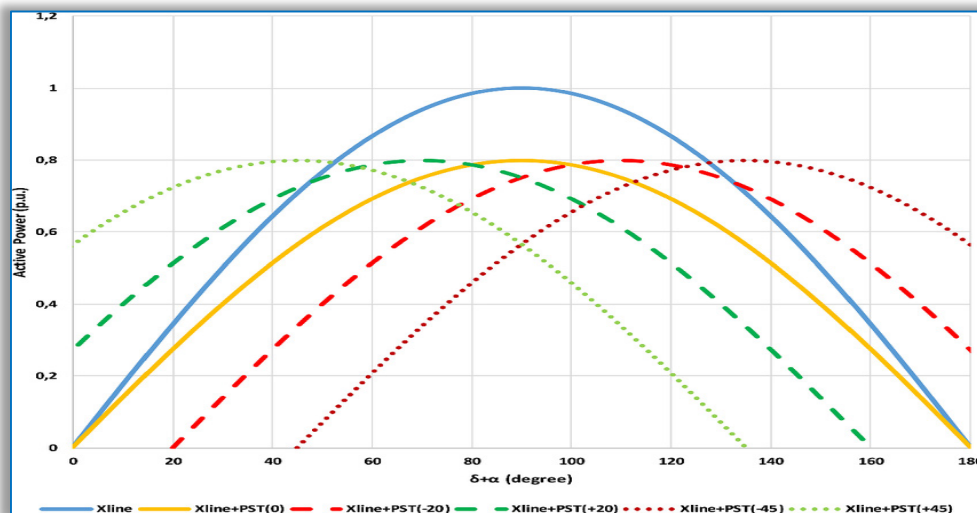


Figure 5. Dependence of active power flow on the voltage phase shift in a transmission line

The advantages of implementing PSTs lie in their ability to precisely direct and distribute power flows between parallel lines. This reduces the risk of overloading, enhances the operational security of the transmission system, and allows for the deferral or reduction of investments in new lines and transformer capacities.

3. PST MODELING

Unlike conventional power transformers, which primarily change the voltage magnitude, PSTs are designed to control active power by introducing a controlled phase angle shift between the secondary and primary ends of a transmission line. In interconnected transmission networks, power flows are determined not only by line impedances but also by the phase angle differences between buses. Consequently, unscheduled loop flows and congestion can occur even during normal operation. PSTs enable these power flows to be influenced without changing generation schedules or network topology, making their modeling crucial for the analysis of real-world systems.

However, in the case of PSTs, the objective is not voltage regulation, but rather the controlled rotation of the phase voltage vector, as shown in Figure 6.

Therefore, PST models must allow for a phase shift of the secondary voltage relative to the primary voltage, while maintaining the voltage magnitude constant or treating its change as negligible. This assumption particularly holds for symmetrical configurations, where the phase shift is achieved by injecting a quadrature voltage without significantly affecting the line voltage magnitude. In power flow calculations, a PST is thus often modeled as an ideal phase regulator that introduces an additional phase angle between two adjacent buses. This enables straightforward integration of PSTs into existing AC or DC load-flow algorithms without requiring a detailed description of the transformer's internal construction.

4. TESTING ON A REAL MODEL

This analysis utilized a real-world transmission network test model corresponding to the actual operating state of the grid recorded on March 11, 2023, at 12:00 PM. At that time, there was an exceptionally high transit of electricity from Bosnia and Herzegovina via the 400 kV K – M transmission line toward Italy, through the 400 kV D - R interconnection line. This specific grid regime provided an ideal reference case for analyzing the impact of phase-shifting transformers on power flows [18].

■ Description of the Simulation Tool Used

A specialized software tool for transmission network analysis was used to calculate power flows and analyze power system operation. This tool enables the modeling of high-voltage transmission networks including transformers, generating units, lines, and loads as well as steady state analysis. The simulation tool allows for power flow calculations in normal operating states, along with power system security analysis according to the N-1 criterion, phase angle adjustments, and the calculation of total active power losses in the network.

PST modeling was performed by defining the phase shift between the primary and secondary voltages, thereby directly managing the distribution of active power flows in the grid. This approach enabled the comparison of different PST installation variants and the analysis of their impact on power flows, total active power losses, and overall system security.

■ Creating a Network Model With and Without PST

In the simulation model under consideration, several generating units were out of service, including the following: Hydroelectric Power Plants D, R, Č, K, V, Vi, O, and P. Among thermal power plants, the following were offline: S, P, J, the Combined Heat and Power Plant Z, and Wind Power Plant B. The exclusion of these plants further highlighted the strain on the transmission network and the impact of cross-border power flows. Three PST installation variants were considered within the analysis:

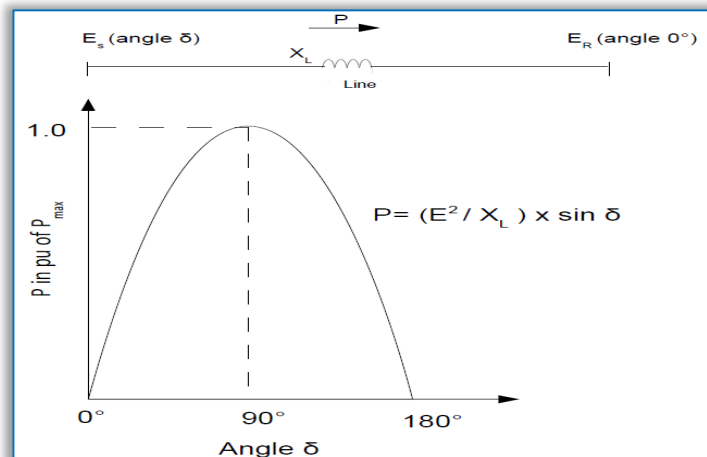


Figure 6. Active power transmission as a function of phase angle difference

- PST South – North: The PST is installed at the 400 kV K substation in the line bay toward the 400 kV M substation.
- PST East – West: The PST is installed at the 400 kV Ž substation in the line bay toward the 400 kV E substation.
- Combined Variant: Involves the simultaneous installation of PSTs in both the South – North and East – West directions.

The reference initial state of the transmission network without PSTs is shown in Figure 7, where the significant loading of network elements and the pronounced transit of electricity from the southern to the northern part of the system are clearly visible.

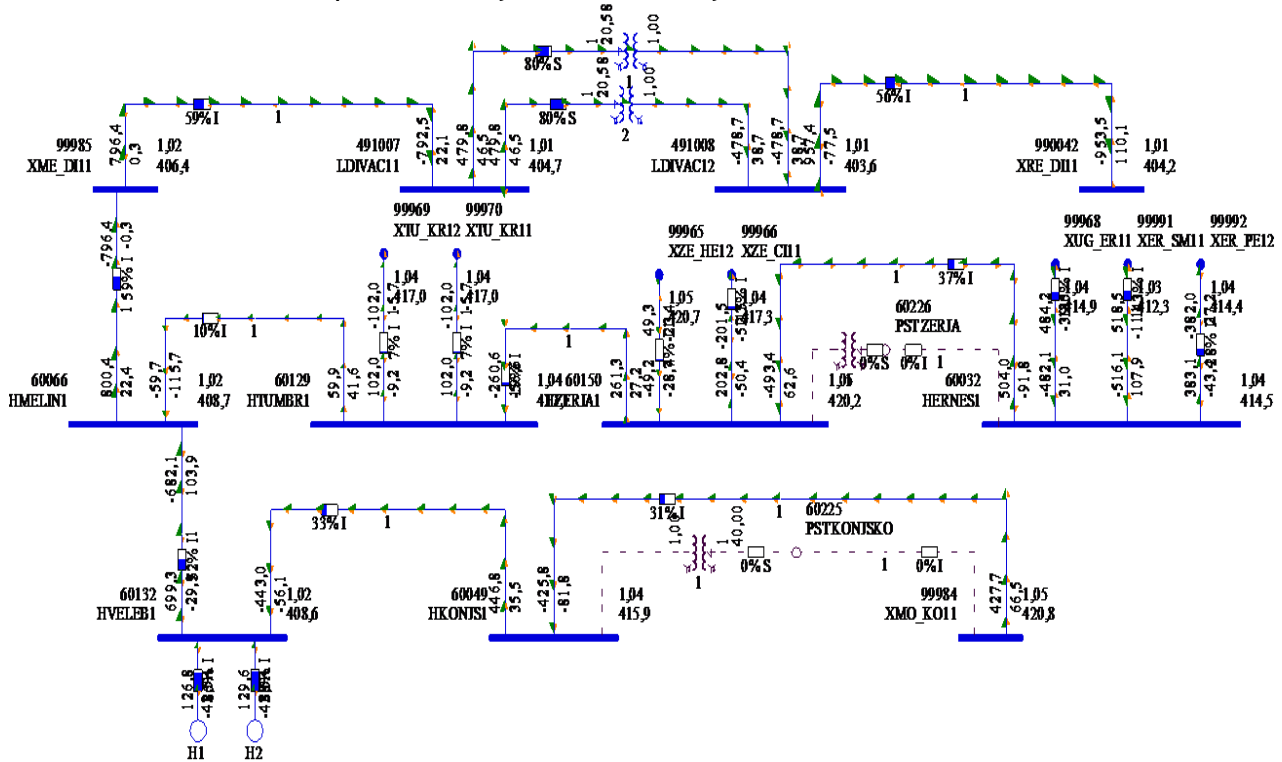


Figure 7. Initial state of the 400 kV network

In the reference operating state, no equipment overloads were recorded under N conditions. However, under N–1 contingency conditions, critical situations were identified, with a total of 11 security violations, as shown in Table 1.

Table 1. List of associated security threats

Primary contingency	Solut. type	Monitored element	Baseca (%)	Contin.(%)
320 601 70–70071(1)	Contingency	60125 HTESIS5 110.00 60170 HTESIS2 220.00 1	75,47	133,13
183 6066–60132(1)	Contingency	60067 HMELIN2 220.00 60109 HSENJ 2 220.00 1	90,64	129,67
188 60067–60109(1)	Contingency	60013 HCRIKV5 110.00 60134 HVEVRA5 110.00 1	26,33	128,43
308 60151–70071(1)	Contingency	60072 HMRACL5 110.00 70071 HMRACL22 220.00 1	58,87	115,92
146 60049–60132(1)	Contingency	60067 HMELIN2 220.00 60109 HSENJ 2 220.00 1	90,64	115,83
346 6066–99985(1)	Contingency	60063 HMATUL5 110.00 99586 XMA IB51 110.00 1	60,69	115,58
199 60067–60109(1)	Contingency	60134 HEVRA5 110.00 60157 HSENJ 5 110.00 1	7,71	110,21
183 60066–60132(1)	Contingency	HTESIS2 220.00 70071 HMRACL22 220.00 1	81,27	110,21
346 6066–99985(1)	Contingency	60063 HMATUL5 110.00 60091 HPHELIS 110.00 1	51,59	104,62
320 601 70–70071(1)	Contingency	60097 HPRACN5 110.00 60125 HTESIS5 110.00 1	61,44	104,55
175 60064–60065 (1)	Contingency	60125 HTESIS5 110.00 60170 HTESIS2 220.00 1	75,47	100,28

By installing a PST in the South - North direction, specifically a 400/400 kV transformer at substation K, the aim is to limit the amount of active power entering the system from Bosnia and Herzegovina. The PST phase shift is set to a maximum value of 40°, achieving a pronounced regulatory effect on power flows. This results in a new state of the transmission network. With the installation of the 400/400 kV PST at substation K, a significant reduction in active power flows is observed in the main sections of the 400 kV network, particularly on the K - V, V - M, and M - D transmission lines. Additionally, a slight decrease in loading on the 400 kV D - R cross-border

line between SI and IT was recorded. The change in phase angle also caused a reversal of power flow direction; energy now flows from K toward M, slightly relieving the northern part of the transmission grid.

A disadvantage of installing the 400/400 kV PST at K is that energy from Bosnia and Herzegovina redirects through Z (due to loop flows and an additional parallel 220 kV interconnection), causing that line to overload in the N state. Furthermore, another drawback is the increased number of security violations in the N-1 operating regime, which rises from 11 to 749. This increase occurs due to the redirection of power flows from the 400 kV level to lower voltage networks, namely the 220 kV and 110 kV levels.

In the second case, the installation of a 400/x type PST was considered to enable more efficient power flow regulation across multiple voltage levels. The installation of the 400/400 kV PST at Ž leads to an additional change in flow direction on the 400 kV Ž - E line section, where power now flows from Ž toward the eastern part of the network. The installation of an additional PST increases flows on the lines between K and D, although these flows remain lower compared to the initial system state. In the N state, the 220 kV S – M line becomes overloaded as a direct consequence of the altered flow direction on the Ž – E line. In the N-1 state, the number of security violations further increases to 1,142 (Table 2), representing a less favorable condition compared to the single PST case. Although PSTs successfully relieve transit on the 400 kV network, they simultaneously increase the number of violations on lower voltage levels.

In the third analyzed case, where only the 400/400 kV PST at Ž is in operation, the power flow from Ž toward E persists. The relief of the 400 kV transmission network in this case is less pronounced than in the previous two scenarios, indicating that the 400/400 kV PST at Ž has a limited impact on the network segment between K and D. The advantage of applying the 400/400 kV PST at Ž is evident in the reduction of transmission power by approximately 800 MW, representing a significant relief for the system. However, this is accompanied by an increase in power losses of about 20 MW, resulting from the occurrence of loop flows in the grid, as shown in Table 2.

Table 2. Impact of PST installation on power system losses

Considered Variant	Impact on Losses [MW]	Delta Losses [MW]
Initial State	90,0	0
PST E–W: Installation at SS 400 kV toward TS E	110,6	–20,6
PST S – N: Installation at SS 400 kV toward TS M	105,6	–15,6
PST S – N + PST E – W	116,2	–26,2

According to the results presented in Table 3, the most favorable effect was achieved by installing PSTs in both the South-North and East-West directions. However, the simultaneous application of PSTs causes new issues in the 220 kV and 110 kV networks, manifested as new overloads in the N operating state and an increased number of violations in the N-1 state. Likewise, the installation of PSTs leads to an increase in total losses within the power system.

Table 3. Results of PST installation on 400 kV transmission lines

Variants	Impact on Transit (E–W)	Delta impact on transit	Impact on transit (S–N)	Delta impact on transit	Impact on transit (SI–IT)	Delta impact on transit
	DV 400 kV Ž – E [MW]	[MW]	DV V – M [MW]	[MW]	DV D – R [MW]	[MW]
0. Initial State (No PST)	–493,4	0	699,3	0	957,4	0
1. E–W: Installation at SS Ž 400 kV	335	828,4	807,3	–108	954,2	3,2
2. S–N: Installation at SS K 400 kV	–590,7	–97,3	386,2	313,1	942,2	15,2
3. Combined S–N +E–W	254,2	747,6	486,2	213,1	938,8	18,6

In addition to the technical analysis of the PST's impact on power flows and system losses, it is important to emphasize that their application enhances operational flexibility. Under conditions of heavy electricity transit from the Southeast toward Italy and Central Europe, the 400/400 kV PST at substation K proves particularly effective in rerouting surplus generation from Bosnia and Herzegovina, thereby relieving key 400 kV transmission lines in the Croatian grid. However, as a

consequence of this power flow management, a portion of the energy from Bosnia and Herzegovina is redirected to the 220 kV Z – M transmission line.

■ Analysis of test results

Proper sizing and utilization of PSTs in the grid require comprehensive analysis, development of operational scenarios through network simulations, and ultimately, an assessment of the economic viability of the installation. This approach pursued several objectives: selecting the optimal PST location for power flow redirection, assessing the impact on cross-border exchanges, reducing system losses, and evaluating the impact on voltage conditions.

From the conducted analysis, it can be concluded that the second test case (PST 400/400 kV) leads to a significant reduction in power transfer through critical lines by approximately 800 MW, representing substantial system relief with a negligible increase in power system losses. Furthermore, it has been demonstrated that PSTs can significantly contribute to reducing the need for redispatching and its associated costs, as unscheduled flows can be technically controlled. The analysis indicates that the PST in this case increases cross-border power flow capacity and allows for more dynamic system operation. Most importantly, it provides significant capabilities for managing power flows from the South toward the North of the Croatian power system, which was the primary objective of the installation.

5. CONCLUSION

This paper analyzes the possibilities of applying Phase-Shifting Transformers (PST) in regulating active power flows in high-voltage transmission networks. The theoretical section details the operating principles of PSTs, their basic topologies, design variations, and different configurations. The analysis focuses on how the phase shift impacts power flow distribution and how phase angle adjustments can alter active power. Consequently, the use of PSTs enables precise direction of grid flows and effectively reduces congestion in critical network segments. In the analytical part of the study, actual operating states of the transmission network were analyzed, comparing various real-world scenarios with and without the application of PSTs. Simulation results showed that the installation and proper adjustment of a PST can significantly influence power flow redistribution, enhance system security, and reduce the loading on specific lines, particularly in N–1 operating states. In this regard, the selection of the installation site is crucial, as uncoordinated PST operation can lead to new bottlenecks in other parts of the transmission network. As demonstrated in this case, proper application enables the reduction of unscheduled power flows, more efficient management of cross-border flows, and better utilization of existing transmission capacities.

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