Optimal Placement of Phase Shifting Transformers for Power Flow Control

A Project Report

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Muhammed shamil

ABSTRACT

Transmission networks connect long distant consumers from producers, sometimes between nations. This huge achievement is efficiently and easily done in the modern world by Phase shifting transformers.

A Phase Shifting Transformer (PST) is a specialised type of transformer, typically used to control the flow of active power on three-phase electric transmission networks. It does so by regulating the voltage phase angle difference between two nodes of the system. Both the magnitude and direction of power flow can be controlled by varying the phase of the transformer. PSTs offer a reliable, complete, and more economical solution for the control of power flow.

This thesis proposes an introduction to phase-shifting transformers. Furthermore, an explanation of the basic principles of phase-shifting transformers, their various types, as well as their role and importance in the power system. Simulation in the Digsilent power factory is also added to understand the basic role of PST. It also comprises Direct approach proposed by J H Teng to do state estimation mathematically in a power grid with PST, and reducing error in this calculation using impedance correction table. A 9-bus test system demonstrates the influence of the impedance correction table on normal operating conditions and its results reveal that impedance correction tables have impacts on power flow solutions and may help alleviate the overloaded lines.

Positioning of PST is equally important as much as its design is concerned. More effective and efficient power flow happens with optimal placement of PST in the power grid and the phase shift applied to it. Many algorithms propose optimal solutions for the same. Finally, this thesis proposes an optimal solution for PST using genetic algorithm, and its credibility is verified with simulation of 57 bus test system in the Digsilent power factory.

KEYWORDS: Phase Shifting Transformer (PST), Tap position, branch current bus voltage (BCBV), Bus injection Branch current (BIBC), genetic algorithm, simulation

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Chapter 1
INTRODUCTION

World's energy demand is increasing day by day. This demand is met by increasing power generation and its transportation through power lines. Power transmission is an integral part of the power sector and is important as power generation; there is no value for generating power until the power reaches to the destination. The huge amount of power generated in power stations is to be transported over a long distance to the load centres and to the consumers with the help of transmission lines and transmission towers. Though India has adequate power generation capacity, it has a substantial proportion of population having limited access to electricity mostly because of lack of proper transmission infrastructure. The power network can be roughly divided in generation, transmission, distribution and consumers. Transmission is the most important sector and optimisation of this transmission network is one of the most difficult tasks.

In this power transmission sector, the transmission grid operates at very high voltages. The connection between this transmission grid and the distribution grid and between the distribution grid and consumers is done by the use of step-down transformers. Transformers are then the link between lines of different voltage levels. These are highly efficient (nearly 100%) and reliable. Transformers of standard connections have a transformation ratio that reflects the ratio between the input and output voltages. They can cause an effect on phase angle or the magnitude or both between the input and output voltages.

Phase shifting transformers, special transformers are used to create a phase shift between the primary side voltage and secondary side voltage. The purpose of this phase shift is to control the power flow over transmission lines. Both the magnitude and direction of power flow can be controlled by varying the phase of the transformer. PSTs offer a reliable, complete, and more economical solution for the control of power flow. The transmission network can connect between a long distant consumer from a producer. These connections can be between nations sometimes.

1.1 Application of PST in Indian power system

India is pushed to double the power generation by 2012, With the result the transmission & distribution is increasing many folds. We need an optimal use of our existing infrastructure to contain investment. It is therefore necessary to load the existing lines to optimal capacity rather than providing the additional corridor. Sustained economic growth continues to drive electricity demand in India. The Government of India’s focus on attaining ‘Power for all’ has accelerated capacity addition in the country. At the same time, the competitive intensity is increasing at both the market and supply sides.

Government has decided to develop large capacity power projects at national level. Already seven Ultra Mega Power Projects (UMPP) of 4000 MW each have been identified. These are planned at pit head and coastal sites. Three pit head sites are Sasan in M. P., Akaltara in Chhattisgarh and a site to be decided in Orissa. Four coastal sites are in Andhra Pradesh, Gujarat, Maharashtra and Karnataka.

Sometimes rather than usage of available infrastructure, it is necessary to provide additional corridors in order to maintain the system's reliability and availability. Heavy usage of the available improvised transmission grid may also cause errors. Overloading of subsystems in a power system sometimes may pose stability issues, which may lead to unwanted tripping, equipment failures which will result in long repair/ replacement cycle and heavy revenue losses. Under these conditions, to ensure economical and reliable operation of the grid, power through the lines should be controlled within their capabilities. There could be uneven loading of parallel transmission lines due to different impedances caused by the tower geometry, conductor sizing, number of sub-conductors and line length. The distribution of the power flow between two parallel lines is dictated by their impedances. The line with the smaller impedance carries more power and vice versa. In most situations, one of the two lines will be operating well below its nominal rating because otherwise the parallel line with lower impedance would be overloaded. In view of above, the power flows need to be controlled in order to achieve the optimum utilization of transmission lines capacity. A phase shifting transformer (PST) can be employed for power control in transmission lines.

The first manufactured Phase Shifting Transformer (PST) in India, has been commissioned in Telangana by Bharat Heavy Electricals Ltd to control and improve power flow between both the networks in either direction, from the Telangana state power generation corporation Ltd.

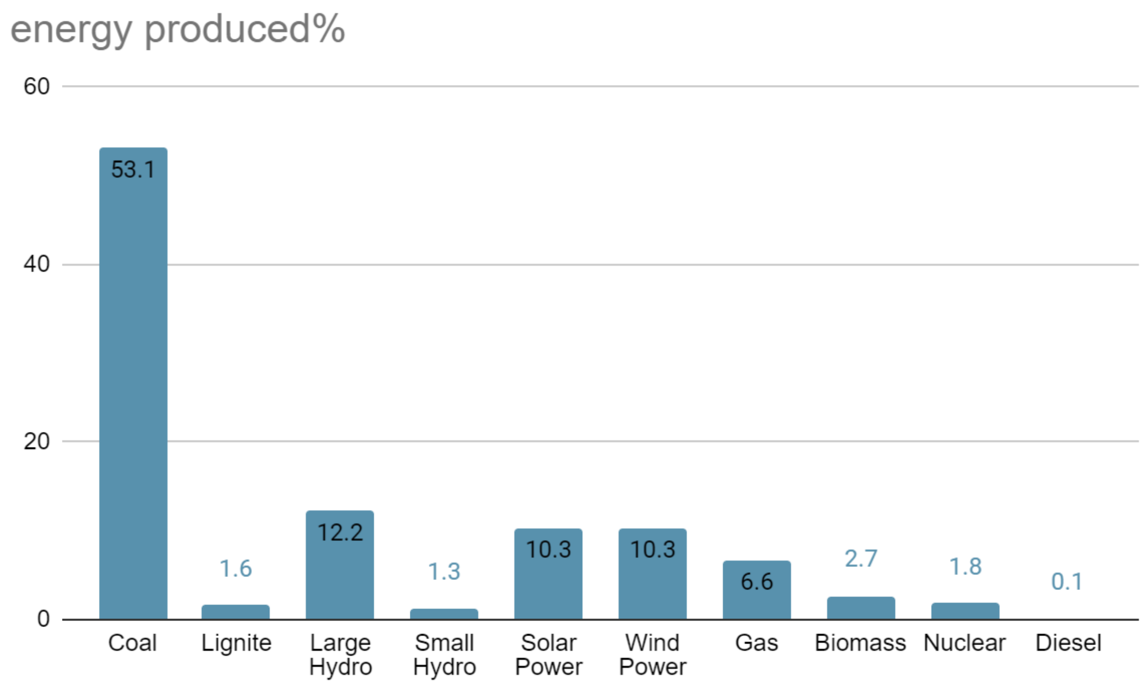


Figure 1.1

Figure 1.1 shows the sources of Electrical energy production in India and its percentage contribution.

1.2 Case study from Netherlands

The Netherlands has five interconnectors with its neighbouring countries Belgium and Germany, the southern region is much denser populated compared to the northern part. As a consequence, import of power causes a heavy loading of the southern interconnectors, especially on the line Maasbracht-Rommerskirchen/Siersdorf,compared to a low loading of the most northern interconnector Meeden-Diele. Additional transmission lines didn't offer instant relief, A better solution was to install a phase-shifting transformer in an appropriate location in the transmission grid. Locating the PST in Meeden would offer the possibility to increase the import in the northern part of the country, distributing the loading of the interconnectors more equally. Figure 1.2 shows the all five interconnectors and the location used to install PST.

Figure 1.2

1.3 Faults in PST

As with any other electrical machine, PSTs are subjected to stresses, power surges, over voltages, over temperatures and ageing. These conditions may eventually lead to faults which will require the shutdown of the transformer and therefore, major costs due to non-operation and need for repair. Hence, the importance of both protection and non-invasive diagnostic procedures that are able to detect the fault at an early stage and while the transformer is in operation. Fault diagnosis comprises the detection, identification and location of a fault in a machine. Sometimes the fault may be incipient, as such, instead of shutting down the transformer, it may be possible to keep it working at lower power level than the rated one, providing this way enough time to find a replacement or reroute the electrical power flow until a repair or a replacement has been set up. In case of a major fault, which may destroy or damage not only the transformer but also the connected apparatus, power should be cut off immediately, in order to prevent larger damage or even dangerous situations.

Chapter 2
PHASE SHIFTING TRANSFORMERS

PSTs, also known as Phase Angle Regulators (PAR), are characterized by having a secondary voltage with a controlled phase-shift in relation to the primary voltage. They are simply special transformers used to create a phase shift between the primary side voltage and secondary side voltage. The purpose of this phase shift is to control the power flow over transmission lines. Both the magnitude and direction of power flow can be controlled by varying the phase shift. The same amount of active power can be transported over the transmission line with a smaller value of delta ,i.e. the phase angle between source and receiving end.

2.1 Types of PST

PST's come in different forms depending on their requirement. PSTs are divided into two main categories in design, being single-core and two-core. This is a relevant aspect as it dictates how the phase shift is accomplished. The symmetry of the PSTs is also an important detail in their construction and operation since it dictates how the load and no-load condition will affect the phase shift of the PST and how the quadrature injected voltage adjusts only the phase angle (symmetrical) or, besides the angle variation, it also adjusts the voltage magnitude (asymmetrical).

2.1.1 Direct PST's

They are based on one 3-phase core. The phase shift is obtained by connecting the windings in an appropriate manner. This PST is also known as single core design because it is manufactured using one single core. It is used at lower voltages, for smaller phase shifts and smaller PST ratings. In addition, it has also fewer winding segments and it does not need a separate excitation transformer. The short-circuit impedance of a PST of single core design is very low at tap positions near 0-degree phase angle shift, hence the ratio between the external fault currents passing through the PST and its rated current may become very high, especially in systems with low fault current impedance.

2.1.1.1 Asymmetrical PST

The asymmetrical single-core PST is also known as half-tap PST due to having just half of a full regulating winding. When the PST is working under no-load conditions, the voltage magnitude on the load side is different from the one on the source side. Frequently, the difference increases as the phase angle shift α increases. In this type of transformer, the commutation between the advance and retard modes is done by a switch in each phase that connects the excitation windings to the series windings. Figure 2.1.a and 2.1.b shows Schematic representation and phasor diagram of a single-core asymmetrical type PST respectively.

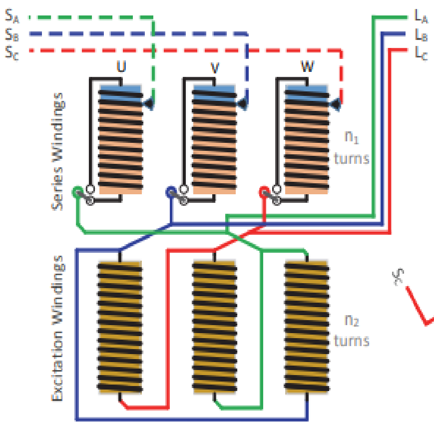


figure 2.1.a

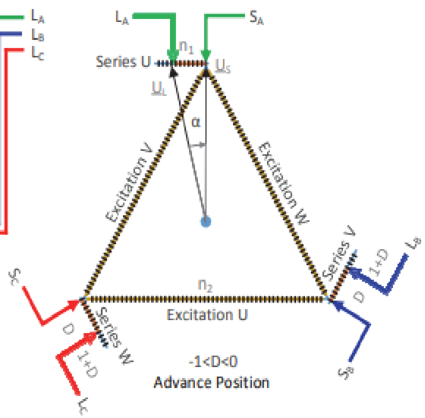


figure 2.1.b

2.1.1.2 Symmetrical PST

The single-core symmetrical type is also known as "Standard/Extended-delta single-core PST". In the symmetrical type, the voltage magnitude under no-load conditions is identical in source and load sides, with the phase angle shift having no effect on them. In this type of transformer, the commutation between advance and retard modes is done by two switches per phase. This differs from the single switch in the asymmetrical type due to the fact that the series windings on this type of PST are in fact split in two. Figure 2.2.a and 2.2.b shows Schematic representation and phasor diagram of a single-core symmetrical type PST respectively.

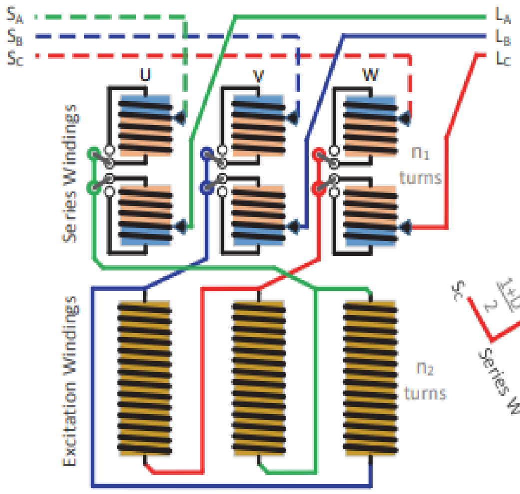


Figure 2.2.a

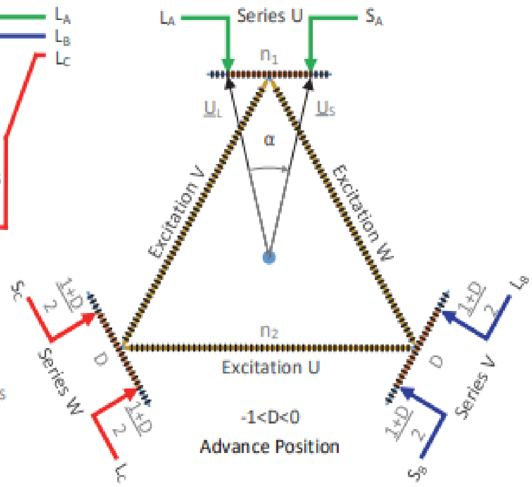


Figure 2.2.b

2.1.1.3 Delta-Hexagonal

The delta-hexagonal PST is with a symmetrical design that falls into the category of squashed-delta PSTs. It is a relatively new scheme whose existence is due to the new advancements in the OLTC technology. It is much more economical to build and install than previous designs mentioned above, thus it improves the economic feasibility of deployment of these heavy devices on the transmission grid. In this delta-hexagonal PST there is a double OLTC with two three-phase taps. Each tap moves its three terminals along the series windings so that a phase-shift is created between the source and load ends. When the taps pass each other, the transformer shifts the operation from retard to advance mode or vice-versa. Figure 2.3.a and 2.3.b shows Schematic representation and phasor diagram of a delta-hexagonal single-core PST respectively.

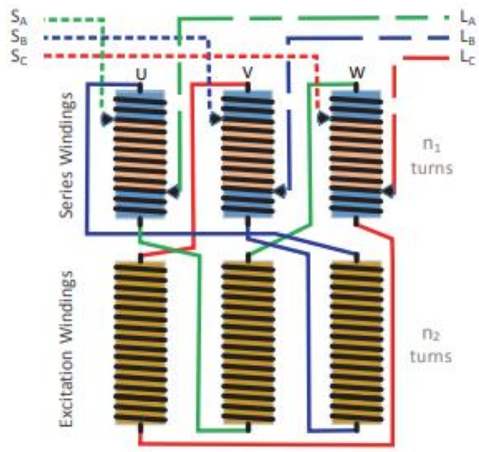


Figure 2.3.a

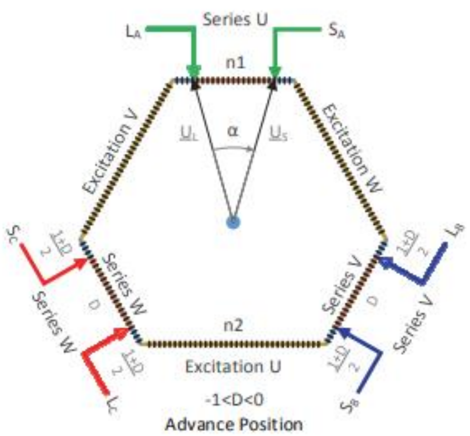


Figure 2.3.b

2.1.2 Indirect PST

This transformer is also called two core design, as the name suggests they are based on a construction with 2 separate transformers; one variable tap exciter to regulate the amplitude of the quadrature voltage and one series transformer to inject the quadrature voltage in the right phase. Each transformer is with its own core and associated coils, coupled by a "throat connection". If reactive power flow needs to be independently regulated from the active power flow, voltage and phase angle control can be combined within a single regulating transformer with two OLTCs operating independently. One OLTC regulates the quadrature-phase voltages and the other one regulates the in- phase voltages, which are combined at the output.

This main category also has different types of operational setup as direct PST. The series transformer primary winding is connected in series with the primary system, between the source and load terminals. In the case of the symmetrical type, this winding is split into two halves, and the primary winding of the excitation transformer is connected to the midpoint between these two half- windings. Thus, total symmetry between source and load side no-load voltages is achieved. In the asymmetrical type case, the primary winding of the excitation transformer is connected directly to the line or source of the series windings.

The regulating circuit consists of a secondary tapped winding in the excitation transformer and a delta connected secondary winding in the series transformer. The ratings of these two windings can be optimized independently of the voltage level of the primary. This provides more freedom for the selection of the OLTC, which sometimes is a limitation factor for a specific design. Figure 2.4 shows the Phasor diagram of the two-core symmetrical PST.

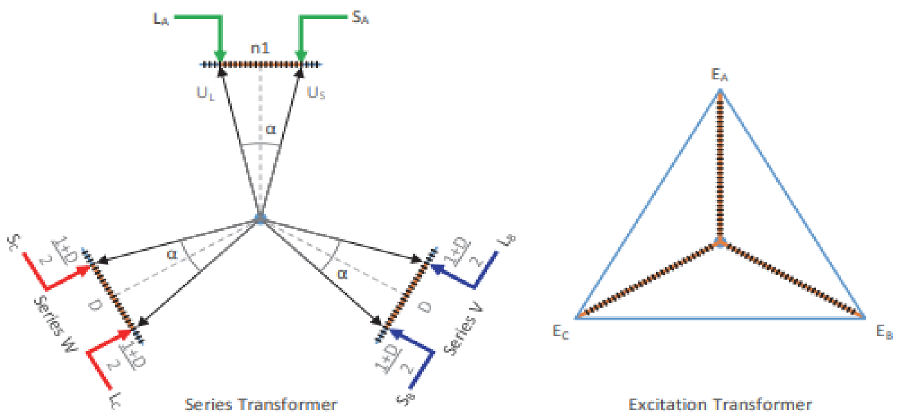


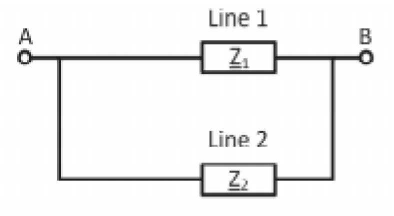
Figure 2.4

2.2 Application

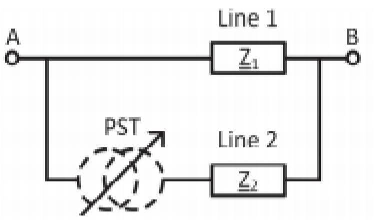
The basic equation that governs the active power flow on the line between two points, is given by

$$P \approx \frac{|U_s||U_L|}{|Z_L|}\sin\delta\ ,$$

where U_s and U_L represent the source-side and load-side voltages at points A and B respectively, is the angle between U_S and U_L (measured from load to source) and Z_L is the line impedance whose resistance is approximately zero. It is possible to observe that the active power is directly proportional to the voltages on the source and load sides and also to the sine of the angle between the two.



current will tend to flow through the line of least impedance causing unbalanced line loading. PSTs create a stepwise variable phase angle shift, advance or retard, between the source and load terminals, and, therefore, they present themselves as a more feasible solution.



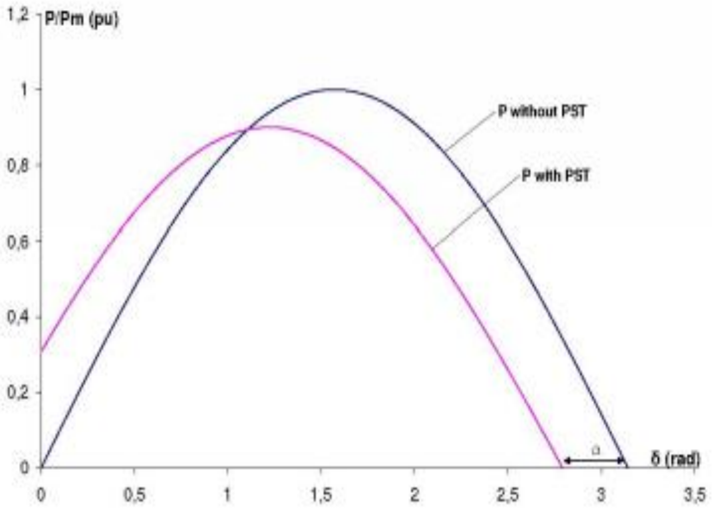
By inserting a PST on one of the branches, it is possible to control the power flow distribution. The PST is modelled as a reactance in series with a phase shift. The power flow through the line is increased by adding an angle α to the existing angle δ. The phase shift is controllable within certain limits. Equation of power becomes:

$$P = \frac{|U_s||U_r|}{X_L + X_{PST}}\ \sin(\delta + \alpha)$$

The equation stated above can also be interpreted in another way, the same amount of active power can be transported over the transmission line with a smaller value of δ.The graph of system with PST is shifted by an amount α in comparison with a system without pst, as can be seen in figure 2.5. The maximum power decreases by a factor $\frac{xl}{xl+xpst}$ when using a PST.

Figure 2.5

Depending upon whether the PST is installed in the branch with the higher or lower



impedance, an “advance” or a “retard” phase angle is needed. On “advance mode” the load terminal voltage U_L, at the output of the PST, is leading the source terminal voltage U_S . On “retard mode”, the voltage vector at the output of the PST lags the input voltage.

2.3 Simulation in power factory

Balancing of active power between two parallel lines using ideal and symmetric pst is simulated in Digsilent power factory.
Generator generates active power of 51MW into a 3 bus system. There one long line connecting bus 1 and 3 of length 10km with 0.05 resistance/km and 0.8 reactance/km, one line between bus 1 and 2 of length 5 km with 0.05 resistance/km and 0.5 reactance/km and another between bus 2 and 3 of length 5km with 0.05 resistance/km and 0.8 reactance/km. System works under nominal voltage of 30kv. When the power flows through 2 or more paths their impedance determines the load sharing. Higher the reactance lowers the power distributed.

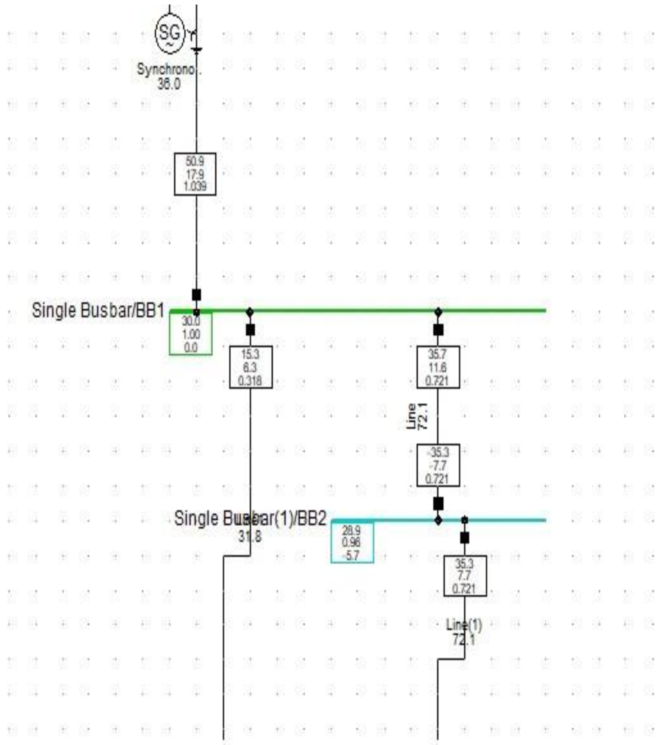


Figure 2.6

- Transmission Line 1 has total reactance of 8 ohms
- Line 2 and line 3 have 2.5 ohms and 2 ohms respectively.
- So the power generated splits as 15.3MW through Line 1 and 35.7MW through line 2 and 3.

We can split the power equally by connecting PST in the low reactance line.

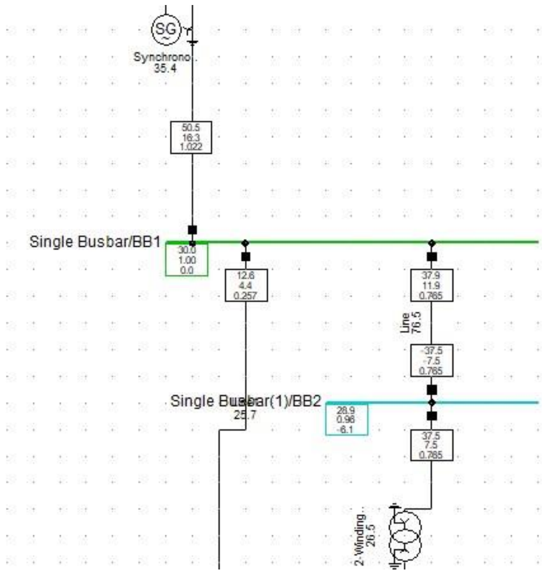


Figure 2.7

Ideal PST is installed at line 3 , ie. the lower reactance side.

- Modelled for phase shift from angle minimum of -20 to maximum of 20 degrees with neutral at 0.
- Each tap can shift an angle of 1 degree
- Here the phase shift α is 0 degree , ie the tap=0
- Since the transformer is ideal the reactance is further decreased and power again shifts to this side.
- Active power through line2 = 37.9 and line 1 = 12.6

Tap is changed to make a particular phase shift in the line so that parallel lines have almost the same active power. When tap is increased from 0 to 10 , α changes from 0^{o} to 10^{o}.the following figure shows tap at balanced load condition.

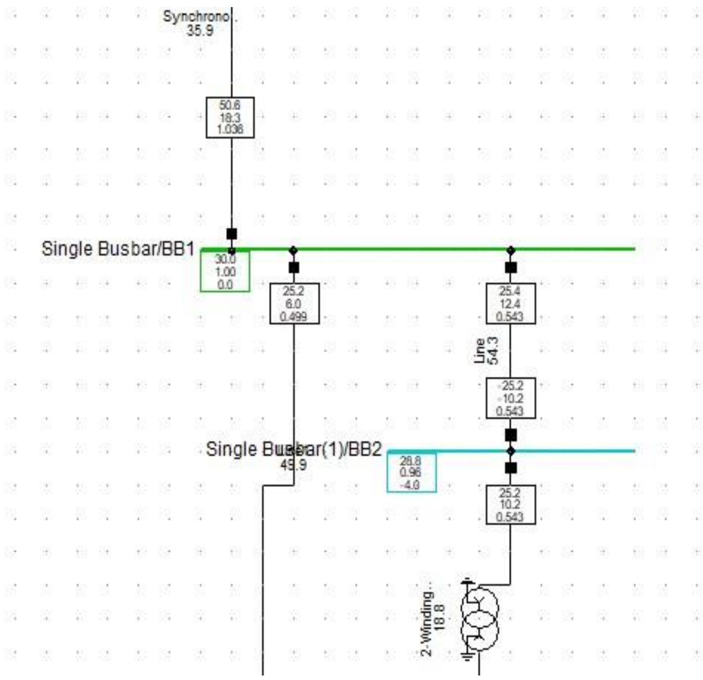


Figure 2.8

Here the line 1 has active power of 25.2MW and line 2 with 25.4 MW at tap 9. That is for α=9^{o} both lines have almost equal active power.

2.4 Conclusion

We have simulated and shown balancing and controlling of active power flow, likewise this can be done in big transmission grids.

Chapter 3

DIRECT APPROACH BASED LOAD FLOW ANALYSIS IN GRID WITH PST

The most traditional power flow methods such as Newton Raphson and Gauss-Seidel, used widely in transmission systems, due to the especial nature of the distribution network, characterized by a radial or weakly meshed topology and a high R/X ratio do not offer the best performance and robustness when applied to the distribution level. Several approaches have been proposed in order to deal with these particular features, such as the implicit Z-bus Gauss method and backward-forward sweep methods. A very efficient formulation called the direct approach (DA) was proposed by J H Teng. The DA method avoids the time-consuming tasks of LU factorization and forward and backward substitution of the Jacobian or admittance matrices, which are a common place in traditional formulations. The characteristics of the DA method make it ideal for real-time applications in the smart grid context.

The DA method is presented in this section, which is modified to include shunt admittances in the DA solver. Thus, those components capable of being represented by pi-equivalent models, such as medium-length lines and transformers with tap changers, can be easily included in the problem. Further the new phase shifting transformer model is presented together with minor modifications to be performed in the DA algorithm. simulation is also included in order to illustrate the implementation procedure and demonstrate the validity of the proposal.

3.1 Direct approach power flow

The equivalent bus current injection vector, I_g , is calculated from the power injection at each bus, i, given the estimation of the bus voltage vector V at iteration (n)as

$$i_g = \frac{Pi - j\,Qi}{conj(Vi)}$$

the branch current vector B can be calculated as ;

$$B = BIBC.\ I_g$$

where BIBC is the so-called bus-injection to branch-current matrix. The entry BIBC equals 1 if the current injection of node i contributes to the branch current B_b, and equals 0 otherwise.

$$\Delta V = BCBV.\ B$$

where BCBV is the branch-current to bus-voltage matrix. The entry $BCBV_{Ib}$ equals the series impedance of branch b if that branch is in the path from node i to the slack bus, and equals 0 otherwise.

From these two equations, we can find

$$\Delta V = [BCBV][BIBC]\ .\ I_g$$

Till now we were considering this as a radial grid. In order to modify with meshed elements teng proposed we have to make specific changes in our approach. Specific branches are selected to break the meshed grid into a radial network. Then, these new entries are included in the current injection vector to account for the currents at the selected branches. Entries with the value -1 appear now to account for the contribution of the receiving node of the branches used to break the network due to the inverted current reference. New rows are added to the BIBC matrix with a single non-null entry in order to identify the currents of the branches used to break the network. The BCBV matrix is built as in the base case, but a new row is added for each loop in the grid to account for KVL. Taking all this into account the modified final matrix equation can be obtained as

$$\begin{bmatrix} \mathbf{\Delta V} \\ 0 \end{bmatrix}^{(n+1)} = \mathbf{BCBV} \cdot \mathbf{BIBC} \cdot \begin{bmatrix} \boldsymbol{I} \\ \boldsymbol{B}_{\text{new}} \end{bmatrix}$$

3.2 Phase shifting transformer model

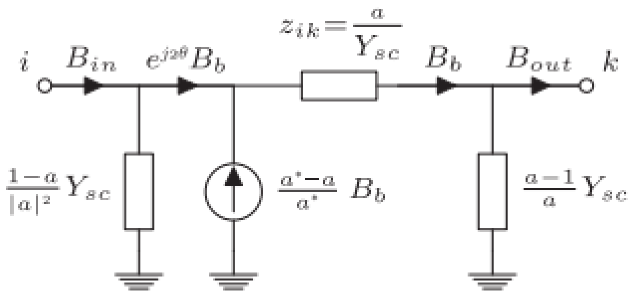


Figure 3.1

- When we are approaching a mesh grid system into a power grid with PST, there are many changes to be made in equations. While calculating its effect on the system we have to consider many situations.
- The series impedance z_{ik} shown in figure is used to represent the impedance between nodes i and k within the BCBV matrix. Y_{sc} stands for its short circuit admittance.
- $B_{out}=a^* B_{in}$
- With phase shifting transformer that a is now a complex number, i.e. $a=|a|e^{i}\theta$; |a| being the regulation between the primary and secondary voltage magnitudes and θ being the phase shift. If it is a simple tap changing transformer angle θ will be equal to 0. ie a won't have any angle only magnitude.
- The calculation of the current injection augmented vector I, Y_B has to include new shunt admittance terms at the sending bus, i, and receiving bus, k.

$$I= i_g + Y_B V$$

- Let us consider i , k and b to be the sending node, receiving node and branch index of a phase shifting transformer. In the same way, let b be the index of a branch located upstream from that transformer. The effect of all the augmented current injections of the nodes downstream from i on the branch current, B_b, can be evaluated as $e^{j2}\theta\ B_b$. This fact can be easily considered by modifying the entries $BIBC_{bi}$ of the matrix. If node i is now downstream from the receiving node of branch b, the following term,

$$BIBC_{bi} = e^{2j\sum_t \theta t}$$

applies instead of 1, with t being the different phase shifting transformers between the receiving node of branch b and node i, and θ_t being their corresponding phase angle shifts.

- If it is a weakly meshed system, we have to consider the double-sided contribution of the current of a branch.

$$BIBC_{bi} = e^{2j\sum_{ts} \theta ts} - e^{2j\sum_{tr} \theta tr}$$

ts stands for the different phase shifting transformers found in the path between the receiving node of branch b and the receiving node of branch c that includes the sending node of branch c. In the same way, tr stands for the different phase shifting transformers found in the path between the receiving node of branch b and the receiving node of branch c that does not include the sending node of branch c. Finally, ts and tr account for their corresponding phase angle shifts.

- If there are no phase shifting transformers exist along the alternative path connecting the same pair of nodes, which obviously leads to -1 in the second addend of above equation.

3.3 Impedance correction

The manufacturers provide 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 piecewise linear curve. 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. Impedance value of PST at each tap position is required to create better modelling of the system. The magnitude of the transformer's impedance is the same for both positive and negative sequences, having an opposite phase angle. Various impedance correction data-sets are used, which bring different results subject to the transformer's phase angle. So, we have to consider different power flow solutions that take the phase angle changes and the impedance correction tables into account. 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 the impedance correction table is not modelled in power flow simulations.

The transformer's impedance correction factor operates as a function of the phase angle and changes the transformer impedance. By adjusting the correction factor, one can see the change in the transformer's impedance subject to an angle.

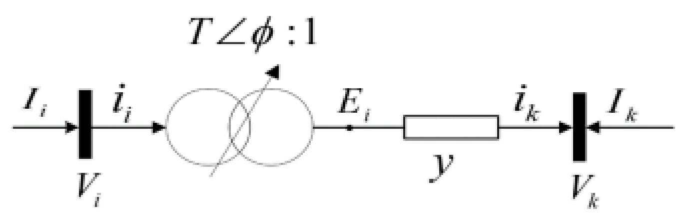


Figure 3.2

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

$$P=\frac{|Vi||Vk|}{Zline}$$

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.
The voltage and current relations for an ideal single-phase two-winding transformer between i and k bus can be expressed as follow

$$\frac{V}{E}=T\angle\Phi=T\ e^{j}\theta=T\ (\cos\Phi+j\sin\Phi)=\alpha+j\beta$$

Here, V_i is the bus voltage at bus i; E_i denotes the transmission line voltage; $\phi$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:

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

The transfer admittance from one bus to another is not equal to each other which makes the admittance matrix not symmetrical. The manufactures provide the correction factors corresponding to different phase angles, which implies that the transformer's impedance correction factor works as a function of the phase angle and it changes the transformer impedance. So, the transformer's impedance changes can be modelled by modifying using the impedance correction factor.

It is calculated using a piecewise-linear linear impedance curve. 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

$$Z_{Transformer} = R + j\,X$$

$$Z_{TK} = K\,Z_{Transformer}$$

$Z_{Transformer}$ is the transformer impedance without correction factor,
K_T is the correction factor,
Z_{TK} is the transformer's corrected impedance.

The correction factor for a three-phase three-winding transformer can be obtained using

$$K_T = 0.95\,\left(\frac{Cmax}{1+0.6\,Xt}\right)$$

$$Xt = X\,\left(\frac{Sr}{V\,r}\right)$$

Where Cmax is voltage factor based on the low voltage side of the transformer; X_t is the per unit relative reactance of the transformer; V_r is the rated voltage of the transformer, S_r is the rated power of transformer; X is the reactance from Z, usually the large transformers have small resistance compared with reactance and hence, the resistance can be neglected.

3.4 Implementing impedance correction of PST into direct approach solution

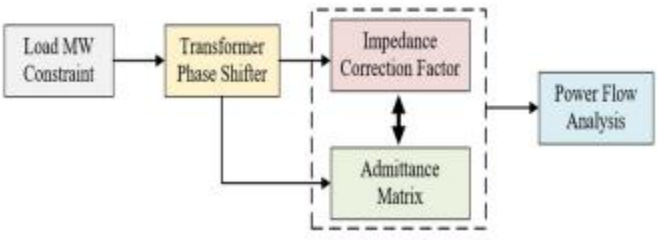


Figure 3.3

Since we have noticed that impedance of a PST varies with the phase shift, we have to take that into account while calculating the BCBV matrix in state estimation. The BCBV matrix consists of impedance values of the line between nodes or it can be the impedance of any element connected between those nodes or it can also be zeroes. If it is a PST connected between two nodes that particular element in the BCBV matrix changes to K times the previous value. Where K is the impedance correction factor of the PST. we have to consider multiple K values if more than one PST is connected and K also varies according to phase shift applied. The flow chart in figure 3.3 shows this impedance correction in admittance matrix further that affects the BCBV matrix before calculating power flow analysis of our power grid.

3.5 Simulations and results

A simplified version of the customer-owned grid of a steelwork in the north of Spain, is considered in this case study. A 9 bus simple power grid with four transformers, four transmission lines and five loads are simulated in Digsilent power factory. This simulation is done to verify the validity of this direct approach with and without the impedance correction factor in this power grid with a phase shifting transformer. So, a PST is also implemented between two nodes with specific characteristics. The grid is shown in a simulation in figure 3.4 and the parameters and configuration of the phase shifting transformers are also listed in table below.

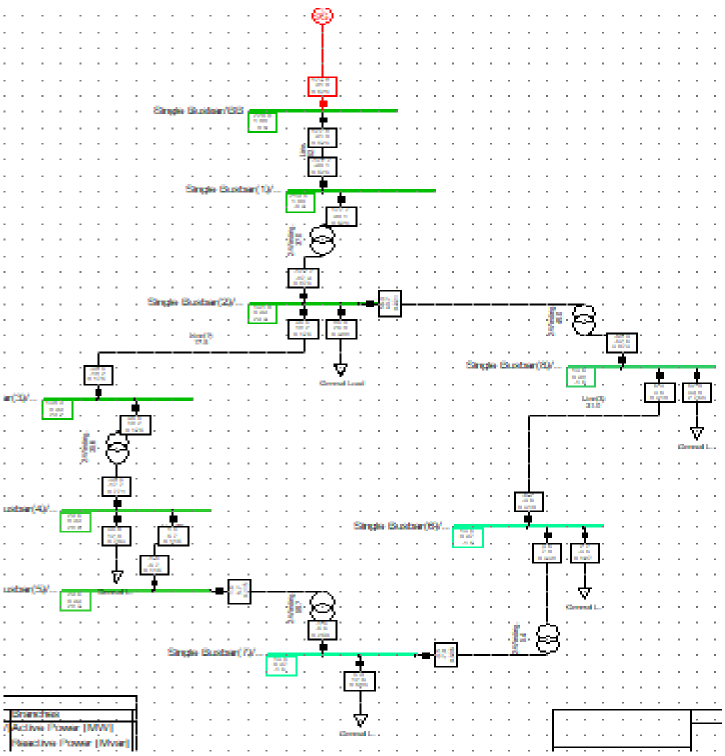


Figure 3.4

PST parameters are shown in below table

Connected between	S_n(MVA)	Z_{ik} (pu)	a	Angle
Node 7 & 9	10	5.280 e-3 + j 4.865e-2	1	5^0

The transformer parameters used for simulation are shown below table

transformer	Connected between	S_n (MVA)	θ
1	2 and 3	540	-30
2	4 and 5	112.5	0
3	6 and 7	10	30
4	3 and 8	150	30

The transmission line parameters used for simulation are shown below table

line	Connected between	Length (km)	Z
1	1 and 2	4.7	0.025+j0.240
2	3 and 4	1.5	0.161+j0.151
3	5 and 6	0.3	0.568+j0.133
4	8 and 9	1.8	0.161+j0.112

The load injection parameters used for simulation are shown below table

Power Injections (bus no)	P (MW)	Q(MVar)
3	84	26
5	34	12
7	4.9	12.6
8	52	39
9	2.7	-3.4

The simulated results of state variables are at PST angle 5^0 in power factory.

Bus no	|V| (pu)	θ
1	1	0
2	0.9973983	-0.2273447
3	0.9923066	29.19558
4	0.9914238	29.14408
5	0.9911057	28.12001
6	0.9861369	27.94632
7	0.9896656	-2.611333
8	0.9797861	-1.152284
9	0.9946102	2.077117

3.5.1 Mathematical Calculation without impedance correction

The solution of this power flow problem, in the form of the bus voltages taken as state variables of the system. They can be mathematically calculated using the direct approach by calculating both BCBV and BIBC matrices. We have to consider impedances of line, transformers and PST same as used for simulation for designing BCBV matrix. Then both the phase shifts in transformers and PST for calculating the BIBC matrix. Both these calculations are mentioned in the above section.

The BIBC matrix is :

1	$e^{j2\theta(23)}$	$e^{j2\theta(23)}$	$e^{j2[\theta(23)+\theta(45)]}$	$e^{j2[\theta(23)+\theta(45)]}$	$e^{j2[\theta(23)+\theta(45)+\theta(67)]}$	$e^{j2[\theta(23)+\theta(38)]}$	$e^{j2[\theta(23)+\theta(38)]}$	$e^{j2[\theta(23)+\theta(45)+\theta(67)+\theta(79)]} - e^{j2[\theta(23)+\theta(38)]}$
0	1	1	$e^{j2\theta(45)}$	$e^{j2\theta(45)}$	$e^{j2[\theta(45)+\theta(67)]}$	$e^{j2\theta(38)}$	$e^{j2\theta(38)}$	$e^{j2[\theta(45)+\theta(67)+\theta(79)]} - e^{j2[\theta(38)]}$
0	0	1	$e^{j2\theta(45)}$	$e^{j2\theta(45)}$	$e^{j2[\theta(45)+\theta(67)]}$	0	0	$e^{j2[\theta(45)+\theta(67)+\theta(79)]}$
0	0	0	1	1	$e^{j2\theta(67)}$	0	0	$e^{j2[\theta(67)+\theta(79)]}$
0	0	0	0	1	$e^{j2\theta(67)}$	0	0	$e^{j2[\theta(67)+\theta(79)]}$
0	0	0	0	0	1	0	0	$e^{j2\theta(79)}$
0	0	0	0	0	0	1	1	-1
0	0	0	0	0	0	0	1	-1
0	0	0	0	0	0	0	0	-1

The BCBV matrix is:

Z_{12}	0	0	0	0	0	0	0	0
Z_{12}	Z_{23}	0	0	0	0	0	0	0
Z_{12}	Z_{23}	Z_{34}	0	0	0	0	0	0
Z_{12}	Z_{23}	Z_{34}	Z_{45}	0	0	0	0	0
Z_{12}	Z_{23}	Z_{34}	Z_{45}	Z_{56}	0	0	0	0
Z_{12}	Z_{23}	Z_{34}	Z_{45}	Z_{56}	Z_{67}	0	0	0
Z_{12}	Z_{23}	0	0	0	0	Z_{38}	0	0
Z_{12}	Z_{23}	0	0	0	0	Z_{38}	Z_{89}	0
0	0	Z_{34}	Z_{45}	Z_{56}	Z_{67}	$-Z_{38}$	$-Z_{89}$	Z_{79}

Using both of these matrices the mathematically calculated state estimation by using direct approach without impedance correction is:

Bus no	|V| (pu)	θ
1	1	0
2	0.9972	-0.223
3	0.9578	27.275
4	0.9569	27.273
5	0.9428	25.766
6	0.9423	25.955
7	0.9485	-2.824
8	0.9574	-4.714
9	0.9478	-5.775

3.5.2 Mathematical Calculation with impedance correction

The solution of this power flow problem, in the form of the bus voltages taken as state variables of the system. They can be mathematically calculated using the direct approach by calculating both BCBV and BIBC matrices. We have to apply changes on the BCBV matrix from the impedance correction table. The impedance correction table used in this case is shown below:

Φ	$K_T(\Phi)$	Φ	$K_T(\Phi)$
0	0.5		
7.5	0.52	-7.5	0.52
12.5	0.54	-12.5	0.54
25	0.6	-25	0.6
35	0.75	-35	0.75

All these values have been plotted and we get the correction factor of angle 5^0 from the figure 3.5 . The value of K_T at angle 5^0 is 0.516.

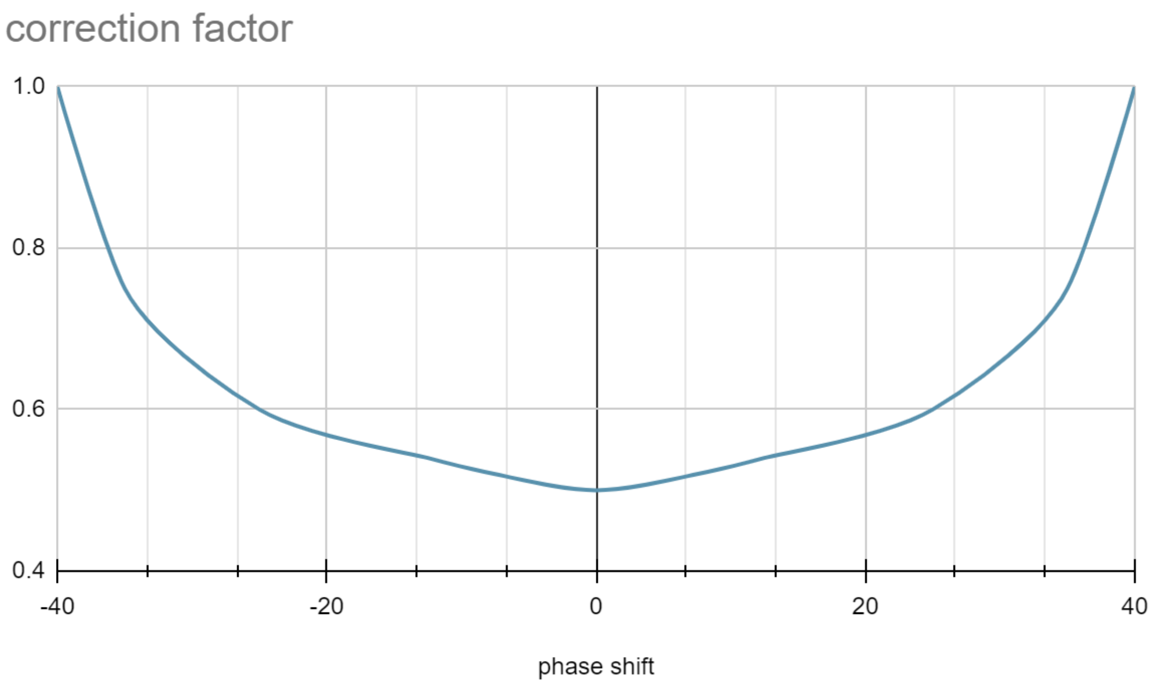


Figure 3.5

In this case only one PST is included in the grid. Its impedance only affects the $BCBV_{99}$.

So the corrected BCBV is :

Z_{12}	0	0	0	0	0	0	0	0
Z_{12}	Z_{23}	0	0	0	0	0	0	0
Z_{12}	Z_{23}	Z_{34}	0	0	0	0	0	0

Z_{12}	Z_{23}	Z_{34}	Z_{45}	0	0	0	0	0
Z_{12}	Z_{23}	Z_{34}	Z_{45}	Z_{56}	0	0	0	0
Z_{12}	Z_{23}	Z_{34}	Z_{45}	Z_{56}	Z_{67}	0	0	0
Z_{12}	Z_{23}	0	0	0	0	Z_{38}	0	0
Z_{12}	Z_{23}	0	0	0	0	Z_{38}	Z_{89}	0
0	0	Z_{34}	Z_{45}	Z_{56}	Z_{67}	$-Z_{38}$	$-Z_{89}$	$0.516Z_{79}$

Using both of BIBC and corrected BCBV matrices the mathematically calculated state estimation by using direct approach with impedance correction is:

Bus no	|V| (pu)	θ
1	1	0
2	0.9973	-0.226
3	0.9723	28.097
4	0.9695	27.945
5	0.9623	26.335
6	0.9573	27.463
7	0.9592	-2.796
8	0.9694	-3.836
9	0.9598	-3.12

3.5.3 Comparison between three cases

The graph in figure 3.6 shows the value of θ,i.e. the voltage angle for all 9 buses in all three cases with phase shift angle of 5^0 in the grid. We can find that calculated values of θ without considering impedance correction shows big variation from the simulated ones. Calculated value with impedance correction is more lenient to the simulated results. Which shows the effect of impedance correction factor on direct approach to calculate state variables in power grid to decrease error in calculation.

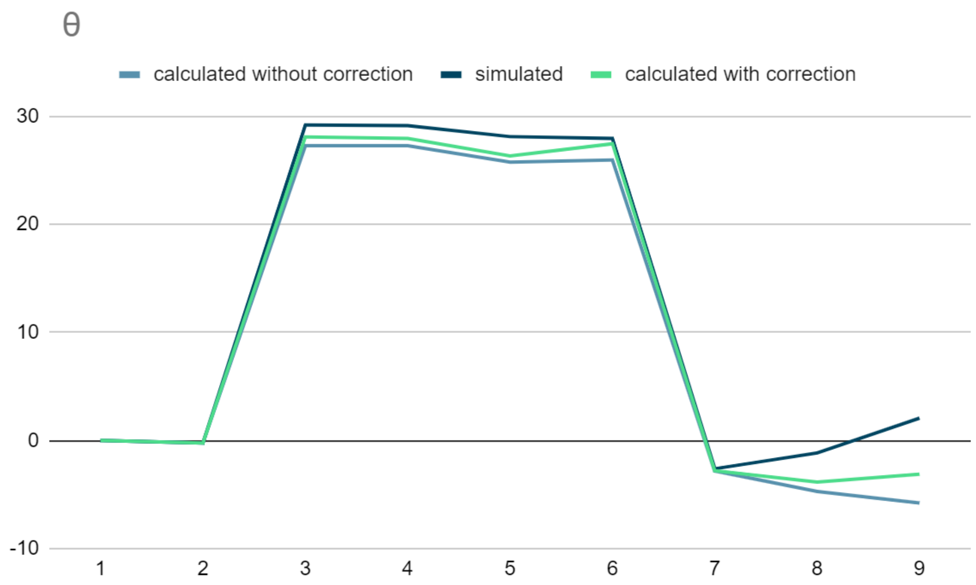


Figure 3.6

The graph below in figure 3.7 shows the value of $|V|$,i.e. the voltage magnitude in pu for all 9 buses in all three cases with phase shift angle of 5^0 in the grid. We can find that calculated values of $|V|$ without considering impedance correction shows big variation from the simulated ones. Calculated value with impedance correction is more lenient to the simulated results. Which shows the effect of impedance correction factor on direct approach to calculate state variables in power grid to decrease error in calculation.

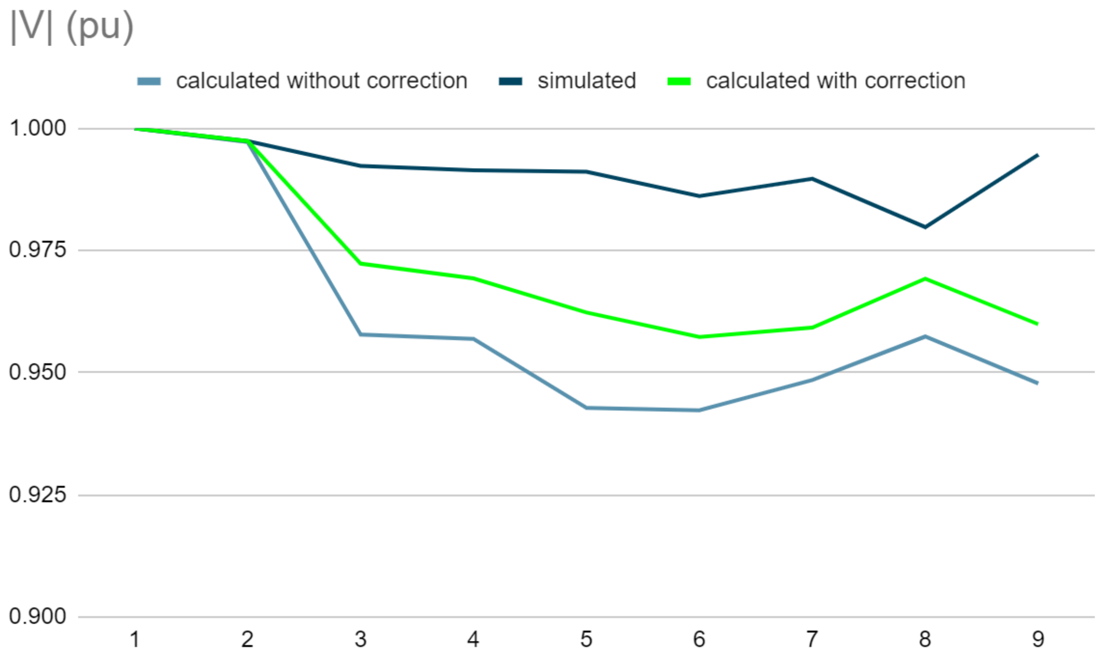


Figure 3.7

Graph below in figure 3.8 shows the standard deviation of voltage |V| in pu of each bus by varying phase angle of the implemented PST. We know that when the phase of the PST is shifted it changes the bus voltage. Every change in angle causes a different slope of change of voltage in each bus. Here we compare the calculated values of voltage in each bus in both the cases for a phase shift from angle -10^0 to 10^0. It can be seen that the standard deviation of voltages in bus 7 and bus 9 is bigger compared to other buses. It is because PST is connected between them so it shows bigger fluctuations. It is visible that the standard deviation of voltage of all the buses shows a decrease in magnitude in the case of calculated with impedance correction factor than without. This shows error in calculation is lesser when we consider impedance correction factor to make BCBV matrix.

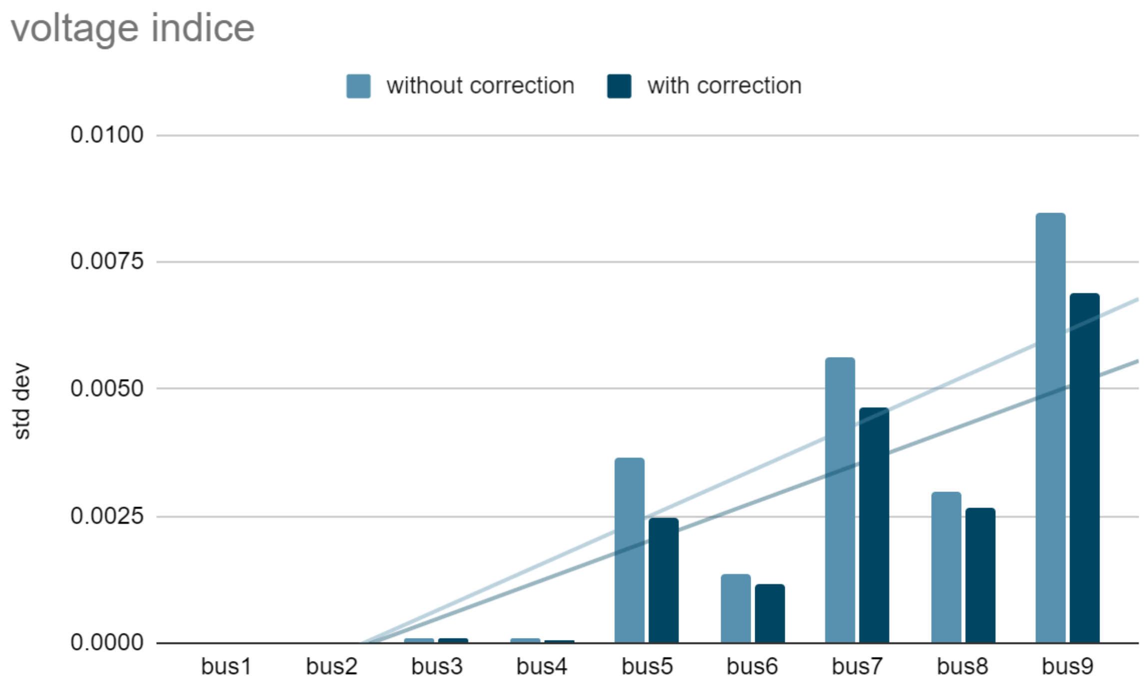


Figure 3.8

The graph below in figure 3.9 shows the loading variation of the line connected in series with the PST between bus 8 and bus 9 simulated with and without considering impedance correction table.

It can be seen that the change of angle of PST from 0^0 to both directions makes the line more loaded in both the cases. The loading of the line is greater without considering the impedance correction of PST for each angle. The line gets overloaded to 107% at 4^0 and -4^0 without impedance correction, while it is at 6^0 and -5^0 if we are considering impedance correction. So we can conclude that the overloading of each line gets shifted wider in the case of impedance correction of PST. So the number of overloaded lines in any power grid will be lesser if we correct the impedance of PST. In this case the number of overloaded lines without using impedance correction at PST angle above 8^0 is two and with correction it is 1 . The second line gets overloaded only after the angle is increased above 14^0 if impedance is corrected.

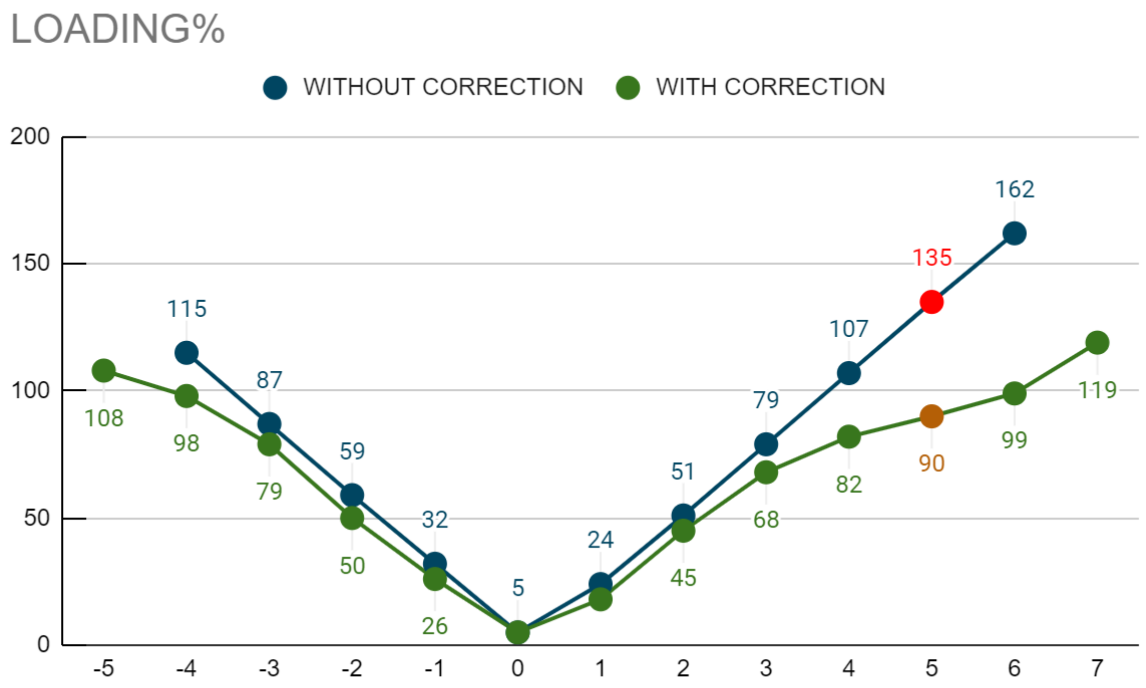


Figure 3.9

PSTs are not used for the purpose of maintaining the voltage issues as they mainly change the active power of the line rather than the reactive power. However, the simulations verify that the impedance correction table also could play a positive role in improvement of the voltage profile. The graphs below in figure 3.10 and figure 3.11 illustrate the low voltage-bus enhancement when the impedance correction table is set into the PST. Since PST is connected to bus7 and bus9, they show maximum fluctuations from mean with change of phase angle. It can be seen that after implementing impedance correction voltage is closer to 1 for each phase shift in both the buses. Maximum difference is at 0^0 in both the buses because lowest value of impedance correction factor K_T is at 0^0, so it shows best voltage profile.

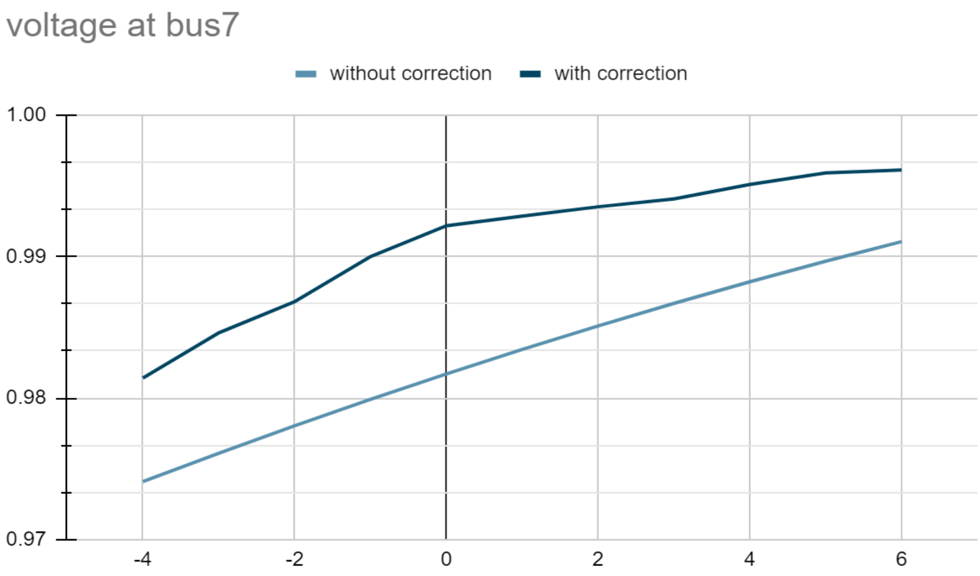


Figure 3.10

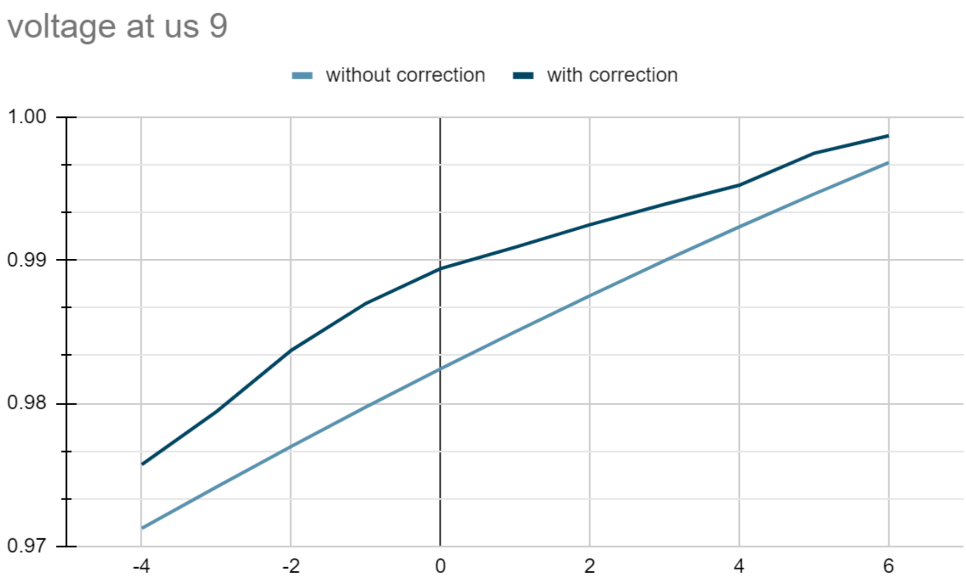


Figure 3.11

Chapter 4

OPTIMISATION OF LOCATION OF TRANSFORMERS

Unscheduled power flows are solved using advanced optimization technique. The best available solution is to install power flow controllers in order to enhance the power transmission capability of the already existing lines. The phase-shifting transformer is the first choice, as it is the cheapest power controller and performs satisfactorily under steady-state conditions. Positioning of PSTs is very important as much as their design is considered. Optimization is also an important issue for the control of PST. A lot of optimization algorithms are present based on the power flow control capability, the coordination, the selection of the best location of PSTs aspects. Well-known methods are Differential Evolution (DE), Genetic Algorithm (GA), Mean Variance Mapping Optimization (MVMO) and Particle Swarm Optimization (PSO). Each optimization algorithm contains its own advantages and disadvantages. Some are shown in figure 4.1

Figure 4.1

4.1 Genetic algorithm

Genetic algorithm simulates the evolution process which also belongs to the category of random search algorithms. It was introduced in 1975. It is based on the Darwinian principle of 'survival of the fittest' and implies that fitter individuals have a greater chance of passing their good characteristics to the next generation. starts with the generation of an initial random population with N_p set of properties, they are the parents. After fitness evaluation of each set of properties, the population is transformed into a new population. With help of different selection methods Roulette Wheel Selection, Tournament Selection or etc two parents are chosen to create a new child. Thereby, 'good' members of the previous generation have a higher probability to be chosen to become parents. The best individuals will pass over unmodified in the next generation. With help of the crossover fraction CF crossover is done, if a random number in the range [0, 1] is less than CF. For the mutation of the chromosomes, a random number in the range [0, 1] is also generated. If the random number is less than the mutation rate MR, mutation is also performed. Replace the parents with the generated children in order to form the new population. This is evaluated by using the objective function. This transformation process continues until a termination criterion is fulfilled.

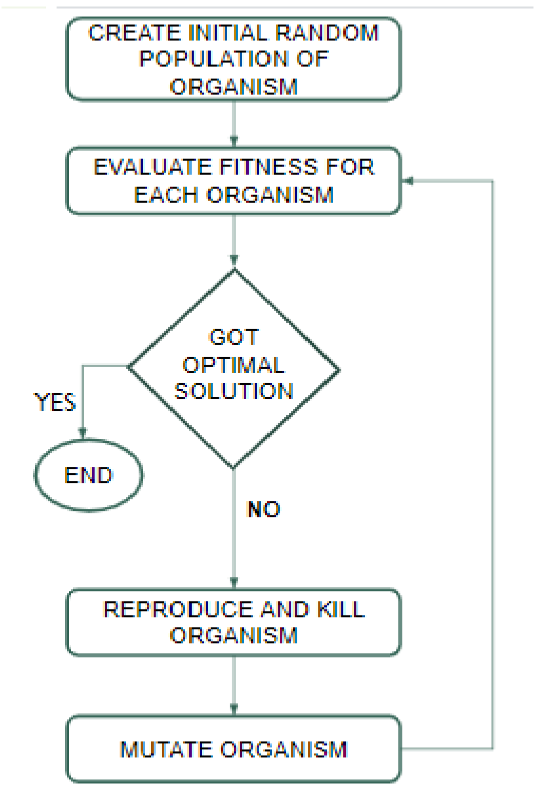


Figure 4.2

4.2 Formulation

Consider an electrical power system consisting of n_N number of nodes and n_B branches, n_L electrical lines and n_T two-winding transformers. The aim of our work is to determine the optimal location and size of the PST. Aiming at minimizing the branch loadings all over the power system, optimization model based on genetic algorithms is made. The control variables are x1 and x2. where x1 is the index of the electrical line that the PST will be inserted on and x2 is the actual operating tap position of the PST. It should be mentioned that both variables x1 and x2 are integer values. The objective function F(x) is defined as the sum of the squares of all branch loadings, γ_{br}, which is multiplied by two penalty functions $P_V(x)$ and $P_L(x)$.so the objective function is

$$\textbf{Min } F(x)=\left[\sum^{nb} \gamma_{br}^{2}(x)\right] . P_V(x)\, P_L(x)$$

- Constrained to:

  $1 \le x_1 \le n_L^{max}$

  $n_t^{min} \le x_2 \le n_t^{max}$

- The branch loading $\gamma_{br}(x)$, for every branch br, is calculated as the ratio between the apparent power flow at the sending end of the branch, $S_{br}(x)$, and the line power rating, S_{br}^{adm} , that is

$$\gamma_{br}(x)=\frac{apparent\ power}{rated\ power}$$

- The penalty function $P_V(x)$ penalizes the x candidate solution if there is at least one nodal voltage that exceeds the admissible upper, or lower the admissible voltage limits.

$$P_V(x)=\begin{cases} 1 & \text{if } V_k^{min} \le V_k \le V_k^{max} \ , \ \forall\ k=\overline{1,n_N} \\ 10 & \text{otherwise} \end{cases}$$

- The penalty function $P_L(x)$ was introduced to penalize the cases for which there is at least one branch loading, $\gamma_{br}(x)$, greater than the admissible threshold power.

$$P_L(x)=\begin{cases}1 \text{ if } \gamma_{br} \le \gamma_{br}^{adm} \ \forall\ br=\overline{1,n_B}\\ \prod_{br\in\gamma} 2^{\gamma_{br}} \text{ where } \gamma=\left\{br \middle| \gamma_{br} \ge \gamma_{br}^{adm}\right\} \text{ otherwise}\end{cases}$$

We propose introducing one PST as a solution to control the power flow on a transmission line that is subjected to overloading under heavy load conditions. The evaluation of the objective function F_{obj} is the most complex and time-consuming step of the genetic algorithm because of the need to perform the load flow calculation for every particular individual x = [x1 x2].

4.3 Simulations and results

The application of the optimization algorithm and its different variants is done with the IEEE 57-Bus System. It contains 57 buses, 7 generators and 42 loads. It is assumed that the maximum allowed line rating for each line $S_{l\ max}$ is 200 MVA. The lines connection and impedances, generator variables, load power and the bus datas used for simulation is given in the table below.

Line data:

Line no	From bus	To bus	R(pu)	X(pu)	Line no	From bus	To bus	R(pu)	X(pu)
1	1	2	0.0083	0.028	21	5	6	0.0302	0.0641
2	2	3	0.0298	0.085	22	7	8	0.0139	0.0712
3	3	4	0.0112	0.0366	23	10	12	0.0277	0.1262
4	4	5	0.0625	0.132	24	11	13	0.0223	0.0732
5	4	6	0.043	0.148	25	12	13	0.0178	0.058
6	6	7	0.02	0.102	26	12	16	0.018	0.0813
7	6	8	0.0339	0.173	27	12	17	0.0397	0.179
8	8	9	0.0099	0.0505	28	14	13	0.0171	0.0547
9	9	10	0.0369	0.1679	29	18	19	0.461	0.683

10	9	11	0.0258	0.0848	30	19	20	0.283	0.434
11	9	12	0.0648	0.295	31	21	20	0	0.7767
12	9	13	0.0481	0.138	32	21	22	0.0736	0.117
13	13	14	0.0132	0.0434	33	22	23	0.0099	0.0152
14	13	15	0.0269	0.0869	34	23	24	0.166	0.256
15	1	15	0.0178	0.091	35	24	25	0	1.182
16	1	16	0.0454	0.206	36	24	25	0	1.23
17	1	17	0.0238	0.108	37	24	26	0	0.0473
18	3	15	0.0162	0.053	38	26	27	0.165	254
19	4	18	0	0.555	39	27	28	0.0618	0.0954
20	4	18	0	0.43	40	28	29	0.044	0.0587

Line no	From bus	To bus	R(pu)	X(pu)	Line no	From bus	To bus	R(pu)	X(pu)
41	7	29	0	0.0648	61	47	48	0.0182	0.0233
42	25	30	0.135	0.202	62	48	49	0.0834	0.129
43	30	31	0.326	0.497	63	49	50	0.0801	0.128
44	31	32	0.507	0.755	64	50	51	0.1386	0.22
45	32	33	0.0392	0.036	65	10	51	0	0.0712
46	34	32	0	0.953	66	13	49	0	0.191
47	34	35	0.052	0.078	67	29	52	0.1442	0.117
48	35	36	0.043	0.0537	68	52	53	0.0762	0.0984
49	36	37	0.029	0.0366	69	53	54	0.1117	0.232
50	37	38	0.0651	0.1009	70	54	55	0.1732	0.2265
51	37	39	0.0239	0.0379	71	11	43	0	0.153
52	36	40	0.03	0.0466	72	44	45	0.0624	0.1242
53	22	38	0.0192	0.0295	73	40	56	0	1.
54	11	41	0	0.749	74	56	41	0.553	349

55	41	42	0.207	0.352	75	56	42	0.2125	0.354
56	41	43	0	0.412	76	39	57	0	1355
57	38	44	0.0289	0.0585	77	57	56	0.174	0.26
58	15	45	0	0.1042	78	38	48	0.115	0.177
59	14	46	0	735	79	38	49	0.0312	0.0482
60	46	47	0.023	0.068	80	9	55	0	0.1205

Bus data:

Bus Number	Bus Voltage		Generation		Load	
	Magnitude (p.u)	Phase Angle (degrees)	Real Power (p.u)	Reactive Power (p.u)	Real Power (p.u)	Reactive Power (p.u)
1	1.04	0	4.78	1.289	0.55	0.17
2	1.01	0	0	-0.008	0.03	0.88
3	0.985	0	0.4	-0.01	0.41	0.21
4	1	0	0	0	0	0
5	1	0	0	0	0.13	0.04
6	0.98	0	0	0.008	0.75	0.02
7	1	0	0	0	0	0
8	1.005	0	4.5	0.621	1.5	0.22
9	0.98	0	0	0.022	1.21	0.26
10	1	0	0	0	0.05	0.02
11	1	0	0	0	0	0
12	1.015	0	3.1	1.285	3.77	0.24
13	1	0	0	0	0.18	0.023
14	1	0	0	0	0.105	0.053
15	1	0	0	0	0.22	0.05
16	1	0	0	0	0.43	0.03
17	1	0	0	0	0.42	0.08
18	1	0	0	0	0.272	0.098
19	1	0	0	0	0.033	0.06
20	1	0	0	0	0.023	0.01
21	1	0	0	0	0	0
22	1	0	0	0	0	0
23	1	0	0	0	0.063	0.021
24	1	0	0	0	0	0
25	1	0	0	0	0.063	0.032
26	1	0	0	0	0	0
27	1	0	0	0	0.093	0.005
28	1	0	0	0	0.046	0.023
29	1	0	0	0	0.17	0.026

30	1	0	0	0	0.036	0.018
31	1	0	0	0	0.058	0.029
32	1	0	0	0	0.016	0.008
33	1	0	0	0	0.038	0.019
34	1	0	0	0	0	0
35	1	0	0	0	0.06	0.03
36	1	0	0	0	0	0
37	1	0	0	0	0	0
38	1	0	0	0	0.14	0.07
39	1	0	0	0	0	0
40	1	0	0	0	0	0
41	1	0	0	0	0.063	0.03
42	1	0	0	0	0.071	0.044
43	1	0	0	0	0.02	0.01
44	1	0	0	0	0.12	0.018
45	1	0	0	0	0	0
46	1	0	0	0	0	0
47	1	0	0	0	0.297	0.116
48	1	0	0	0	0	0
49	1	0	0	0	0.18	0.085
50	1	0	0	0	0.21	0.105
51	1	0	0	0	0.18	0.053
52	1	0	0	0	0.049	0.022
53	1	0	0	0	0.2	0.1
54	1	0	0	0	0.041	0.014
55	1	0	0	0	0.068	0.034
56	1	0	0	0	0.076	0.022
57	1	0	0	0	0.067	0.02

Transformer data:

From Bus	To Bus	Tap Setting Value (p.u)
4	18	0.97
4	18	0.978
21	20	1.043
24	26	1.043
7	29	0.967
34	32	0.975
11	41	0.955
15	45	0.955
14	46	0.9
10	51	0.93
13	49	0.895
11	43	0.958
40	56	0.958
39	57	0.98
9	55	0.94

24	25	1
24	25	1

The simulation is done in the Digsilent power factory, the simulated power grid and the model grid are shown below in figure 4.3 and figure 4.4 respectively.

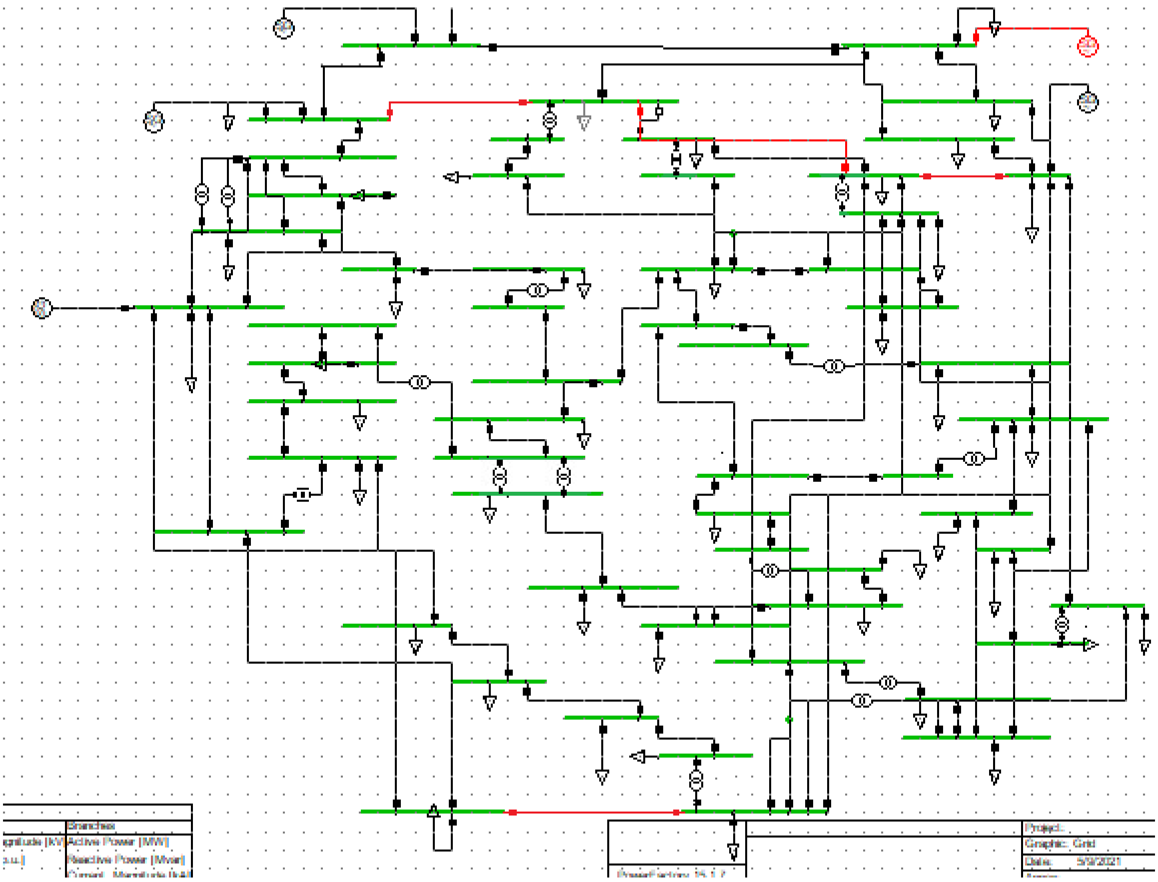


Figure 4.3

There are 80 lines, out of these 4 lines show line loading greater than 60%, line 18 has the highest with 90.343% and line 25, line8, line 14 have crossed threshold loading percentage. Line 10, line 3, line 13, line78 shows greater than 55% and all this loading percentage is also shown in the same figure 4.5 below. To avoid this overflowing situation PST’s are implemented according to genetic algorithm.

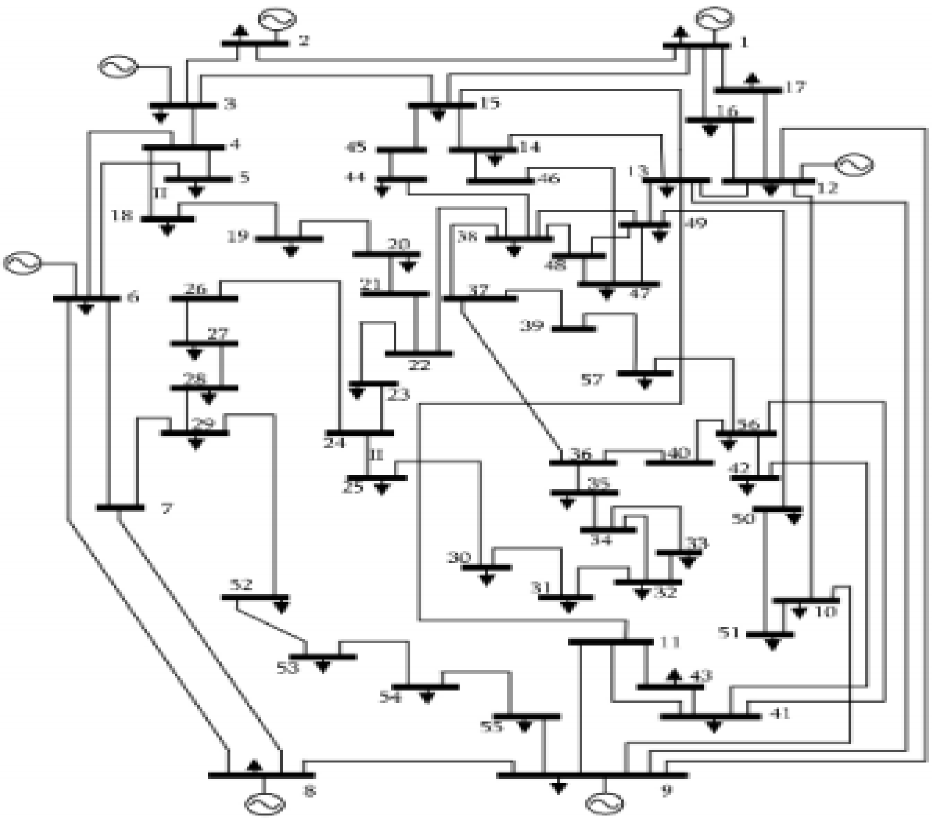


Figure 4.4

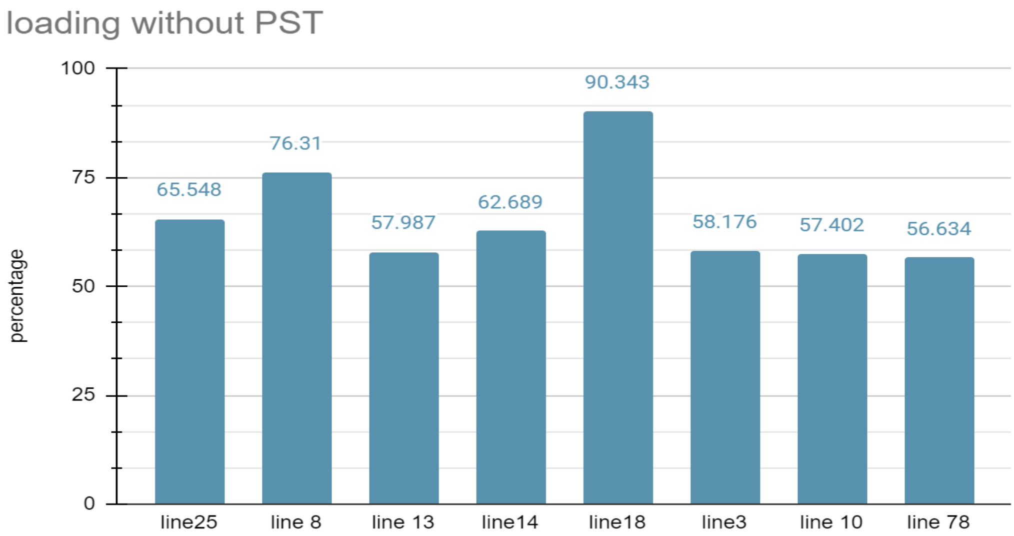


Figure 4.5

4.3.1 MATLAB and Digsilent

To implement genetic algorithm in our bus system, the data exchange code is written as part in Matlab and part in Digsilent in its own simulation language Digsilent Programming Language (DPL), through a script. Here we are implementing 4 psts ,so we have to run four times to find the position of each PST and its tap position. The data exchange is made using as a link layer of three buffer .cvs files. One for transferring the data from Matlab to Digsilent (Test1.csv), one for transferring the data from Digsilent to Matlab (Test2.csv) and one for read/write protocol of the involved programs (Protocol.csv).

To read output data from matlab and digsilent ,codes should be generated. For a fast and reliable communication, the protocol file acts like a switch taking the values 0 and 1. If the value of Protocol.csv is 0, Matlab reads the Data2.csv file, writes the Test1.csv file and Digsilent waits. On the other hand , if the value of Protocol.csv is 1, Digsilent reads the Data1.csv file, runs the modal analysis, writes the Data2.csv file and Matlab waits.

During this procedure, both platforms scan and change the value of the Protocol.csv file after each of them finishes its work. This is an improved automatic data exchange procedure between MATLAB and Digsilent and is less time consuming and error free. With few alterations, this technique can become a powerful tool for solving any problem of power system analysis which involves both platforms working together.

The GA parameters used in these are population size NP = 50, crossing fraction CF = 0.8, mutation rate MR = 0.01, elite amount = 2 . The selection strategies 'Roulette' and 'Tournament' are combined with the crossover strategies 'Single-Point Crossover' and 'Two-Point Crossover'. All in all, this results in four different variants of the GA algorithm, which are then investigated.

4.3.2 Simulation after implementing PST

After using both this platforms we get 4 vector solutions with 2 variables in each, ie x_1 and x_2. The range of variable x_1 that is the position of PST in the power grid can take values from 0 to 79. The range for the variable x2 is inspired from real situations. Thereby, the tap position can take values in the domain [–30; +30], considering that the index of the middle tap is 0. In case of three PST's we have considered 1 tap position equals to 1^o angle and in one case 1 tap position equals to 2^o α phase angle. The PST will be able to set the phase angle shift α between the –30° and +30° and -20^o to 20^o in fourth case.

Four PSTs are implemented in this test case. The positions and suitable tap angle is shown in table below.

Number of PST	First node	Second node	line	Tap position	Angle shift
1	12	13	25	6	12^{0}
2	8	9	8	-4	-4^{o}
3	3	15	18	-2	-2^{o}
4	9	11	10	-9	-9^{o}

The tap settings for all 4 PSTs are shown in figure 4.6(a-d) below. It shows maximum and minimum available phase shift, its neutral position, angle shifted per tap and tap position we chose for simulation.

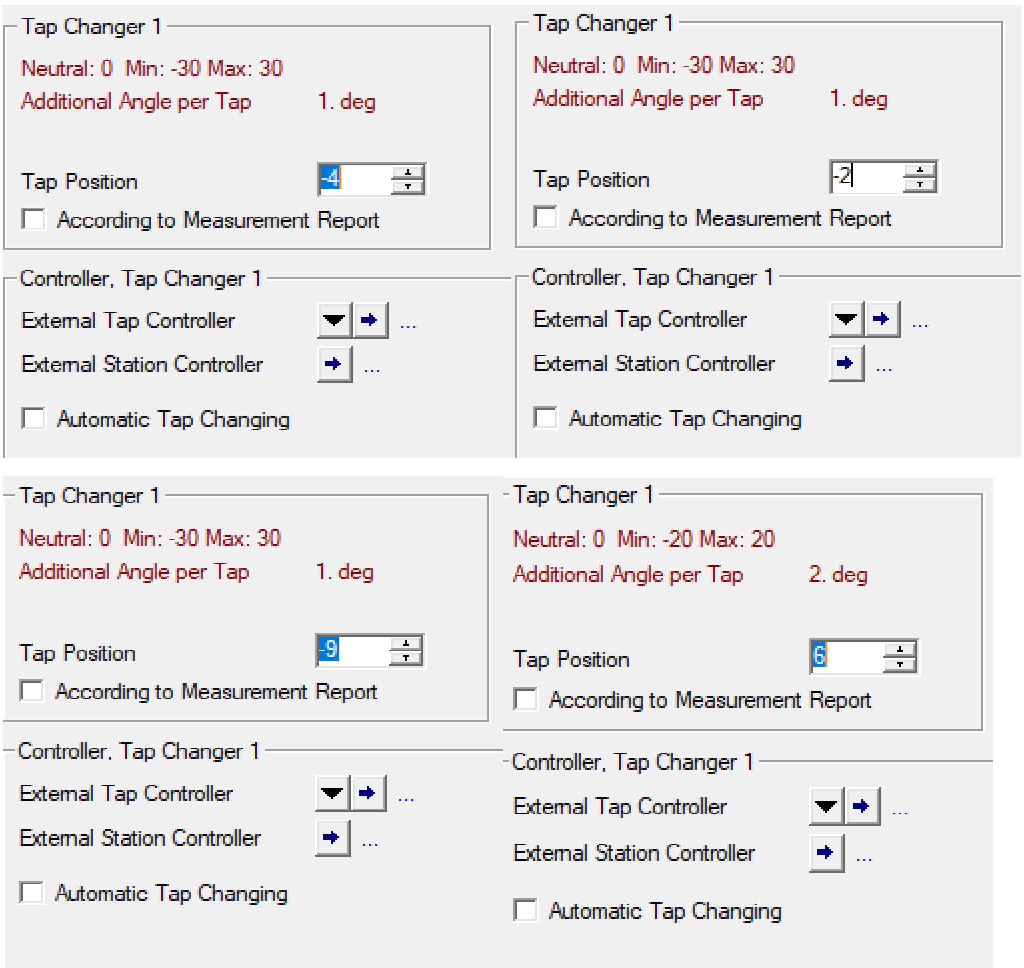


Figure 4.6 (a-d)

In order to limit the transmission lines loading below a threshold lower than 100%, γ_{br}^{adm} from the expression of the penalty function PL from equation is set to 60%.. In consequence, the GA will determine a solution for which all the line loadings are below γ_{br}^{adm} =60%, thus improving the static security of the power system.

It can be seen that the PSTs are installed in parallel with the heavy loaded lines, and that it reduces this line loading from 90.3% to 56.1% in the heaviest loaded case. Loading gets reduced in all other lines which had loading greater than 60%. In some lines loading shows a slight increase than 60% , for example line 50 has an increase of loading from 46% to 61.3%. Line 8 has a decrease from 76.3% to 64.4% . It is not possible to reduce the loading for this line under 60 %, because all other outgoing lines from the power feed-in node already operate at the maximal load of 60 %. These variations are shown in the figure 4.7 below. Which is considered to be an optimal solution for this case of 57 bus power grid. Further constraints are not violated, but due to the shifted power flows, the grid losses increase from 29.6 MW to 38.2 MW. This will result in the increase in the active power losses by 29%. Thereby, the quality of finding the best solution varies depending on the used algorithm.

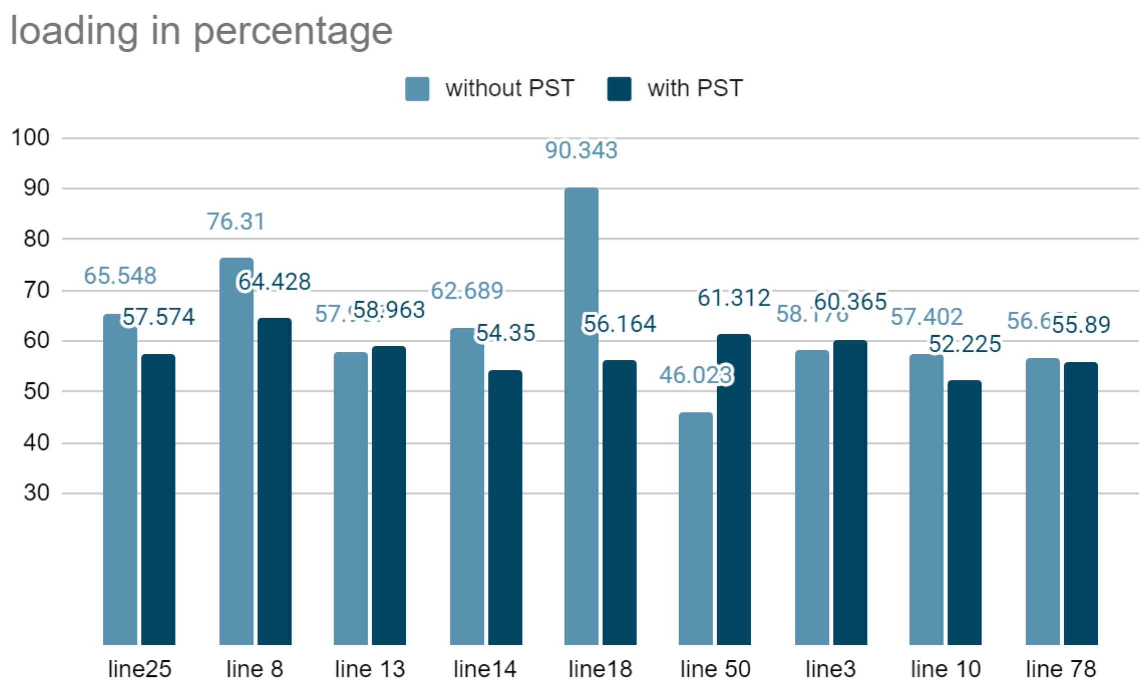


Figure 4.7

PST is installed on different lines around the chosen overloaded line Standard deviation for all buses together for each angle is calculated. The line with lowest standard deviation for every angle is chosen as the line for PST installation. Since it shows lowest fluctuations after installing PST for each angle.

Graph below in figure 4.8 shows the standard deviation of voltage |V| pu for all buses by varying phase angle for overloaded line 18. So PST is installed on line 18, line 72, line 4, line 28, line3 once at a time. standard deviation for voltages at each angle once after installing PST on a line is plotted. Line 18 shows the lowest Y value curve and is chosen as optimal solution for PST installation in this case. Which is same as optimised using genetic algorithm. Similar graphs are plotted for all other PST's to verify the validity of the genetic algorithm and it shows positive response in all cases.

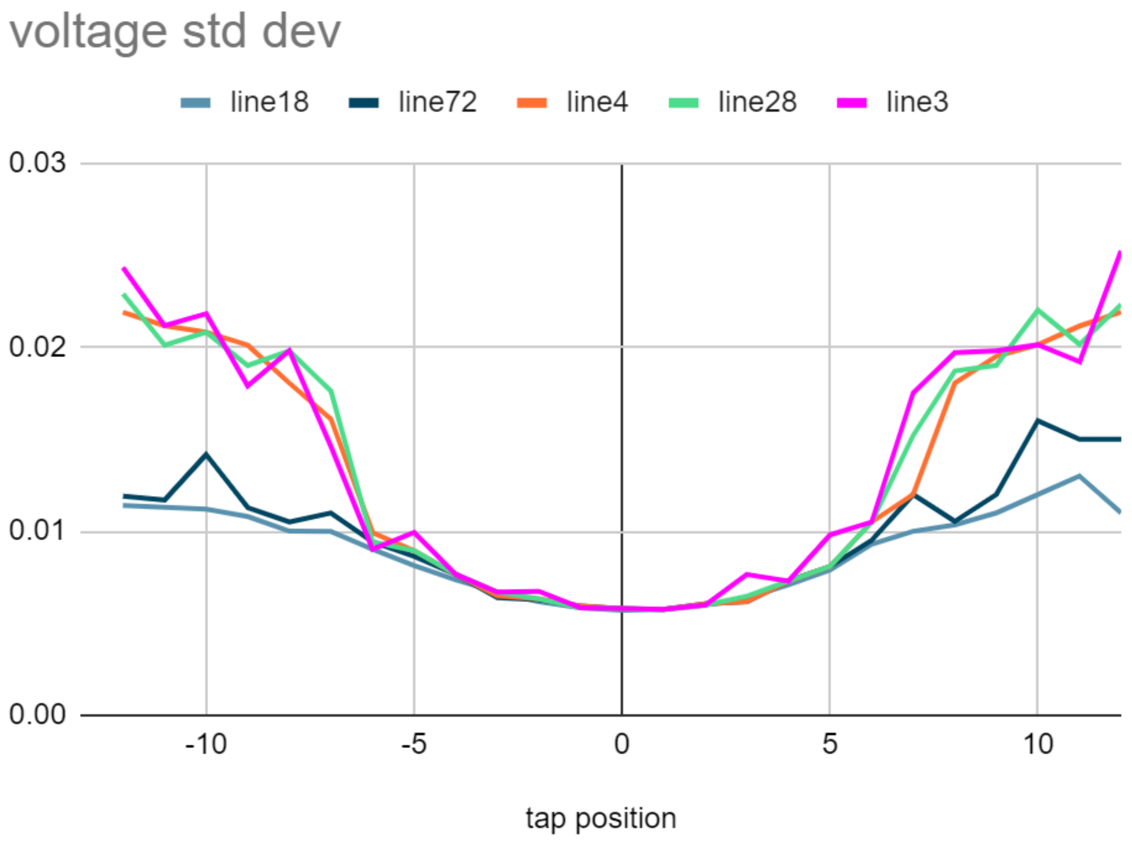


Figure 4.8

Chapter 5
CONCLUSION

The number of PST is going to increase in India and all over the world. PST s avoid risk of overloading in transmission grids and help to deviate power flow in our required direction. PST s exist in different forms, all types are detailed in chapter 2. The type and specification is chosen according to the requirement of power flow in the transmission system. . The asymmetrical version is relatively simple compared to the symmetrical PST but changes the voltage amplitude. The indirect configuration offers an easier modular design, but the overall cost is higher than the direct version. Meeden PST's in Netherlands proves the control of active power flow and shifts into populated areas according to its requirement, which is also mentioned as case study. The working methodology of PST is simulated in Digsilent power factory which can be applicable to higher meshed system.

Direct approach in power grids is a well known method for state estimation. BCBV and BIBC matrix analyses the power flow. In chapter 3 an extension of this methodology for grids with PST is described. The considerable change in formation of this matrix elements change their form from simple to complex structure which consists of the angle between buses and the phase shift applied to PST’s. This method of calculation is described using 9 bus system. Same grid is simulated using power factory and state estimation done in both these methods shows considerable difference.

The impedance correction table sets affect the power flow solutions and could be useful in alleviating the overloaded lines. when the phase angle is varied during the power flow solution impedance variation due to the impedance correction table comes into play. Hence it is unavoidable. In our case of state estimation phase angle is changed effectively so the elements of both the matrix are altered using the impedance correction table and calculated using this table. Newly calculated state variables are more inclined towards simulation results, so it shows effective alteration in the calculation of BCBV and BIBC matrix using the impedance correction table. Various graphs of results in this chapter remind the importance of impedance correction factor in calculation, and considerable error in calculation can be avoided. The loading of a transmission line is decreased for the same phase shift applied to PST while considering impedance correction. 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. It also shows the number of overloaded lines decreases in the power system for a particular shift in PST.

There are various algorithms to optimise positioning of PST in transmission grid and to choose its tap position. Chapter 4 describes the genetic algorithm, its formulation in PST and the function considered to optimise PST's location and tap position using the same. To implement genetic algorithm in bus systems, the data exchange code is written as part in MATLAB and part in Digsilent in its own simulation language Digsilent Programming Language (DPL), through a script. This script shows solutions for each PST implemented in the transmission grid. Their credibility is verified using a simulation of 57 bus system in Digsilent power factory. It can be seen that the number of overflowed lines decreases after using PST's. The loading in each line can be reduced after PST installing in optimal position under threshold except very few cases that show slight increase. The graphs in results compare the stability of location of PST chosen using script by genetic algorithm. It can be seen that this algorithm produces optimal position in location as well as phase shift for PST. The genetic algorithms can be successfully applied to optimization problems in power systems. However, as the network dimension increases, and the number of scenarios is multiplied, more powerful computers are needed capable of processing the increasing volume of data.

We can also see an increase in power loss of the system after installing PST. The PST is installed in series with the transmission line that is at the highest risk of overloading. The purpose is to reduce the line loading by controlling the phase angle difference between voltage phasors at the two ends of the line. However, if no change in the generation-load pattern or voltage set-points is done, increased power losses will result. Therefore, security is improved, while the economic operation is worsened. A simplified cost-benefit analysis for the proposed solution for minimizing power losses can be conducted by comparing the investment costs of PST and savings obtained through decreasing the losses. This loss can be considerably decreased using PST itself and it is economically more beneficial to use PST compared to complexities and improvisation done into the power grid without using PST.

The simulated results in chapter 3 verify that considering embedding impedance correction factor into PST can lead to a more optimal solution and can also be taken into account after finding location and settings for PST specified in chapter 4 using genetic algorithm especially in the local zone of contingencies and should be greatly considered in power flow analysis and simulation tools. The accelerated growth of Indian power sector and the need for installing the PST in the transmission network are to be further discussed. There could be such situations in the entire Indian grid where application of PST for control of the power could be studied. With the world India is also stepping forward with the application of PST in its power grid.

Chapter 6

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