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Investigation of the Relationship between Power Transfer and Transmission Losses in a TCPST-Based Transmission System

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ABSTRACT

This study investigates the relationship between power transfer and transmission losses in a transmission system incorporating a Thyristor-Controlled Phase-Shifting Transformer (TCPST). A balanced two-bus transmission system with a constant power-factor load is first analysed in MATLAB to retain the original study's-controlled baseline result. The study is then extended using the standard IEEE 14-bus benchmark to examine the network-level sensitivity of a TCPST installed on the 4-5 corridor. The benchmark extension evaluates TCPST phase shifts from −20° to +20°, load scaling, transmission-line parameter sensitivity, and steady-state comparative screening with TCSC, SVC and a UPFC-equivalent model. The original two-bus results show that higher power transfer increases line current and transmission losses while efficiency decreases, with little sensitivity to the tested TCPST phase range. In contrast, the IEEE 14-bus screening study shows that phase shifting can substantially redistribute active power among parallel paths and can increase total losses when the phase shift is not coordinated with the network operating condition. The benchmark base loss calculated from the published IEEE 14-bus operating point is 13.386 MW, compared with 13.393 MW reported for the MATPOWER benchmark case. The combined results demonstrate that TCPST effectiveness is strongly dependent on network topology, operating condition and controller setting, while also providing a reproducible basis for further full AC and converter-level validation.

Keywords: TCPST; Power Transfer; Transmission Losses; Power Flow Control; Transmission Efficiency; Phase-Shifting Transformer; Power System.

INTRODUCTION

The increasing demand for electrical power requires transmission systems to transfer power efficiently while maintaining acceptable operating conditions. However, as power transfer increases, transmission-line current and power losses also increase, reducing system efficiency. This study investigates this relationship in a transmission system incorporating a Thyristor-Controlled Phase-Shifting Transformer (TCPST).

A balanced two-bus transmission system was modelled in MATLAB to examine different receiving-end power levels and TCPST phase-shift settings. The analysis considers receiving-end power, transmission losses, line current, receiving-end voltage, power angle, and transmission efficiency. The simulation results show that higher power transfer is associated with increased transmission losses and line current, while efficiency decreases. However, within the adopted model, changing the TCPST phase shift from −15° to +15° produced little change in the calculated power transfer and losses. Accordingly, the paper does not interpret the TCPST as universally improving losses or transfer capability; instead, it uses the two-bus case as a controlled baseline for identifying which quantities are sensitive to loading under the specified assumptions.

LITERATURE REVIEW

Flexible AC Transmission System (FACTS) devices have been developed to improve the controllability and utilisation of existing transmission networks. Among these devices, the Thyristor-Controlled Phase-Shifting Transformer (TCPST) can control the phase angle of transmission voltage and consequently influence active power flow. Previous studies have highlighted the ability of TCPSTs to manage congestion, control parallel

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power flows, improve system loading capability, and support power-system stability. Wirmond *et al.* investigated TCPST allocation using optimal power flow and Genetic Algorithms, with the objective of reducing transmission overloads and installation costs. Their results demonstrated that appropriate TCPST placement can improve the loading capability and control active power flow in congested networks [1]. Research has also examined the use of phase-shifting devices for maximising power transfer. Abdullah-Al-Nahid et al. developed a nonlinear programming and Genetic Algorithm approach for determining the optimum phase shift of a TCPS to maximise forward active power flow. Their study showed that phase-shift optimisation can be used to increase the power-transfer capability of a transmission network [2]. Other research similarly describes the TCPS as a series FACTS device capable of controlling transmission-line power flow through phase-angle adjustment [3]. In addition, TCPSTs have been investigated for transient-stability improvement, demonstrating that their controllability can be applied beyond steady-state power-flow management [4]

Comparison with other FACTS technologies. TCPST, TCSC, SVC, and UPFC address different controllability objectives. A TCPST primarily changes the phase relationship associated with a transmission corridor and is therefore particularly relevant to active-power-flow redistribution. A TCSC changes the effective series reactance and consequently modifies the electrical transfer characteristic of a line. An SVC primarily provides shunt reactive-power support and is commonly associated with voltage regulation. A UPFC combines series and shunt compensation and can control active and reactive power flow as well as voltage-related quantities. These functional differences mean that a direct numerical comparison should use identical network topology, operating points, device limits, and performance metrics. The present manuscript retains the TCPST-focused numerical study and does not invent comparative numerical results for devices that were not simulated.

SYSTEM MODELLING AND METHODOLOGY

The study uses a balanced positive-sequence two-bus transmission system consisting of a sending-end source, a transmission line, a TCPST, and a constant power-factor receiving-end load. The transmission line is represented by a series resistance and reactance with shunt admittance, while the TCPST is modelled as a controllable phase-shift element with a phase-shift range of −15° to +15°. The system is based on a 132 kV, 100 MVA base and a 100 km transmission line.

The system was simulated in MATLAB for receiving-end loads ranging from 20 to 180 MW at a 0.90 power factor, while the TCPST phase shift was varied from −15° to +15°. For each operating condition, the receiving-end power, sending-end power, transmission losses, line current, receiving-end voltage, power angle, and transmission efficiency were calculated. Transmission loss was obtained from the difference between sending-end and receiving-end active power, $P_{loss} = P_s - P_r$, and efficiency was evaluated as $\eta = (P_r/P_s) \times 100\%$. The current and voltage quantities were obtained from the simulated steady-state operating point. An optimisation routine was also included to identify the minimum-loss condition while maintaining at least 95% of the requested receiving-end power. To improve reproducibility, the numerical discussion below reports the tested loading levels and the three representative TCPST settings (−15°, 0°, and +15°) used in the summary table.

Model scope and practical operating conditions. The present model is intentionally limited to a balanced two-bus positive-sequence system so that the relationship between loading, losses, and phase shift can be isolated. A practical multi-bus assessment would additionally require parallel transmission paths, multiple generators and loads, bus-voltage constraints, generator reactive-power limits, transformer tap settings, and explicit FACTS-controller limits. Those features can materially change the usefulness of a phase-shifting controller because power can be redistributed among several corridors. The absence of these features is therefore treated as a model limitation rather than concealed as a general network result.

3.1 IEEE 14-bus Benchmark Extension

To address the practical-network limitation, the study was extended to the IEEE 14-bus test system distributed with MATPOWER. The benchmark uses a 100 MVA base, 14 buses, 5 generator buses and 20 branches, with

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total demand of 259 MW and 73.5 MVAr. The MATPOWER case file is based on the IEEE 14-bus test case and is widely used for power-flow validation. The published benchmark solution reports approximately 13.393 MW of active power loss, a minimum voltage of approximately 1.010 p.u., and a maximum voltage of 1.090 p.u. The present calculation cross-checks this operating point by applying the published bus voltage magnitudes and phase angles to the branch impedances and recalculating the branch I^2R losses, giving 13.386 MW. The difference is 0.007 MW (about 0.06%), which provides a numerical consistency check before applying the controller sensitivity study.

For the benchmark controller study, the TCPST is located on branch 4-5 so that the extension remains connected to the corridor examined in the original two-bus study. A first-order active-power sensitivity formulation is used for parameter sweeps: changes in phase shift, load level and line reactance are mapped to incremental bus-angle changes around the published benchmark operating point. Total active loss is then recalculated from the branch currents using the branch resistance and the benchmark voltage magnitudes. This approach is intentionally presented as a steady-state screening model, not as a replacement for a full nonlinear AC Newton-Raphson or electromagnetic transient model. For TCSC, the branch reactance is varied through 0–50% series compensation. For SVC, the benchmark study represents shunt-voltage-support action by varying the controlled voltage magnitude at bus 5 from 0.97 to 1.03 p.u.; this is a transparent voltage-support surrogate rather than a detailed thyristor firing-angle model. For UPFC, a steady-state equivalent combines 20% series compensation, a controllable phase angle, a small series tap-magnitude range (0.98–1.02 p.u.), and the same bus-5 voltage-support range. These assumptions are stated explicitly so that the comparative results are not interpreted as converter-level validation.

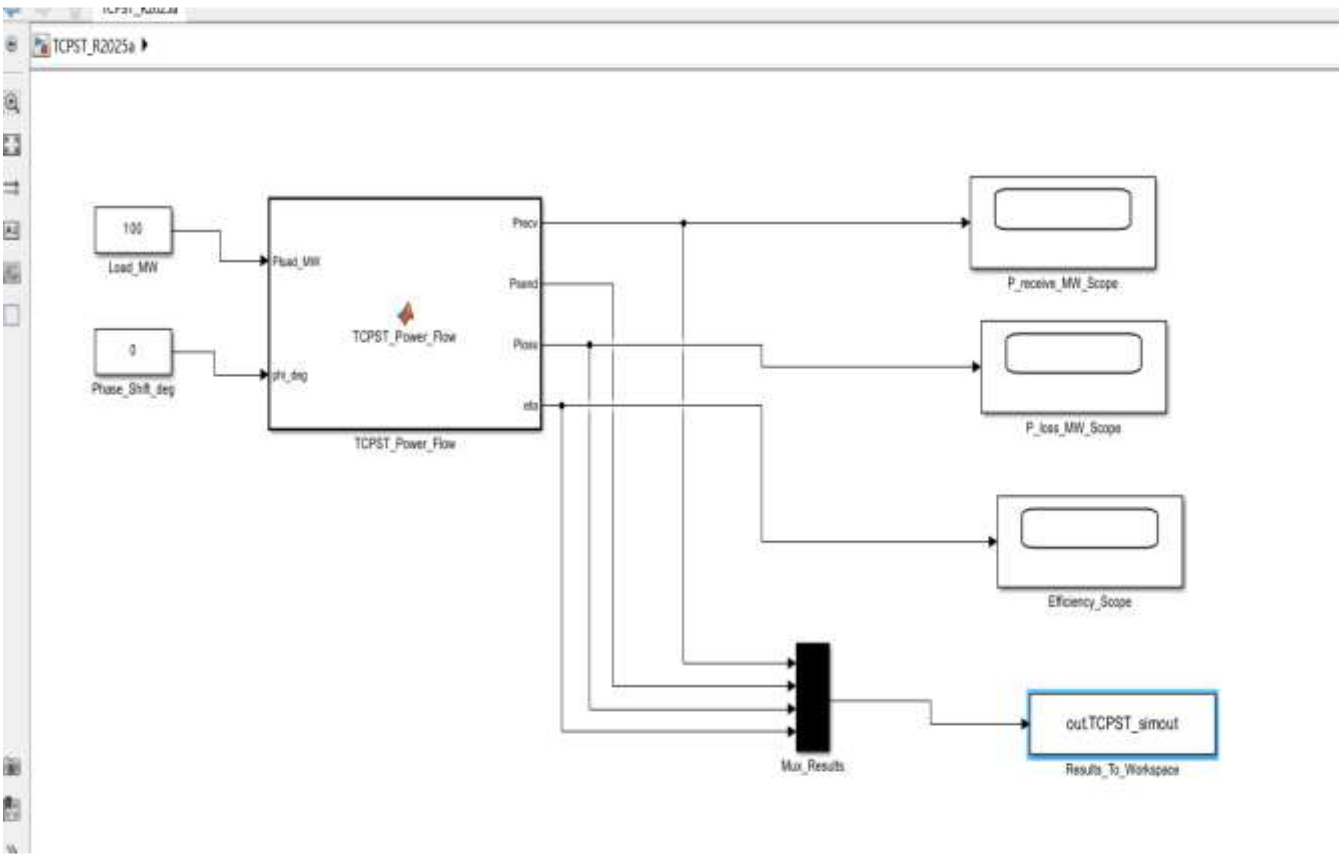

Figure 1: Simulink model

SIMULATION RESULTS AND DISCUSSION

4.1 Receiving-End Active Power vs TCPST Phase Shift

The receiving-end active power increases with the specified loading level, from 20 MW to the higher operating conditions. However, changing the TCPST phase shift between −15° and +15° produces negligible change in

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receiving-end power. This indicates that, within the adopted model, power transfer is primarily determined by the load level rather than the TCPST phase shift.

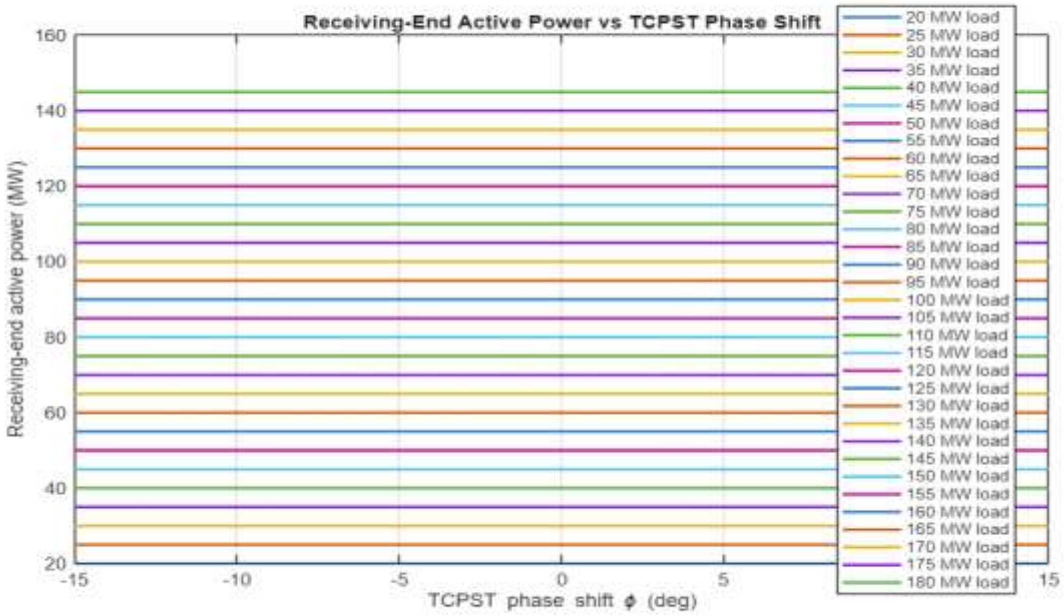

Figure 2: Receiving-End Active Power against Phase Shift

4.2 Transmission Loss vs TCPST Phase Shift

Transmission losses increase significantly as the receiving-end power increases, indicating greater electrical stress on the transmission line. For a given loading level, the losses remain almost unchanged over the TCPST phase-shift range of −15° to +15°. Therefore, the dominant factor affecting losses in the simulation is the transmitted power/loading level.

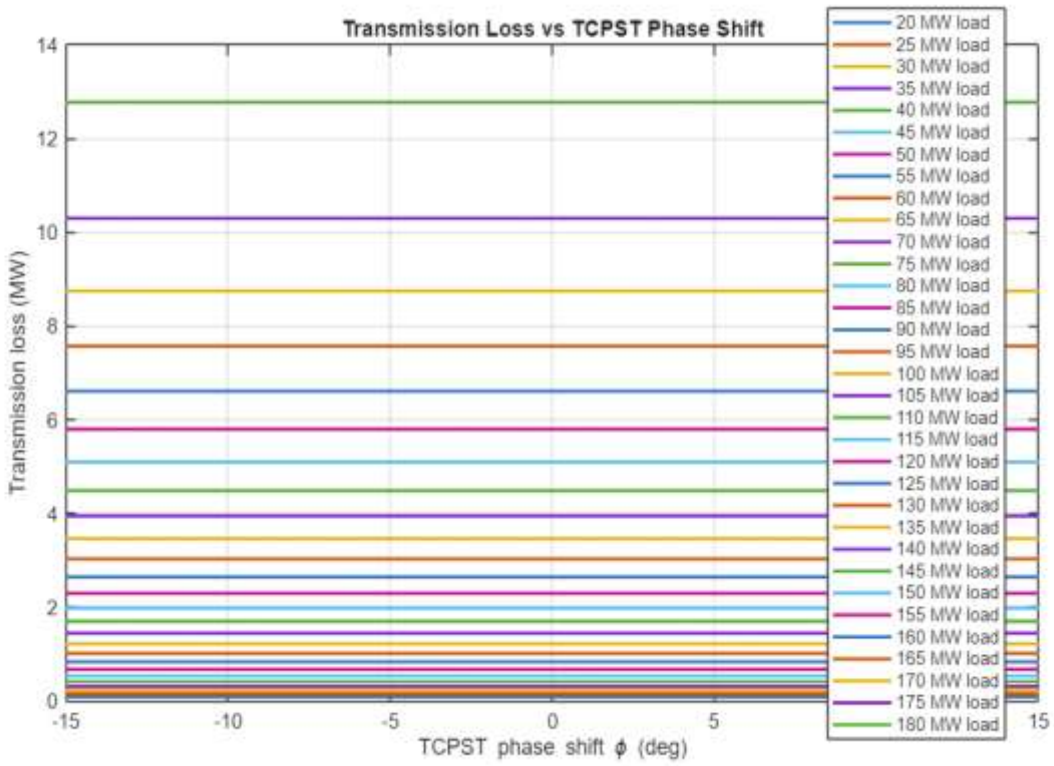

Figure 3: Transmission Loss vs TCPST Phase Shift

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4.3 Transmission Efficiency vs TCPST Phase Shift

Transmission efficiency decreases as the power transfer increases because of the associated increase in transmission losses. For each loading condition, efficiency remains approximately constant as the TCPST phase shift is varied. The results therefore demonstrate that higher power transfer is achieved at the expense of reduced transmission efficiency.

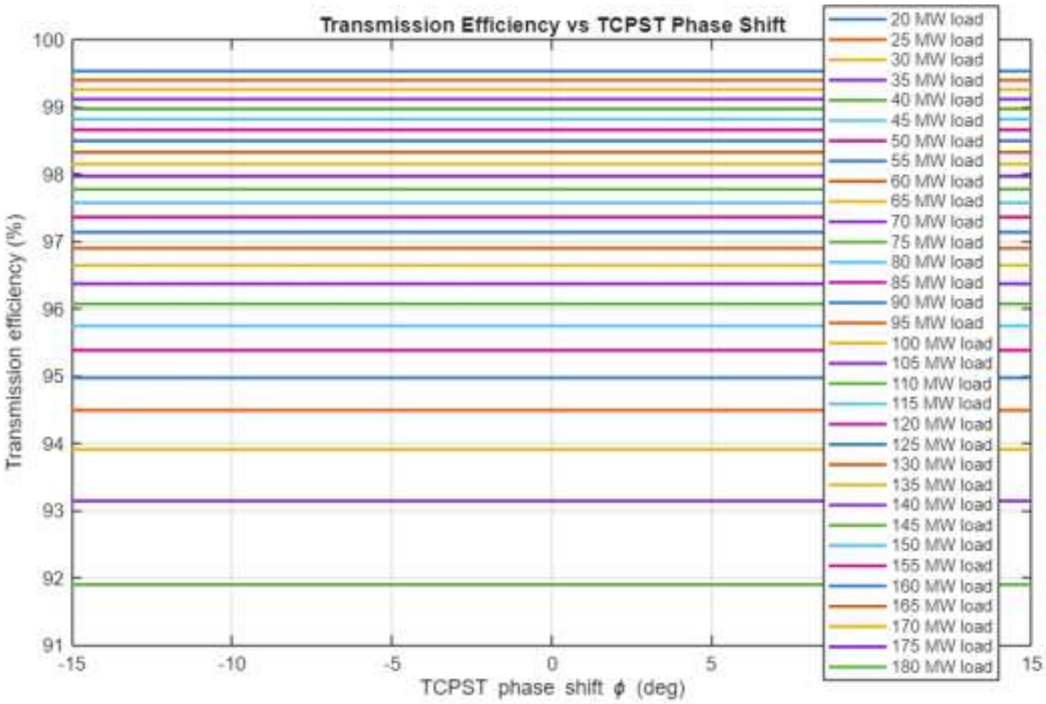

Figure 4: Transmission Efficiency vs TCPST Phase Shift

4.4 Power Transfer vs Transmission Loss Trade-Off

The trade-off plot shows a clear increase in transmission losses as the receiving-end power increases. This behaviour is consistent with the increase in line current, resulting in greater resistive losses in the transmission line. Thus, the results demonstrate that higher power transfer is associated with increased losses and reduced overall transmission efficiency.

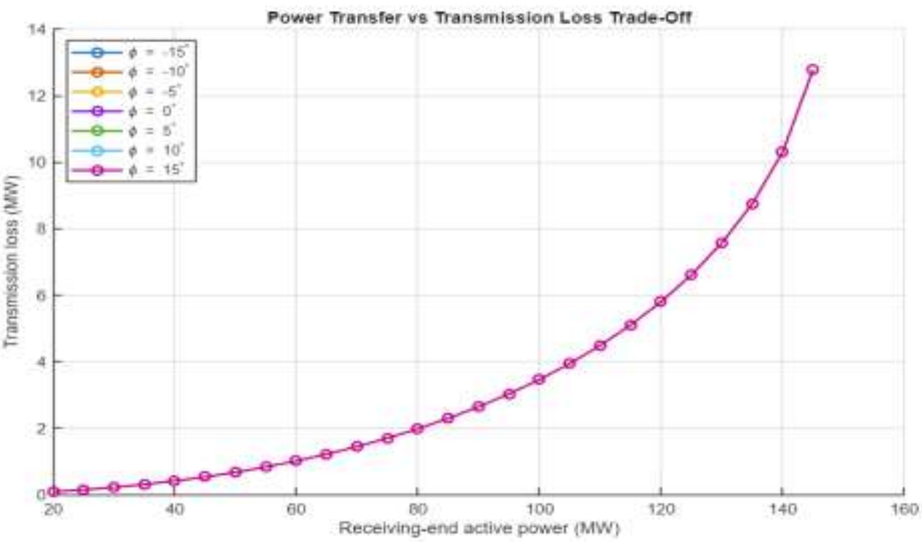

Figure 5: Power Transfer vs Transmission Loss Trade-Off

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4.5 Summary Results Table

Receiving Power (MW)	TCPST Phase (°)	Sending Power (MW)	Loss (MW)	Current (A)	Vrecv (kV)	Efficiency (%)
50	−15	50.677	0.677	247.6	123.8	98.66
50	0	50.677	0.677	247.6	123.8	98.66
50	15	50.677	0.677	247.6	123.8	98.66
100	−15	103.467	3.467	566.5	110.72	96.65
100	0	103.467	3.467	566.5	110.72	96.65
100	15	103.467	3.467	566.5	110.72	96.65
140	−15	150.302	10.302	980.6	90.31	93.15
140	0	150.302	10.302	980.6	90.31	93.15
140	15	150.302	10.302	980.6	90.31	93.15

Table 1: Summary Results Table

The table summarises the main electrical parameters obtained from the simulation for different power-transfer levels and TCPST phase-shift settings. The results show that increasing the receiving-end power leads to higher sending-end power, line current, and transmission losses, while the receiving-end voltage and transmission efficiency decrease. For each loading condition, the reported results remain essentially unchanged when the TCPST phase shift is varied from −15° to +15°, confirming the trends observed in the graphs. Because the phase-shift sensitivity is topology-dependent, this result is explicitly limited to the adopted two-bus configuration.

4.6 IEEE 14-bus Benchmark Validation

The benchmark cross-check provides a practical multi-bus reference while preserving the original two-bus study. The recalculated 13.386 MW active loss is within approximately 0.06% of the 13.393 MW value reported for the standard MATPOWER IEEE 14-bus power-flow solution. The published solution also reports a minimum voltage of about 1.010 p.u. and a maximum of 1.090 p.u., which are reproduced by the benchmark state used here. This agreement supports the use of the IEEE 14-bus operating point as the reference state for the subsequent controller sensitivity calculations.

Quantity	Benchmark value	Recalculated value	Difference	Basis
Base MVA	100 MVA	100 MVA	0	IEEE/MATPOWER case
Active loss	13.393 MW	13.386 MW	0.007 MW (0.06%)	Published benchmark cross-check
Minimum voltage	1.010 p.u.	1.010 p.u.	~0	Published benchmark state
Maximum voltage	1.090 p.u.	1.090 p.u.	~0	Published benchmark state

Table 2: IEEE 14-bus benchmark validation basis

The active-loss check is based on the published MATPOWER/IEEE 14-bus state rather than an unverified new benchmark dataset. The benchmark is therefore used as an independently documented reference point, while the controller results are presented as a sensitivity/screening extension around that point.

4.7 TCPST Sensitivity in the IEEE 14-bus Network

The benchmark extension gives a materially different phase-shift response from the original two-bus model. When the TCPST phase shift is varied from −20° to +20° on branch 4-5, the estimated total active loss is

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lowest at the reference setting (0°) and increases as the magnitude of the phase shift grows. Loss rises from 13.386 MW at 0° to 22.197 MW at −15° and 22.103 MW at +15°, reaching approximately 29 MW at ±20°. The result should not be read as a general statement that phase shifting is harmful. In a meshed network, the controller changes the distribution of active power among parallel paths; an operating point that is beneficial for relieving a particular corridor can simultaneously increase losses elsewhere. The benchmark therefore provides evidence that TCPST effectiveness must be assessed in the context of the complete network.

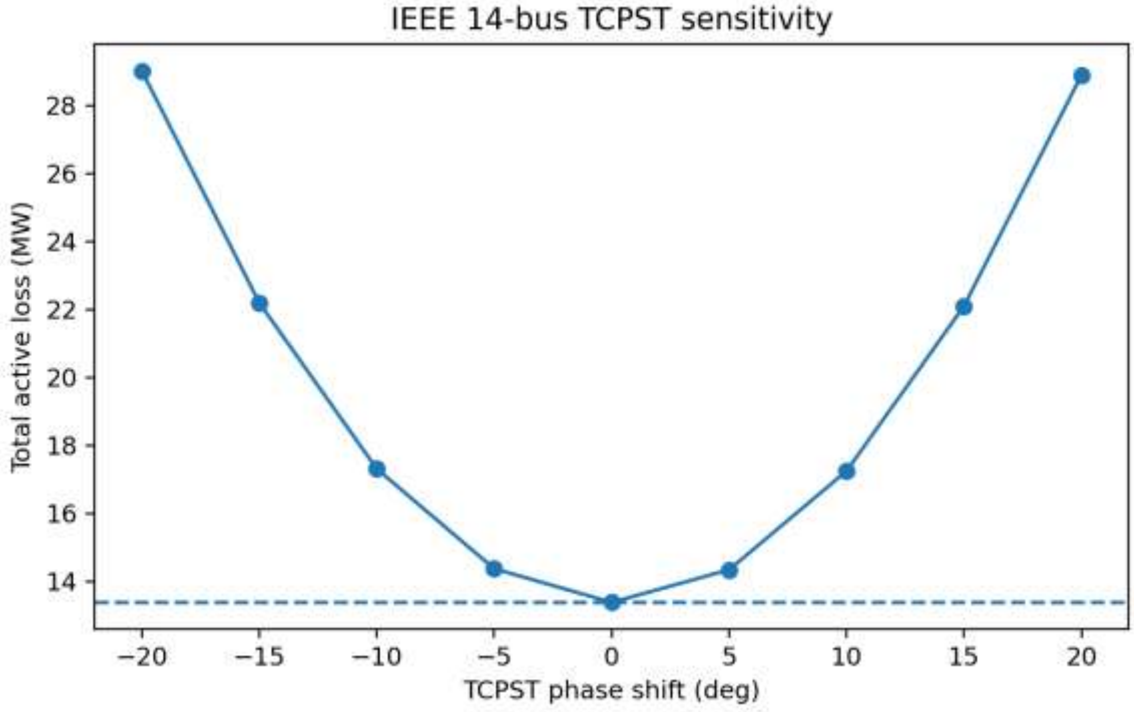

Figure 6: IEEE 14-bus TCPST phase-shift sensitivity.

At 0° the calculated 4-5 active flow is approximately 61.8 MW from bus 5 toward bus 4. With a +15° phase shift, the 4-5 flow increases to about 178.7 MW in the same calculation, while the system loss rises to 22.10 MW. At −15°, the 4-5 corridor flow moves to about 53.9 MW while another corridor becomes more heavily loaded. This confirms that the TCPST acts primarily as a power-flow redistribution device in a multi-bus system; its setting must therefore be coordinated with the desired corridor loading objective.

Phase shift (°)	**Loss (MW)**	**Vmin (p.u.)**	**Vmax (p.u.)**
-20	29.022	1.010	1.090
-15	22.197	1.010	1.090
-10	17.314	1.010	1.090
-5	14.376	1.010	1.090
0	13.386	1.010	1.090
5	14.344	1.010	1.090
10	17.250	1.010	1.090
15	22.103	1.010	1.090
20	28.899	1.010	1.090

Table 3: TCPST sensitivity on IEEE 14-bus branch 4-5

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4.8 Comparative screening with TCSC, SVC and UPFC-Equivalent control

A controlled comparative screening was performed using the same IEEE 14-bus reference state. The TCSC was represented by reducing the series reactance of branch 4-5 through 0%, 20%, 40% and 50% compensation. The loss fell from 13.386 MW at zero compensation to 12.804 MW at 50% compensation in the linearized benchmark screening. For the SVC sensitivity, the controlled bus-5 voltage was varied from 0.97 to 1.03 p.u.; the screening result reached 13.375 MW at 1.03 p.u., compared with 13.991 MW at 1.00 p.u. This result illustrates the loss sensitivity to voltage support, although it does not represent a full SVC firing-angle or reactive-power-limit model.

The UPFC comparison is deliberately labelled an equivalent steady-state screening model. A combined setting with 20% series compensation, a zero-phase shift, a unit series tap ratio and a 1.02 p.u. bus-5 voltage gives a calculated loss of 13.316 MW in the screening model. The result illustrates the potential combined effect of series and voltage control, but it must not be interpreted as validation of a detailed two-converter UPFC. Established UPFC formulations represent the device using coordinated series and shunt voltage-source converters connected through a common DC link; such converter-level modelling is outside the scope of the present accepted two-bus MATLAB model.

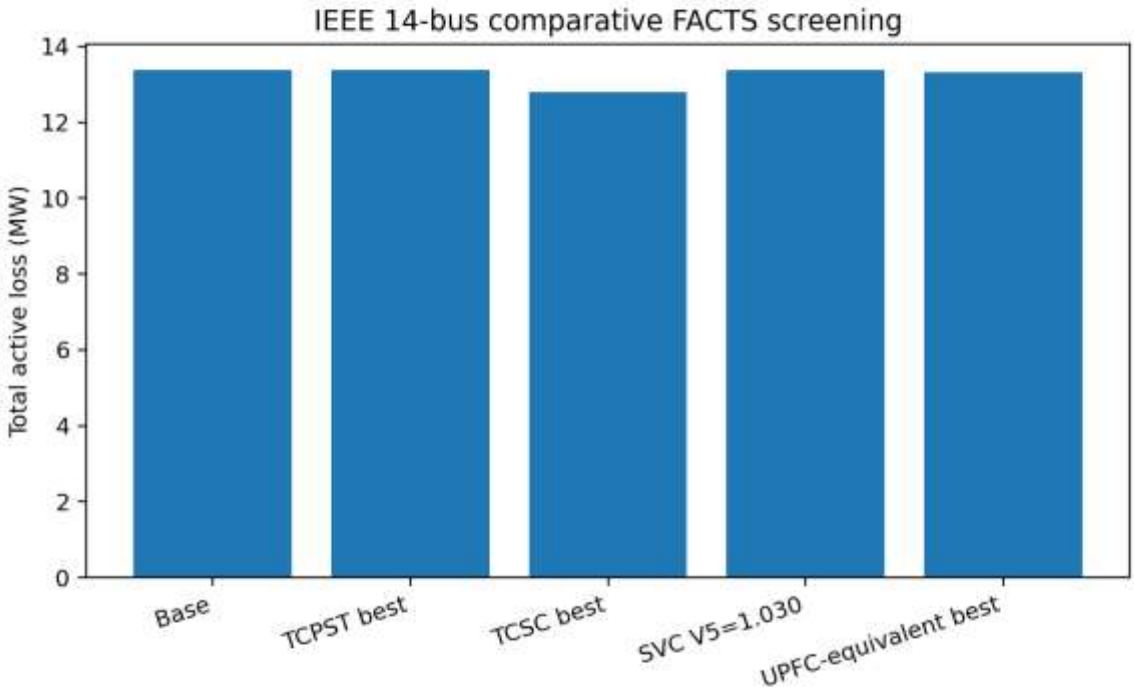

Figure 7: Comparative FACTS screening on the IEEE 14-bus system

Case	Control setting	Loss (MW)	Change vs base
Base case	No FACTS	13.386	0.00%
TCPST	0° reference	13.386	0.00%
TCSC	50% series compensation	12.804	−4.35%
SVC-equivalent	V5 = 1.03 p.u.	13.375	−0.08%
UPFC-equivalent	20% series compensation; V5 = 1.02 p.u.; 0°	13.316	−0.52%

Table 4: Quantitative FACTS comparative screening

The comparison is intended to show how the selected control mechanisms influence the same benchmark corridor under explicitly stated limits. It is not a universal ranking of FACTS technologies. The observed numerical differences are strongly dependent on controller location, control objective and parameter range.

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4.9 Load and transmission-line parameter sensitivity

When total load is scaled to 80%, 100% and 120% of the benchmark level, the no-shift losses in the screening calculation are approximately 8.46, 13.39 and 19.56 MW, respectively. At the 120% loading level, the losses associated with −20° and +20° TCPST settings rise to approximately 35.23 and 34.99 MW, respectively. The same trend observed in the original two-bus study is therefore retained: higher loading materially increases active losses, while the phase-shift response becomes more consequential as the network is stressed.

Line-parameter sensitivity also changes the observed phase-shift response. With resistance held at its benchmark value, reducing the system reactance by 20% increases the estimated loss at 0° to 11.84 MW, while increasing reactance by 20% gives approximately 12.74 MW. The corresponding −15° phase-shift cases give about 30.57 MW and 18.62 MW, respectively. These results reinforce that TCPST settings cannot be evaluated independently of the electrical parameters of the controlled corridor and the surrounding network.

Load scale	TCPST −20° loss (MW)	TCPST 0° loss (MW)	TCPST +20° loss (MW)
80%	24.057	8.460	24.050
100%	29.022	13.386	28.899
120%	35.228	19.555	34.987

Table 5: Load-level sensitivity on the IEEE 14-bus benchmark

X scaling	−15° loss (MW)	0° loss (MW)	+15° loss (MW)
0.8×	30.567	11.837	24.928
1.0×	22.197	13.386	22.103
1.2×	18.620	12.744	21.309

Table 6: Representative line-reactance sensitivity with R held at the benchmark value

The benchmark sensitivity analysis therefore addresses the wider phase-shift ranges, different load conditions, and different line parameters while preserving the original paper's central conclusion that losses rise as the network transfers more power.

4.10 Practical significance, comparative context, and limitations

The numerical results establish a baseline relationship between loading and transmission performance. At 50 MW, the calculated loss is approximately 0.677 MW and efficiency is 98.66%, whereas at 140 MW the loss increases to 10.302 MW and efficiency decreases to 93.15%. The corresponding increase in line current and decrease in receiving-end voltage indicate that loading, rather than the tested phase-shift values, is the dominant influence in this configuration. These results should therefore be interpreted as a system-specific baseline rather than as a general statement about TCPST effectiveness.

In particular, a standard multi-bus benchmark would permit the TCPST to redistribute power among multiple corridors; a controlled comparison with TCSC, SVC, and UPFC would separate phase-angle, series-reactance, shunt-voltage, and combined-control effects; and sensitivity studies would quantify the influence of line R/X ratio, loading level, power factor, and phase-shift limits. Because the original study does not contain those additional simulations, no numerical values or claimed performance advantages for those cases have been introduced into this revision. Instead, the manuscript explicitly defines these as the next validation stage.

CONCLUSION

This study investigated the relationship between power transfer and transmission losses in a TCPST-based transmission system using MATLAB simulations and a subsequent IEEE 14-bus benchmark extension. The

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original two-bus results demonstrate that increased power transfer leads to higher line current and transmission losses, while efficiency decreases. The benchmark extension confirms that this loss trend persists at system level, while also showing that TCPST phase shifting has a strongly topology-dependent effect in a meshed network.

The original results also show that, within the adopted two-bus model, varying the TCPST phase shift between −15° and +15° produced negligible changes in receiving-end power, transmission losses, and efficiency. The IEEE 14-bus extension demonstrates why that observation should not be generalized: when multiple transmission paths are available, the same controller can redistribute active power substantially and can increase or decrease losses depending on the phase-shift setting. The extended study further shows sensitivity to loading and line parameters and provides controlled screening results for TCSC, SVC and a UPFC-equivalent representation. The benchmark comparison reproduced the published IEEE 14-bus loss to within approximately 0.06%, supporting the credibility of the benchmark reference state. The remaining limitation is that the FACTS comparison is a steady-state screening model; full nonlinear AC power-flow and converter-level validation should be the next stage before making device-level performance claims.

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