Power Flow Consideration of Impedance Correction for Phase Shifting Transformers

Ju Hee Yeo, *Student Member*, *IEEE*, Pooria Dehghanian, *Student Member*, *IEEE*, and
Thomas Overbye, *IEEE Fellow*
Department of Electrical and Computer Engineering, Texas A&M University, College Station, Texas, USA
Yeochee26@tamu.edu; Pooria.dehghanian@tamu.edu; Overbye@tamu.edu

Abstract— **In high voltage electric grids, phase shifting transformers (PSTs) are devices in which the phase shift across the device can be varied to control the flow of real power. A consequence of this phase variation is that PST's series impedance often varies with the phase shift, sometimes substantially. In power system analysis applications this variation is often modeled using a piecewise-linear impedance correction table. This paper analyzes the influence of incorporating impedance correction tables on a power flow solution. The presented method is implemented in two different test systems. A two-bus test system shows various transformer correction tables can make different power flow solutions. A 37-bus test system demonstrates the influence of the impedance correction table on both normal operating condition and contingency scenarios. The results reveal that impedance correction tables have impacts on power flow solutions and may help alleviate the overloaded lines following a contingency.**

Index Terms— **PST; Impedance correction factor (table); Power flow control; Line power flow analysis, Contingency analysis.**

I. INTRODUCTION

AS POWER SYSTEMS have become more complex with heavier load-penetration, intermittent renewable-resource power generation, and various control devices, getting power flow solutions tends to be challenging. A key issue is that actual power systems are quite complicated with many nonlinearities such as generators' reactive power limits, switched shunts, Load Tap Changers (LTCs), Phase Shifting Transformers (PSTs), etc.

Particularly, the PSTs control the real power by changing the phase angle of transformers. In some references, they are called "*phase angle regulators*" [1]. The PSTs share the power flow on other parallel lines and avoid possible overloads on the transmission lines [2], [3]. However, placing the PSTs into the system could change the power flow, especially within the local vicinity of the PST. The value of transformer impedance also changes depending on the PST's angle. Therefore, Y-bus matrix is no longer symmetric, which can make solving the power flow more complicated [4]-[6].

To have a good model of a PST for both a balanced and unbalanced system condition, the impedance of windings at each tap position is required. The transformer winding impedance can be calculated using positive, negative, and zero-sequences models. The magnitude of the negative sequence impedance and positive sequence impedance is the same, however, their phase angles are in the opposite direction [7]. Usually, the manufactures provide a detailed test report data based on short-circuit and open-circuit tests of the transformer including the transformer impedance correction factors, maximum no-load phase shift and positive and zero sequence impedance at the maximum tap position. The impedance correction (multiplier) factor operates as a function of the angle, which varies the impedance using a piece-wise linear curve. The transformer impedance correction table can be used for the PST or LTC transformers to model the transformer impedance based on the phase shift or off-nominal turn ratio [8]. However, adding the impedance correction factors to the transformer setting changes the Y-bus matrix, which makes solving the power flow complex. Because of this, sometimes impedance correction table is not modeled in power flow simulations.

The purpose of this paper is to show how a power flow solution can vary in both normal and contingency conditions depending on the settings of the impedance correction tables. Various impedance correction data-sets are used, which bring different results subject to the transformer's phase angle. This paper describes different power flow solutions that take the phase angle changes and the impedance correction tables into account.

Despite common usage of impedance correction tables in commercial power flow solutions tools, there are few papers in the literature that consider their impact on power flow solutions. However, work has been published to assess the general impact of the PSTs on power flow convergence. A fast-decoupled power flow method and fault analysis with asymmetrical PSTs are proposed in [9]. The main contribution is to identify the features of the power flow deviations by the PSTs, based on the analysis of the Eigenvalues of the matrix. A power flow control mechanism using a phase shifter transformer is proposed in [10] to investigate the power flow solution with the aim of minimizing the power loss in transmission lines. In [11], a line power flow sensitivity analysis to control power flow in the presence of large-scale PV penetration is presented. A frequency response analysis has been proposed to study for the maintenance and troubleshooting of the PSTs in the system [12]. The application of the PSTs as a correction power flow control mechanism in parallel EHV interconnection transmission lines is investigated in [13] and its impact on voltage stability is addressed.

The influence of the PSTs in power system dynamic is assessed in [14] using an FP-PST model with a fixed phase between the terminal voltage and voltage boost. In [15] the impact of employing the PSTs for improving the power quality and harmonic mitigation is addressed. A short-step Chebyshev impedance transformer approach is discussed in [16] to obtain the semi-lumped element impedance transformers. A frequency-based method for impedance correction of wave filters is presented in [17] in which an improved approximation method is proposed to calculate the network resistivity. A method to identify the type of internal fault on an indirect symmetric PST using a pattern recognition network algorithm is presented in [18].

The rest of the paper is structured as follows. A background on the concepts of the PSTs and impedance correction factor are introduced in Section II. Section III describes the proposed formulation for power flow solution considering the impedance correction factor. A 2-bus and 37-bus systems are studied to test the influence of impedance correction table sets on the power system solutions in both normal and contingency operating conditions, and the numerical results are presented in Section IV. Finally, discussion and conclusions are included in Section V and Section VI, respectively.

978-1-5386-9284-4/19/$31.00 ©2019 IEEE

II. BACKGROUND ON PHASE-SHIFTING TRANSFORMERS

The PSTs are considered as variable-impedance devices, which can have high rating power (greater than 1000 MVA), and are mainly utilized in high voltage power systems. An important application of the PST is to control and regulate the real power flow within the transmission grid [2]. The main principle configuration of the PST application is to control the power flow in parallel transmission lines when a PST is connected to one line [19], [20]. Additionally, in a more complex system where the power grid has intersections at more than one point, the PSTs provide load balance in loops. They not only increase the grid security but also enhance the transmission capacity by reducing line losses [9], [21]. Like the standard transformer, the PST is mainly protected using differential protection technique in addition to the other mechanical and electrical protection mechanism.

The major functions of phase shifting transformers are summarized below:

- *Alleviate the harmonic issues*: through adding phase displacement between the primary and secondary of line-line voltage.
- *Enhance the transmission line thermal overload protection and its stability*: through maintaining the power flow injection to the line.
- *Regulating the secondary voltage.*

Fig. 1 illustrates an equivalent circuit for a PST. Where I_i is the injection current at bus *i*; i_i is outflow current at bus *i*; I_k is the bus injection current at bus *k*; i_k is the outflow current at bus *k*; V_i is the bus voltage at bus *i;* V_k is the bus voltage at bus *k*; *T* is the off-nominal turns ratio of the PST; E_i denotes the transmission line voltage and y is the admittance of the PST. The circuit consists of the line admittance in series with a PST.

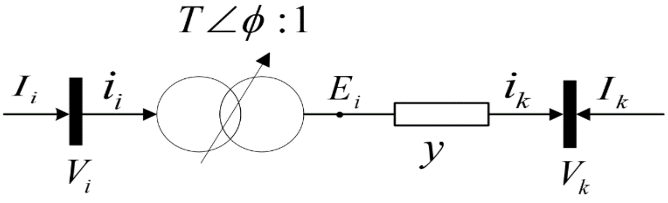

Figure 1. Single-line diagram representation of phase shifting transformer.

The phase angle step size might vary in different tap positions. To make the computational burden simple, the equal step size is mostly used in power flow and transient stability analysis.

The active power flow injection into the transmission line connected between buses *i* and *k* can be calculated as follows:

$$P=\frac{|V_i|.|V_k|}{Z_{line}}\sin\theta_{ik} \tag{1}$$

where V_i is the bus sending voltage; V_k is the receiving-side voltage; θ_{ik} is the angle difference between V_i and V_k ; and Z_{line} is the transmission line impedance value.

One way to change the active power flow over the transmission line is to implement voltage control analysis. However, it might not be a practical solution since the voltage has a greater impact on reactive power variations. Another approach is to use FACTS devices that change the line impedance or employ the shunt capacitors to lower the transmission line reactance. However, the focus of this paper is to control the real power through the PST devices.

The voltage and current relations for an ideal single-phase two-winding transformer can be expressed as follow [5]:

$$\frac{V_i}{E_i}=T\angle\phi=Te^{j\phi}=T(\cos\phi+j\sin\phi)=\alpha+j\beta \tag{2}$$

where, ϕ is the phase shift of the transformer from bus *i* to *k*. The phase shift is positive when V_i leads E_i . The relationship between the phase shifter terminal voltage and current for the transformer would be as follows:

$$\begin{bmatrix} I_i \\ I_k \end{bmatrix}=\begin{pmatrix} \dfrac{y}{\alpha^2+j\beta^2} & -\dfrac{y}{\alpha\ +j\beta} \\ -\dfrac{y}{\alpha\ +j\beta} & y \end{pmatrix}\begin{bmatrix} V_i \\ V_k \end{bmatrix} \tag{3}$$

One can observe from (3) that the Y-bus matrix is not symmetrical which means that the transfer admittance from one bus to another is not equal to each other.

As mentioned in the Section I, the transformer's impedance correction factor operates as a function of the phase angle and changes the transformer impedance. It is calculated using a piecewise-linear linear impedance curve. Usually, the manufactures provide the correction factors corresponding to different phase angles. So, the transformer's impedance changes can be modeled by modifying the impedance correction factor [19]. Therefore, by adjusting the correction factor, one can see the change in the transformer's impedance subject to an angle. According to the IEC 60909-0 guideline, the correction factor K_T for the three-windings transformers with or without step switching can be calculated as follows [22]:

$$Z_T=R_T+jX_T \tag{4-a}$$

$$Z_{TK}=K_T*Z_T \tag{4-b}$$

$$x_T=X_T*\frac{S_{rT}}{V_{rT}^2} \tag{4-c}$$

where, Z_T is the transformer impedance without correction factor, K_T is the correction factor, Z_{TK} is the transformer's corrected impedance, V_{rT} is the rated voltage of the transformer, S_{rT} is the rated power of transformer, x_T is the per unit relative reactance of transformer, and $c_{\max}$ is a voltage factor based on low voltage side of the transformer. The correction factor for a three-phase three-winding transformer can be obtained using (5). Usually, the large transformers have small resistance comparing with reactance and hence, the resistance can be neglected.

$$K_T=0.95*\frac{c_{max}}{1+0.6\,x_T} \tag{5}$$

III. IMPEDANCE CORRECTION FORMULATION

A. Y-Bus Matrix Formation Considering the Impedance Correction Factor

To assess the influence of the phase shifter's angle and impedance correction factor on a power system solution, take a two-bus system consisting of two parallel lines (shown in Fig. 2) as an example. It is assumed that the tap ratio is fixed to 1. The Y-bus matrix can be constructed as follows:

$$\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{pmatrix} y_{11}^{L1} + y_{11}^{L2} & -\dfrac{y_{12}^{L1}}{e^{j\phi}} - y_{12}^{L2} \\ -\dfrac{y_{21}^{L1}}{e^{-j\phi}} - y_{21}^{L2} & y_{22}^{L1} + y_{22}^{L2} \end{pmatrix} . \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} \tag{6}$$

L1 and L2 are the lower and upper lines, respectively. The phase shifter is located on L1.

However, taking into account the embedding of impedance correction factors into the transformer database, the Y-bus matrix would slightly be changed. Equations (7(a-d)) demonstrate the impact of considering the impedance correction factor on the Y-bus matrix. The overall framework of the influence of the PSTs on power system solution is presented in Fig. 3.

$$Y_{11} = \frac{y_{11}^{L1}}{K_T(\phi)} + y_{11}^{L2} \tag{7-a}$$

$$Y_{12} = -\frac{y_{12}^{L1}}{K_T(\phi)\, e^{j\phi}} - y_{12}^{L2} \tag{7-b}$$

$$Y_{21} = -\frac{y_{21}^{L1}}{K_T(\phi)\, e^{-j\phi}} - y_{21}^{L2} \tag{7-c}$$

$$Y_{22} = \frac{y_{22}^{L1}}{K_T(\phi)} + y_{22}^{L2} \tag{7-d}$$

B. *Active Line Power Flow Analysis Considering the Impedance Correction Factor*

The complex power on the line can be calculated using bellow:

$$\mathbf{S_{12}} = \mathbf{V}_1 [(\mathbf{V}_1 - \mathbf{V}_2) . Y_{Bus}]^* \tag{8}$$

Without having a phase shifter, the active power mismatch equation is expressed using (9).

$$P_i = \sum_{k=1}^{2} |V_i||V_k| (G_{ik} \cos\theta_{ik} + B_{ik} \sin\theta_{ik}) = P_{G_i} - P_{D_i} \tag{9}$$

Given that an impedance correction table is set into the phase shifter transformer which is connected to L1 as shown in Fig. 2, which makes Y-bus matrix like (7). The conductance G_{L1} and G_{L2} are assumed to be zero and the slack bus's voltage magnitude and angle are set to 1 (p.u.) and 0^0, respectively. Voltage magnitude at the load side is assumed to be the same as the one at the slack bus since the phase angle has a greater influence on the voltage angle than its magnitude. The complex power on the transformer line is formulated in (10) and its real part which refers to the active power on the transformer line is derived in (11). Note that B_{11}^{L1} is assumed to be equal to B_{12}^{L1}.

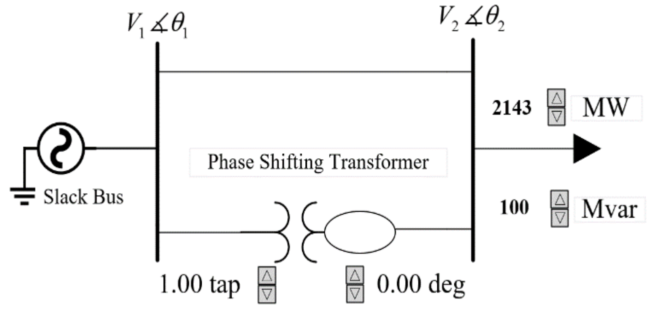

Figure 2. The 2-bus test case configuration.

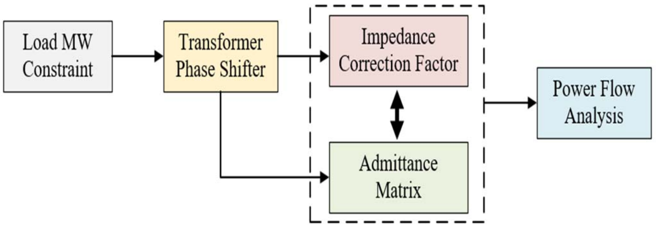

Figure 3. The overall studied procedure framework.

$$\boldsymbol{S}_{12} = V_1[(V_1 - V_2\cos\theta_2 - jV_2\sin\theta_2)\{j\frac{B_{12}^{L1}}{K_T(\emptyset)e^{j\emptyset}} - \frac{B_{11}^{L1}}{K_T(\emptyset)}\}] \tag{10}$$

$$P_{\emptyset} = \frac{B_{11}^{L1}}{K_T(\emptyset)}\{\sin\theta_2(\cos\emptyset - 1) - \sin\emptyset\cos\theta_2\} \tag{11}$$

IV. CASE STUDY AND NUMERICAL RESULTS

A. ***Case Study 1****: Impact of Impedance Correction Factor on the Power System*

The approach is simulated in a 2-bus test system with two parallel transmission lines as shown in Fig. 2. Bus 1 is considered a slack bus and its voltage magnitude and angle are set to 1 (p.u.) and 0^0, respectively. Bus 2 is a load bus with a constant P-Q demand. A PST is located on L1. For convenience, it is assumed that the transmission lines are lossless with the reactance value of 0.2 (p.u.) and 0.25 (p.u.) at L1 and L2, respectively.

To assess the impact of impedance correction factor on power flow solution, different impedance correction data sets corresponding to various phase angle values are tabulated in Table I. Note that the data sets for the impedance correction table are collected from the Eastern Interconnection Reliability Assessment Group (ERAG) [23].

Three different MW load constraints - 500MW, 1000MW, and 1500MW - are tested to see if the system is capable of convergence. If not, one can detect when the voltage drops below 0.9 V (p.u.) depending on the phase angle variations. Figures 4-6 illustrate the voltage profile of the three different system loadings corresponding to various impedance correction sets shown in Table I.

The goal is to see that various datasets have a different impact on power system convergence. Fig. 4 represents the bus voltage response for the case with a load of 500 MW and 100 Mvar. The voltage drops more drastically when the impedance correction set has a relatively high correction factor for the same phase angle. The voltage is below 0.9 V (p.u.) at phase angles $\pm 46^0$, $\pm 43^0$, and $\pm 37^0$ for Table 1, Set 1, Set 2, and Set 3, respectively. Unlike the other table sets, the correction factor for Table 1, Set 3 becomes smaller for phase angle above 37^0 or below -37^0 which makes the voltage profile of the Table 1, Set 3 larger than that of the Table 1, Set 2.

As the load is increased to 1000MW and 100 Mvar, Fig. 5 illustrates that the two solutions of Table 1, Set 2 and Set 3 meet at points ($\pm 37^0$, 0.9V(p.u.)), whereas for the Table 1, Set 1, the same voltage of 0.9 V (p.u.) occurs at phase angles $\pm 43^0$. Further increases in loading augment the distance between the solutions of all sets and expedite voltage drop as presented in Fig. 6. As discussed earlier, and the simulated results elaborate, utilizing various impedance correction table sets brings about different power flow convergence. For a specific phase angle, the larger correction factor has higher transformer impedance value. Hence, the power limit flowing into the transformer line can be reduced. As a result, power flow sometimes could not converge to a solution.

B. **Case Study 2**: *Multiple Power Flow Solutions*

To realize the influence of the impedance correction table on power flow solutions, three case studies are simulated using the same 2-bus test system with a constant P-Q demand of 500MW, 100Mvar as follows: i) power flow solution with the Table I, set 1; ii) power flow solution with Table I, set 2; iii) power flow solution with no utilization of impedance correction table.

It can be seen in Figures 7-8 that the active power on the transformer line is strongly affected by the changes of the voltage angle θ_2 .This makes it possible to have multiple power solutions (equal real power but different phase angles). In Fig. 9, since no impedance correction table is considered, no multiple power flow solutions are found. As seen in (10) and (11), if an impedance correction table is added into the transformer data set, the transformer impedance B_{11}^{L1} is replaced with $\frac{B_{11}^{L1}}{K_T(\emptyset)}$ which leads to change of the voltage angle at load side. As a result, the same voltage angle for different phase angle might be obtained as presented in Fig. 7-8. When using an impedance correction table, any change in the PST's angle could alter its impedance value.

TABLE I
THE UTILIZED IMPEDANCE CORRECTION TABLE SETS

Set 1		**Set 2**		**Set 3**		**Set 4**	
ϕ	K_T	ϕ	K_T	ϕ	K_T	ϕ	K_T
-60	1	-40	1	-70	1	-47	6.34
-50	0.733	-35	0.75	-50	0.837	-41.7	5.44
-36	0.358	-25	0.6	-43	0.78	-33.3	4
-24.4	0.192	-12.5	0.55	-37	0.818	-27.5	3.06
-8.3	0.024	-7.5	0.52	-32	0.85	-18.5	2
0	0.01	0	0.5	0	0.5	0	1
8.3	0.024	7.5	0.52	32	0.85	18.5	1.76
24.4	0.054	12.5	0.55	37	0.818	27.5	3.278
36	0.358	25	0.6	43	0.78	33.3	3.643
-50	0.733	35	0.75	50	0.837	41.7	5.25
60	1	40	1	70	1	47	6.34

ϕ : Phase Shifter's Angle K_T : Impedance Correction Factor

As demonstrated in Fig 7 and Fig 8, when the PST is used to do real power control, this results in the possibility of multiple power flow solutions.

C. *A 37-Bus Test System: Impact of Impedance Correction Table on Power System Contingency Analysis*

The next example is a 37-bus system with 43 transmission lines, 10 generators, 26 loads, 10 LTC transformers, and one PST. Two separate contingency scenarios have been implemented to assess the impact of impedance correction table on both pre-contingency (normal operating condition) and post-contingency conditions.

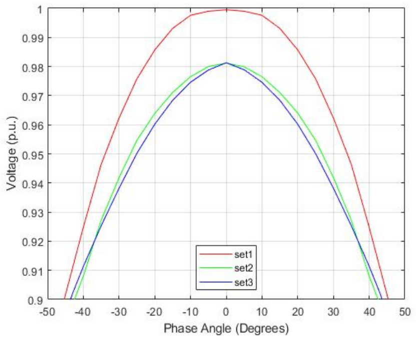

Figure 4. Load voltage profile corresponding to different table sets for the fixed Load of 500MW and 100Mvar.

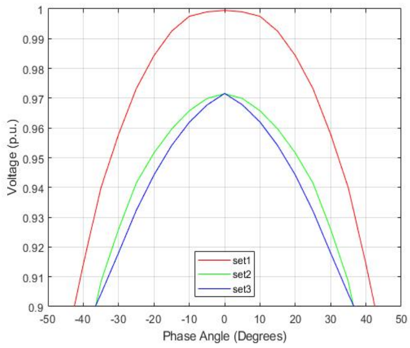

Figure 5. Load voltage profile corresponding to different table sets for the fixed Load of 1000MW and 100Mvar.

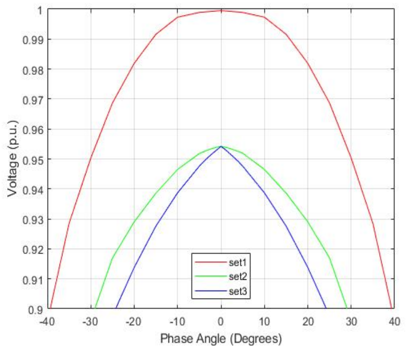

Figure 6. Load voltage profile corresponding to different table sets for the fixed Load of 1500MW and 100Mvar.

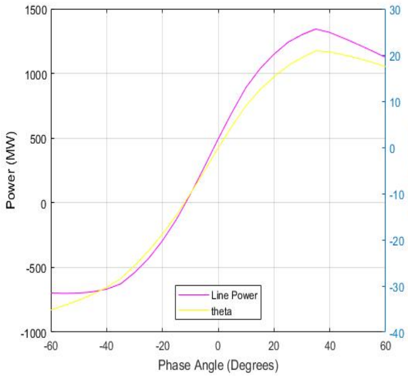

Figure 7. Power flow solution considering Table set 1 for the Load of 500 MW and 100 Mvar.

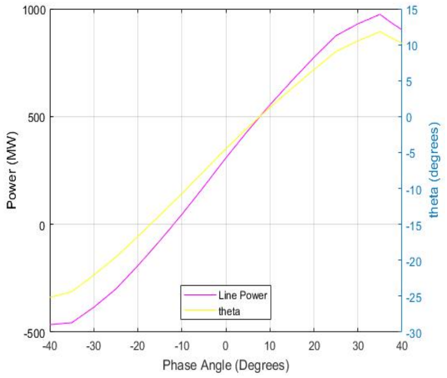

Figure 8. Power flow solution considering Table set 2 for the Load of 500 MW and 100 Mvar.

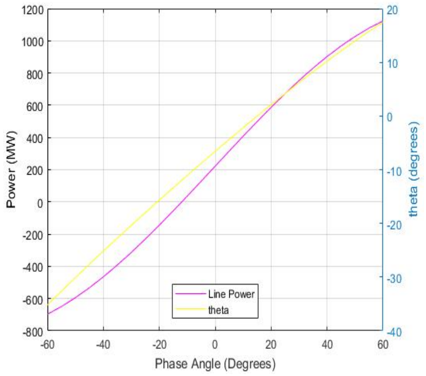

Figure 9. Power flow solution with no impedance correction table utilization for the Load of 500 MW and 100 Mvar.

- ***Scenario (S1):*** *Contingency Analysis with No Impedance Correction Table Consideration*

The 37-bus test system has the total capacity of 1460.6 MW which serves a total load of 1429.3 MW. In the first scenario (S1), no impedance correction table is considered. In the normal operating condition at zero phase angle, there would be no system violation. It is obvious that changing the phase angle would affect the power flow direction and may cause overloaded lines (See Table II).

A contingency analysis is implemented by disconnecting the transmission line which is connected from the bus 29 to 41. The purpose is to see if the PST without utilizing the impedance correction table is capable of eliminating the imposed overloaded line following the contingency. As a result of this contingency, the line connected between buses 32 and 29 would be overloaded which is the target line in our study. Incrementally increasing the phase angle of the PST still aggregates that overloaded line and eventually leads more lines to be overloaded. However, decreasing the phase angle reduces the power flow into the target line till the phase angle reaches -13^0.

By decreasing the phase angle beyond -13^0, the target line is no longer overloaded, however, another line overpasses its capacity. Fig. 10 presents the one-line diagram configuration of the studied 37-bus system when the phase angle is set to -13^0. This case shows that just by changing the phase angle of the PST (no impedance correction table is considered) the system operator may not be able to fully maintain the power flow of the overloaded lines following a contingency.

- ***Scenario (S2):*** *Contingency Analysis Considering the Impedance Correction Table*

The similar approach is used to realize the impact of impedance correction table on the power grid. The same contingency case used in S1 is studied in S2 but the impedance correction table set 4 is considered (see Table I). In S2, the initial response of the system when the phase angle is 0^0, for both pre-contingency and post-contingency, is identical to S1. It means that immediately, the target line would be overloaded after applying the contingency. By increasing the phase angle of the PST, the target line becomes more overloaded. However, by decreasing the phase angle down to -12^0, not only the target line is no longer overloaded, but also the other lines operate within their line capacities. Fig. 11 zooms to the portion of the system (S2) which shows how the power flow changes when the phase angle is set to -12^0. The results obtained from the contingency analysis highlight that employing the impedance correction table set into the PST settings could maintain the power system stable. Table II presents in detail the impact of impedance correction table in both pre and post- contingency scenarios (*S1* and *S2*).

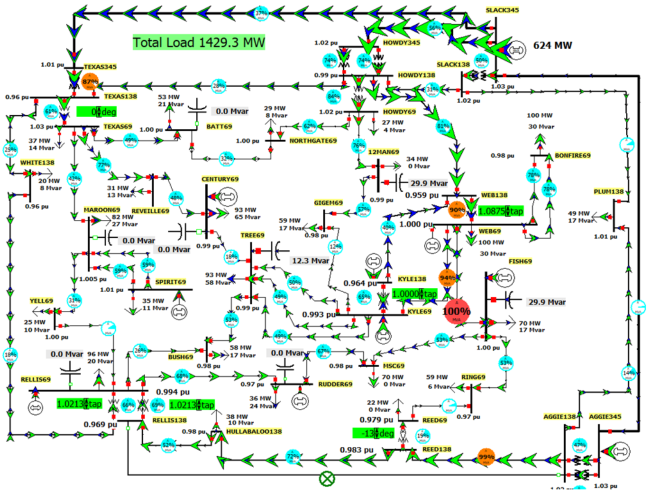

Figure 10. The one-line diagram of the 37-bus case: Scenario 1 during contingency with no consideration of impedance correction table. (The phase angle is set to -13^0)

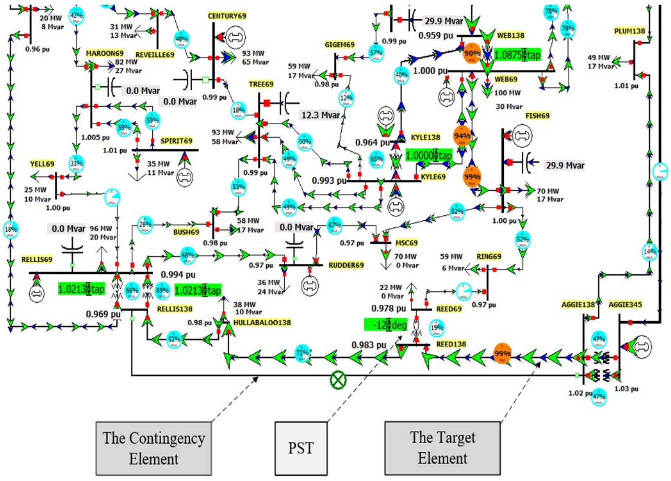

Figure 11. Scenario 2: Impact of considering impedance correction table on power system contingency analysis. (Phase angle is set to -12^0)

TABLE II
IMPACT OF IMPEDANCE CORRECTION TABLE ON CONTINGENCY ANALYSIS

No Impedance Correction						With impedance Correction					
Pre-Contingency			Post- Contingency			Pre-Contingency			Post- Contingency		
ϕ	P_{ϕ} (MW)	Overloaded Lines	ϕ	P_{φ} (MW)	Overloaded Lines	ϕ	P_{ϕ} (MW)	Overloaded Lines	ϕ	P_{ϕ} (MW)	Overloaded Lines
-20	3.37	2	-20	1	2	-20	3.20	2	-20	1.10	2
-13	-27.19	-	-13	-29.51	1	-13	-23.77	-	-13	-25.58	1
-12	-31.61	-	-12	-33.95	1	-12	-28	-	-12	-30.06	-
-5	-63.34	-	-5	-65.61	1	-5	-60.15	-	-5	-62.30	1
0	-86.65	-	0	-88.66	1	0	-86.65	-	0	-88.66	1
5	-110.2	-	5	-111.92	1	5	-105.86	-	5	-107.49	1
12	-143.1	1	12	-144.48	1	12	-130	-	12	-131.21	1
16	-161.5	3	16	-162.93	3	16	-142.13	1	16	-143.32	1
20	-179.8	4	20	-181.16	4	20	-148.8	1	20	-149.16	1

P_{ϕ} : The MW power flow into the PST; ϕ : The transformer phase angle;

V. DISCUSSION

Phase shifter transformers are used in electric power grid and there is an impedance correction table associated with them. While many commercial power system simulation tools have the capability to model impedance correction tables, some other widely used tools, such as [24], do not. Obviously, impedance variation due to the impedance correction table only comes into play when the phase angle is varied during the power flow solution. In this paper, the simulation results highlight that the impedance correction table sets have an impact on power flow solutions and could be useful in alleviating the overloaded lines and hence, need to be considered.

VI. CONCLUSIONS

This paper presents the impact of impedance correction tables on power flow convergence. It is demonstrated that the power flow solution can be varied depending on the value of the PST's impedance correction factor. As discussed in the paper, embedding the impedance correction table set which includes a larger impedance correction factor for the same phase angle makes the transformer impedance value relatively high. In some cases, it results in power flow divergence due to the line constraint. As the results revealed, multiple power flow solutions (the same real power but different phase angles) can be achieved when the impedance correction factor is set into the transformer's data set. A contingency analysis is implemented to assess the influence of the transformer impedance correction table on power flow solutions. The results show that it is possible to even alter an overloaded line to operate within its normal line flow limit by using the impedance correction table.

REFERENCES

[1] J. S. Nyati, M. Eitzmann, J. Kappenman, D. VanHouse, N. Mohan and A. Edris, "Design issues for a single core transformer thyristor controlled phase-angle regulator," *in IEEE Transactions on Power Delivery*, vol. 10, no. 4, pp. 2013-2019, Oct. 1995.

[2] J. Verboomen, D. Van Hertem, P. H. Schavemaker, W. L. Kling and R. Belmans, "Phase shifting transformers: principles and applications," *International Conference on Future Power Systems*, Amsterdam, 2005, pp. 6 pp.-6.

[3] P. Dehghanian, S. Aslan and P. Dehghanian, "Maintaining Electric System Safety Through An Enhanced Network Resilience," in IEEE Transactions on Industry Applications, vol. 54, no. 5, pp. 4927-4937, Sept.-Oct. 2018.

[4] J. Verboomen, D. Van Hertem, P. H. Schavemaker, W. L. Kling and R. Belmans, "Border-Flow Control by means of Phase Shifting Transformers," *IEEE Lausanne Power Tech*, pp. 1338-1343, 2007.

[5] P. Kundur, *Power system stability and control*, McGraw-Hill Professional, 1994.

[6] M. H. R. Koochi, S. Esmaeili and P. Dehghanian, "Coherency detection and network partitioning supported by wide area measurement system," *2018 IEEE Texas Power and Energy Conference (TPEC)*, pp. 1-6, College Station, TX, 2018.

[7] U. Khan, "Modeling and protection of phase shifting transformers," Ph.D. dissertation, University of Western Ontario, 2013, [Online]. Available: https://ir.lib.uwo.ca/etd/1701/

[8] IEEE Guide for the Application, Specification, and Testing of Phase-Shifting Transformers - Redline," *in IEEE Std C57.135-2011 (Revision of IEEE Std C57.135-2001) - Redline*, vol., no., pp.1-71, 19 Aug. 2011.

[9] R. D. Youssef, "Phase-shifting transformers in load flow and short-circuit analysis: modelling and control," *in IEE Proceedings C - Generation, Transmission and Distribution*, vol. 140, no. 4, pp. 331-336, July 1993.

[10] Z. X. Han, "Phase shifter and power flow control," *IEEE Transaction on Power Apparatus and Systems*, vol. PAS-101, Oct. 1982.

[11] Y. Kawaura, S. Yamanouchi, M. Ichihara, S. Iwamoto, Y. Suetsugu and T. Higashitani, "Phase-shifting transformer application to power-flow adjustment for large-scale PV penetration," *IEEE Region 10 Conference (TENCON)*, Singapore, pp. 3328-3331, 2016.

[12] X. Liang, A. El-Kadri, J. Stevens and R. Adedun, "Frequency Response Analysis for Phase-Shifting Transformers in Oil Field Facilities," *in IEEE Transactions on Industry Applications*, vol. 50, no. 4, pp. 2861-2870, July-Aug. 2014.

[13] A. El Hraïech, K. Ben-Kilani and M. Elleuch, "Control of parallel EHV interconnection lines using Phase Shifting Transformers," *IEEE 11th International Multi-Conference on Systems, Signals & Devices (SSD14)*, Barcelona, pp. 1-7, 2014.

[14] R. Mihalic and P. Zunko, "Phase-shifting transformer with fixed phase between terminal voltage and voltage boost: tool for transient stability margin enhancement," *in IEE Proceedings - Generation, Transmission and Distribution*, vol. 142, no. 3, pp. 257-262, May 1995.

[15] J. -. Boudrias, "Power factor correction and energy saving with proper transformer, phase shifting techniques and harmonic mitigation," *Large Engineering Systems Conference on Power Engineering (IEEE Cat. No.04EX819)*, Halifax, NS, Canada, pp. 98-101, 2004.

[16] P. W. Van Der Walt, "Short-Step-Stub Chebyshev Transformers Impedance," *in IEEE Transactions on Microwave Theory and Techniques*, vol. 34, no. 8, pp. 863-868, Aug 1986.

[17] H. W. Bode, "A method of impedance correction," *Bell System Technical journal*, pp. 794-835, Oct. 1930.

[18] S. K. Bhasker, M. Tripathy and V. Kumar, "Identification of type of internal fault in indirect symmetrical phase shift transformer based on PRN," *IEEE 7th Power India International Conference (PIICON)*, Bikaner, pp. 1-4, 2016.

[19] J. M. Cano, Md. R. R. Mojumdar, J. G. Nomiella, and G. A. Orcajo, "Phase shifting transformer model for direct approach power flow studies," International Journal of Electrical Power and Energy Systems, vol. 91, pp. 71-79, 2017.

[20] E. Csanyi, "Where and why do we use phase-shifting transformers?," April. 2018. [Online]. Available: https://electrical-engineering-portal.com/where-and-why-do-we-use-phase-shifting-transformers.

[21] F. Salehi, A. Brahman, R. Keypour and Wei-jen Lee, "Reliability assessment of automated substation and functional integration," *IEEE Industry Applications Society Annual Meeting*, pp. 1-7, Portland, 2016.

[22] I. Kasikci, "*Short circuits in power systems: A practical guide to IEC 60909-0*," Wiley-VCH, second edition, 2018.

[23] —, "Multiregional modeling working group: Procedure Manual," Eastern Interconnection Reliability Assessment Group, version 19, Oct. 2017.

[24] R. D. Zimmerman, C. E. Murillo-Sanchez, et.al, "MATPOWER," [Online]. Available: http://www.pserc.cornell.edu/matpower/