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Investigation of control of power flow by using phase shifting transformers: Turkey case study

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Abstract: Transmission systems are needed to be upgraded based on expected/unexpected load growth factor by years. However, it is not so easy to install and upgrade the transmission system, which requires transmission planning calculation ahead of time. Traditionally, transmission companies built extra transmission lines to meet that load growth, but it is not easy and cost-effective to upgrade the system every time loads increase. Some unexpected load growth may occur for some load points that is not in the part of planning calculation. For those situations, the transmission system may face serious congestion problems. Transmission companies have been looking for a way to control power flow rather than building extra electricity capacity. With the development of technology, more complex and integrated flexible alternating current transmission system technologies that can control power flows by changing the voltage amplitude, the angle, and the impedance of the transmission line are now widely used. Phase-shifting transformer (PST) is one of the most widely used devices that can be used for controlling power flow. PST can vary the amount or direction of the active power flow by injecting voltage at different phases into the transmission line on which PSTs are installed. In this study, possible location case studies of PST in the Turkish transmission network will be investigated. Static analyses will be performed using the PSS/E and Python programs. The maximum and minimum production status of distributed wind power plants will be analyzed comparatively in the energy corridor with PST. Capacity improvement and power flow dispatch from each case study with and without PST will be compared. Finally, we propose a mathematical model to suitably determine the angle of PST in order to minimize real power losses that are caused by PST and provide N-1 security.

Key words: Phase-shifting transformer, total transfer capacity, transmission system operation, power loss reduction, power flow

1. Introduction

The Turkish transmission network consisting of over 68.000 km of power transmission lines is managed by Turkish Electricity Transmission Company. To transmit the electrical power that is produced, 400 kV or 154 kV AC voltage is used. A phase-shifting transformer (PST) consists of equipment that can change the active load flow by changing the phase angle of the voltage in the energy transmission line (ETL) to which it is connected. Changing the load flow provides lots of advantages on ETL. For example, it is important to reduce losses resulting from energy transfer in electrical networks. Optimum power flow (OPF) algorithms can reduce network losses due to energy transfer. The usage of PSTs while providing OPF can greatly simplify the system operator work. This issue can be seen as another perspective. For example, if you are connected to another country's network, the PST can help to provide some amount of power that must be exported or imported.

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The contribution of PST, thyristor controlled series capacitor (TCSC), or any other flexible alternating current transmission system (FACTS) equipment to the total transfer capacity should be calculated before a new line investment is made. The transfer capacity of the existing energy corridor can be increased with PST or other FACTS equipment. Therefore, it should be decided in which direction the investment should be made by taking into account factors such as N-1 conditions, power plant investment plans, PST investment cost, and new energy transmission line cost.

In the literature, there are many studies related to PSTs in different applications. It is stated that system security can be compromised by uncertain and uncontrollable power flows between Germany and Austria or similar European countries. In [1], a situation assessment was carried out and 25% more power flow was observed in the Polish system due to unplanned flows. It is clear that PST can be used to prevent unnecessary load flows that endanger N-1 security. In [2], High voltage direct current (HVDC) and PST devices were placed in the Belgian network and comparative situation analyses were carried out. In [3], an improved control method for PST and HVDC was proposed by aiming to reduce operating costs while maintaining N-1 security. The proposed method is tested in IEEE 118-300 bus systems and in the Polish system. In [4], PST and unified power flow controller are compared. In [5], different FACTS devices were installed and analyzed in order to increase the reliability of the Hydro-Quebec power system. Methods in [6–12] are genetic algorithm and particle swarm optimization that is used to determine the optimal placement or optimal angle of the PST. In [13–20], new protection algorithms such as special differential protection systems, adaptive distance protection relay are proposed to protect the PST. In [21,22], controller approaches were studied for PSTs with a converter. In [23], it was stated that very high transient voltages can occur in the system where PST exists. In [24], thyristor controlled phase-shifting transformer parameters optimization was studied by stating that the power and frequency oscillations in the connection lines can be damped better with the optimized parameters.

The research subject of [25] is similar to our study; it investigated the solution of a problem in the country network but we are interested in a parallel corridor in the transmission system for using PST instead of connection to other countries as in this study. Furthermore, when PST is added to the transmission system, power losses will increase. Thus, we have studied to find a suitable angle of the PST for reducing active power losses and providing N-1 security; however, in [25], N-1 security and losses of the transmission system were not taken into account. The author used a static VAR compensator to adjust the system voltage. We have not used any special device for regulating the system voltage because there are many natural gas power plants and thermal power plants in the studied region.

Significant investments in alternative energy sources are made in Turkey. As the uncertain energy sources such as solar and wind integration have been increased, total load flow in the network becomes much more complicated. The aim of this study is to prevent overloading of the specific energy corridor on Turkish transmission network. This overload of the ETL could be eliminated by different investments such as TCSC or PST, but here a PST will be used to relieve overloading. Even though it is not the most technologically advanced device, PST has been chosen since it meets all the technical requirements for flexible control. Furthermore, PST has many advantages such as simplicity and high reliability, and it requires less maintenance.

Total power transfer limits in the transmission system are restricted by the capacities of the transmission line and voltage levels. Power transfer capacity can be increased by using PST which shifts angles of voltages between buses. However, the power capacity of the autotransformer(AUT) in the transmission system can impress the total power transfer capacity that includes N-1 security. Therefore, while the transfer capacity is improved at 400 kV voltage level via PST or any of FACTS devices, loading of AUT which allows to connect to 154 kV voltage level from 400 kV is to be considered. Provided that we want to increase the loadability of transmission lines through PST, we need to know that system losses will increase and new constraints may arise. The west of the Turkish transmission system has not only a significant amount of wind power potential both also many natural gas and thermal power plants. There are two corridors between Bekirli High Voltage Substation (HVS) and Bursa Industry HVS and these corridors are not in the same loading rating when the amount of wind power generation is at low level. We can use a PST so that transfer capacity increases, but in this situation, losses will rise and new constraints may occur. Therefore, the location and angle of the PST must be determined properly in order that it will provide suitable results that assure N-1 security and is to satisfy energy requirement as economically as possible. This paper presented analyses and a discussion of the effects of different allocations and angles of the PST on the steady-state performance of the west of the Turkish transmission network. As a result, the power flows can be managed in a flexible manner without installing additional transmission lines.

The second part of the study summarizes general information about PST. Section 3 describes a suitable place to install the PST in the west of the Turkey network and the mathematical formulation to reduce real power losses that are caused by the PST. The proposed mathematical model is applied to the Turkish system and the results are shown in Section 4. Finally, Section 5 draws the conclusions of the paper.

2. Phase-shifting transformer

The power flow in an energy corridor is distributed based on the amplitude and angle of the bus voltage, and reactance of the transmission line. It is possible to change the load flow by changing the reactance of the transmission lines. At the same time, the active load flow can be changed by changing the amplitude and phase angles of the bus voltages. PSTs are equipment that controls active power flow in electrical power systems. This control is accomplished by varying the phase angle between bus voltages. In Figure 1, 100 MW of active power flow is measured from bus A to bus B. The voltage amplitude of both buses is 154 kV. Under normal conditions, an unbalanced load occurs due to the difference between the impedances of the energy transmission lines. In the present case, the angle difference between the two bus voltages is +0.966° degree. PST is 200 MVA and the U_k value is 8%. The PST angle required for equal loading of parallel lines can be determined by Eq. 1.

When the required calculations are made according to Eq. 1, it is seen that the load flows in the lines are equal when the PST angle is +1.935°. Provided that you want to know reactive power flow in another transmission system, you can calculate approximately according to Eq. 2.

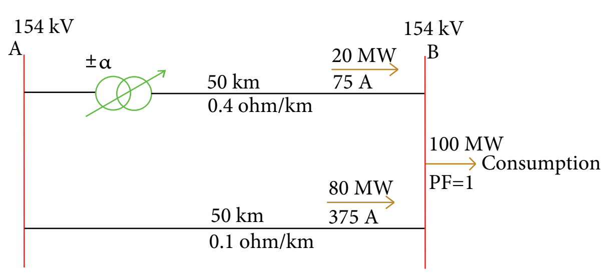


Figure 1. Power transmission line with PST.

$$P = \frac{U_A U_B}{X + X_{PST}} \sin(\delta + a), \tag{1}$$

$$Q = \frac{U_A^2}{X + X_{PST}} - \frac{U_A U_B}{X + X_{PST}} \cos(\delta + a). \quad (2)$$

There are 4 types of PST structure: direct symmetric (single core), direct asymmetric (double core), indirect symmetric, and indirect asymmetric. The most commonly used PST architecture is the indirect asymmetric design. The indirect asymmetric phase shifter consists of a combination of excitation and series transformers. In this PST, it changes the magnitude and angle of the voltage between the primary and the secondary. PST's working principle is simple as can be seen in Figure 2.

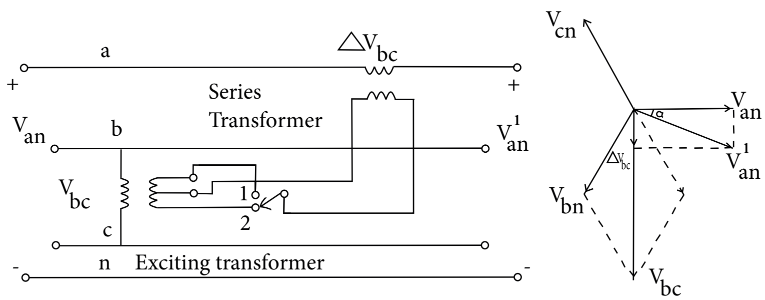


Figure 2. Single-phase circuit and phase diagram of PST [26].

The injected voltage is in a different phase than the input voltage. Therefore, a phase shift occurs in the resultant voltage with respect to the input voltage. As can be seen in the figure, the phase a of the series transformer is fed by the secondary of the excitation transformer in phases b and c. Similar connections are made in other phases to produce the balanced three-phase output voltage.

2.1. Nonideality properties of PST

We have used two nonideal properties of PST. These nonideal parameters are load and angle dependence. When PST is added to the transmission line, an extra series reactance is added as well. This reactance causes a voltage change in the transmission system depending on load. Furthermore, the angle of PST causes its own reactance change. Normally, the voltage is shifted ideally by the angle of PST under no-load condition. Nonetheless, a voltage drop that is caused by the reactance of PST has to be taken into account.

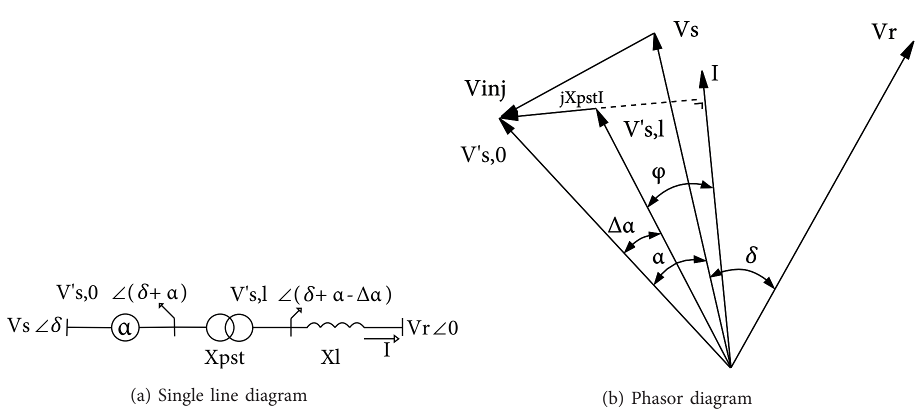


Figure 3. Single-phase diagram and phasor diagram of a PST that is under load.

Single-phase diagram of a PST is given in Figure 3a. The sending end voltage V_s is shifted by injecting a voltage V_{inj} under no-load condition. However, under load, as it is seen in Figure 3b, a voltage drop $jX_{pst}I$ takes place. This situation results in a deviation from the no-load condition. The angle deviation is calculated using Eq. 3. The reactance of the PST is written in pu and I_n is the rated PST current. For more detailed information, see reference [27].

$$\triangle a = \arctan \frac{\frac{I}{I_n} * X_{pst,pu} * \cos\varphi}{1 + \frac{I}{I_n} * X_{pst,pu} * \sin\varphi}. \tag{3}$$

The PST reactance changes as a function of its angle. Measurements show that the relation between the angle of PST and its reactance can be approximated by a quadratic curve [27]. We have defined a quadratic equation in Eq. 4 in order to represent the relation between the angle of PST and its reactance. We have used this equation in the Python code and reactance graph of the PST that we used is seen in Figure 4.

$$Q = 1.07x10^{-4} * tap^2 + 1.3x10^{-4} * tap + 0.0925 \tag{4}$$

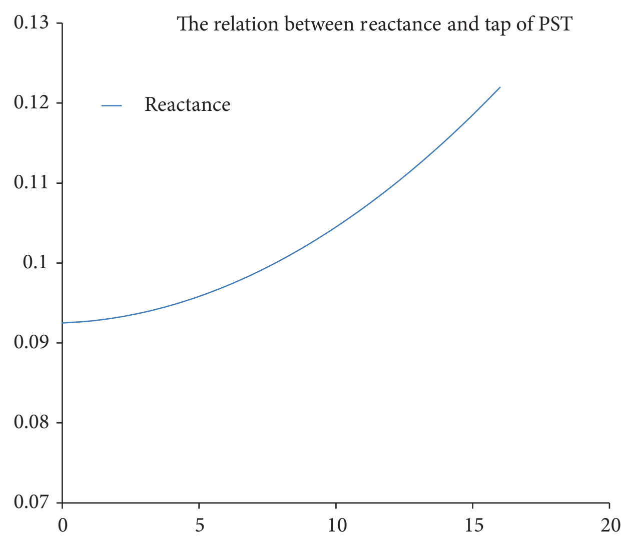


Figure 4. The relation between reactance and tap of PST.

3. Placement of PST on Turkey's grid

There may be many locations in the interconnected networks where PST can be placed. Various iterative methods are used in order to find relevant places and make the optimum location. In this study, the actual power flows on the transmission system in Turkey is used based on January 2018.

The wind power plants' generation is of 555.57 MW in the related date. Table 1 shows the installed capacity of some wind farms and the hourly production. In the case of wind power plants not working, 400 kV Bekirli Thermal Power Plant (TPP)–Cenal TPP–Bandırma Natural Gas Combined Cycle Power Plant (NGCCPP)–Bursa NGCCPP–Bursa Industry corridor have a lot of energy flow. In this study, the relevant route will be called Corridor-1 with the total length of 216 km. While 199.1 km of the corridor was installed with 3B Cardinal conductor, 16.9 km of the corridor was 2B Cardinal. Bandırma NGCCPP–Bursa NGCCPP

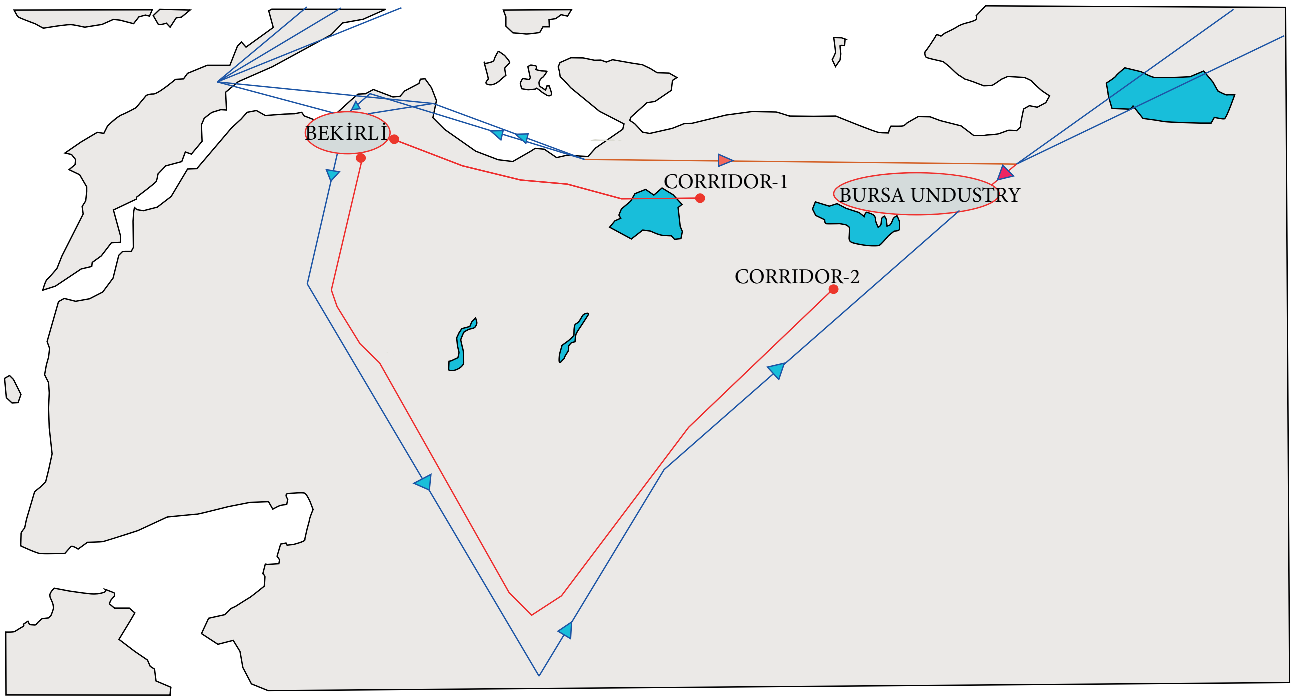


Figure 5. Bekirli TPP – Bursa Industry - Corridor-1 and Corridor-2.

ETL is 120-km long and is 3B Cardinal with its thermal load limit of 1510 MVA. Bursa NGCCPP–Bursa Industry ETL is 16.9-km long and is 2B Cardinal with its thermal load limit of 1005 MVA. In the base case, there is 1025 MVA power flow from Corridor-1 to Bursa Industry High Voltage Substation (HVS). There is a power flow of 84 MVA from the Bekirli TPP–Can-2 TPP–Soma-B–Balıkesir-2–Bursa Industry corridor as called Corridor-2 to the Bursa Industry HVS. The total length of Corridor-2 is 352.4 km. While 176.2 km of the corridor is 3B Cardinal, 176.3 km is 2B Cardinal. Balıkesir-2–Bursa Industry ETL is 111.25-km long and 2B Cardinal. Relevant corridors are indicated in Figure 5.

On 10.01.2018 at 9 AM, the wind production is quite low while it is almost at the middle level at 7 PM on 09.01.2018. The productions of natural gas and thermal power plants in these two dates are shown in Figure 6. Turkey's peak consumption is 40,596.06 MW on 01.10.2018. The production amount is 37,370.00 MW, the export amount is 199.00 MW, the import amount is 244.00 MW and the consumption amount is 37,415.00 MW at 9 AM on 10.01.2018. Related hourly wind production in Turkey is 555.57 MW. However, the day before the wind output was 2107.33 MW at 7 PM on 09.01.2018. Therefore, with the spread of wind power plants, the direction of the load flows in the network becomes dependent on the weather situation. If wind power plants do not produce power at all, 400 kV Bursa NGCCPP–Bursa Industry ETL is overloaded. This is a clear example of the dependency of wind generation. Figure 7 shows the production of wind power plants on different days.

Figure 8 shows the power flows of some 400 kV ETLs. The generation of wind power plants is 555.57 MW on 10.01.2018 and is 2,107,33 MW on 09.01.2018. In addition, as a third option, the generation differences in the NGCCPs and TPPs were reset and only the effect of the increase in wind output was observed as shown modified in Figure 8.

The N-1 analysis in 400 kV level on 01.10.2018 at 9 AM shows that the worst case scenario in the related region is that 400 kV Bekirli TPP–Can-2 TPP ETL is out of service. However, if 400 kV Bursa NG–Bursa Industry HVS transmission line is out of service, problems occur at 154 kV voltage level. Therefore, this should

Table 1. Installed power and production data of some wind farms.

Plant name	Turbine number	Installed power (MW)	Electricity production quantity (MW) (10.01.2018, 09:00)
Soma WF	169	240	0
Balıkesir WF	52	142.5	0
Aliağa Bergama WF	46	120	24
Lodos WF	50	120	0
Şamlı WF	43	114	0
Şah WF	31	93	8.9
Bandırma WF	29	87	4
Soma-1 WF	32	84	0
Edincik WF	30	77.4	3.4
Susurluk WF	29	72.5	0
Total	511	1150.40	40.3

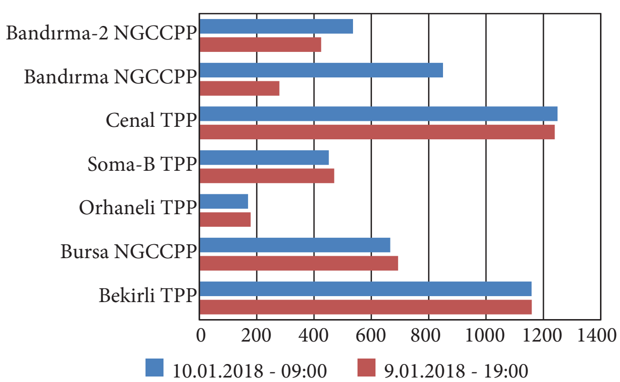


Figure 6. The production quantities of some NGCCPPs and TPPs on different days.

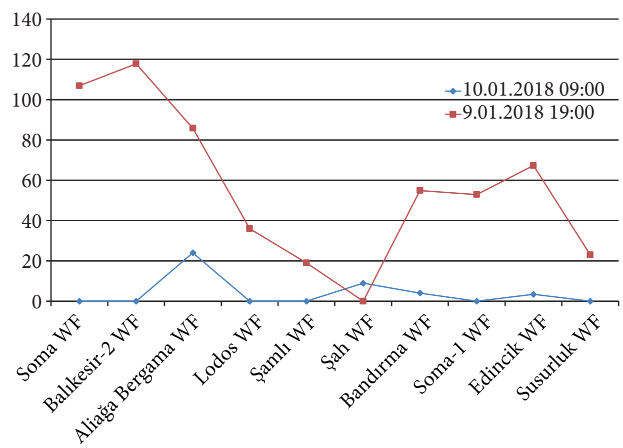


Figure 7. The production quantities of some wind power plants on different days.

be taken into consideration.

When the 400 kV Bekirli TPP–Can-2 TPP ETL is opened, 1340 MVA from Corridor-1 and 207 MVA from Corridor 2 are flowing to Bursa Industry. As it is seen, Corridor-1 is overloaded in both basic case and in the case of N-1. Conversely, the capacity of Corridor-2 cannot be used. Therefore, in this study, it was aimed to decrease the loading rate of Bursa NG–Bursa Industry ETL and increase the transfer capacity of Corridor-2. As can be seen from Figure 9, statistical analyses were carried out by placing PST in 400 kV Bandırma NG–Bursa NG, Bursa Industry–Bursa NG and Balıkesir-2–Bursa Industry ETL, respectively.

3.1. Case studies for placement of PST

Base-case load flow and N-1 analysis were performed in all three topologies. In the simulation, a PST with 400 kV and 1400 MVA is used. While the U_k of the PST is 9.25% in the first tap of PST, it is 12.19% in the last tap of PST. The relationship between the change in step and the change in reactance has been embedded in

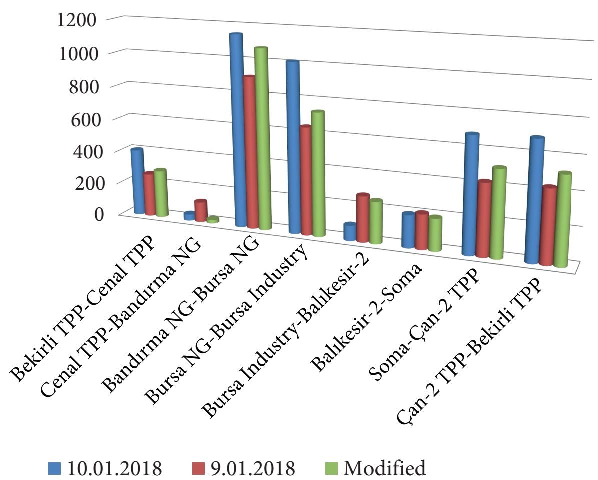


Figure 8. Power flows in some ETLs with change in the production quantity of wind power plants.

Python code. Additional angle difference of 24 degrees between buses is created with PST. In Table 2, power flow ratings are given in the base-case and N-1 condition. In Table 3, three different PST scenarios are applied and power flow ratings in some transmission lines are given. In the PST scenarios, because PST has been adjusted to the last tap, the U_k of the PST is 12.19%.

Table 2. Some % rating power flows in the base case and N-1 case (Bekirli TPP - Can-2 TPP does not work in the N-1 case).

Energy transmission line	Apparent power flow	
	Base case	N-1 case
Bandırma NG–Bursa NG	74.7	92
Bursa NG–Bursa Industry HVS	101.9	133.6
Bursa Industry HVS–Balıkesir-2 HVS	8.4	20.6
Bekirli TPP–Gelibolu-2 HVS–1-2	50.1	62.8
Cenal TPP–Gelibolu-2 HVS–1-2	46.6	49.7
Bursa NG–Adapazarı HVS	13.4	11
Bursa NG–Kocaeli HVS	21.8	17.8
Tutes Şalt HVS–Bursa Industry HVS	19.8	22.9

When Tables 2 3 are examined, it is seen that 400 kV Bursa NGCCPP–Bursa Industry HVS ETL is loaded more than the thermal limit in the case of N-1 in the network without PST. The three lines with the installation of PST are compared. If PST is placed in energy transmission line Bursa NG–Bursa Industry or Bursa Industry–Balıkesir-2, overloads occur at 154 kV level in the case of N-1. The most suitable place to install the PST is 400 kV Bandırma NG–Bursa NG ETL according to the N-1 analysis. It is important to determine the PST location and angle. The mathematical model we have developed to obtain the suitable angle is explained in the next section.

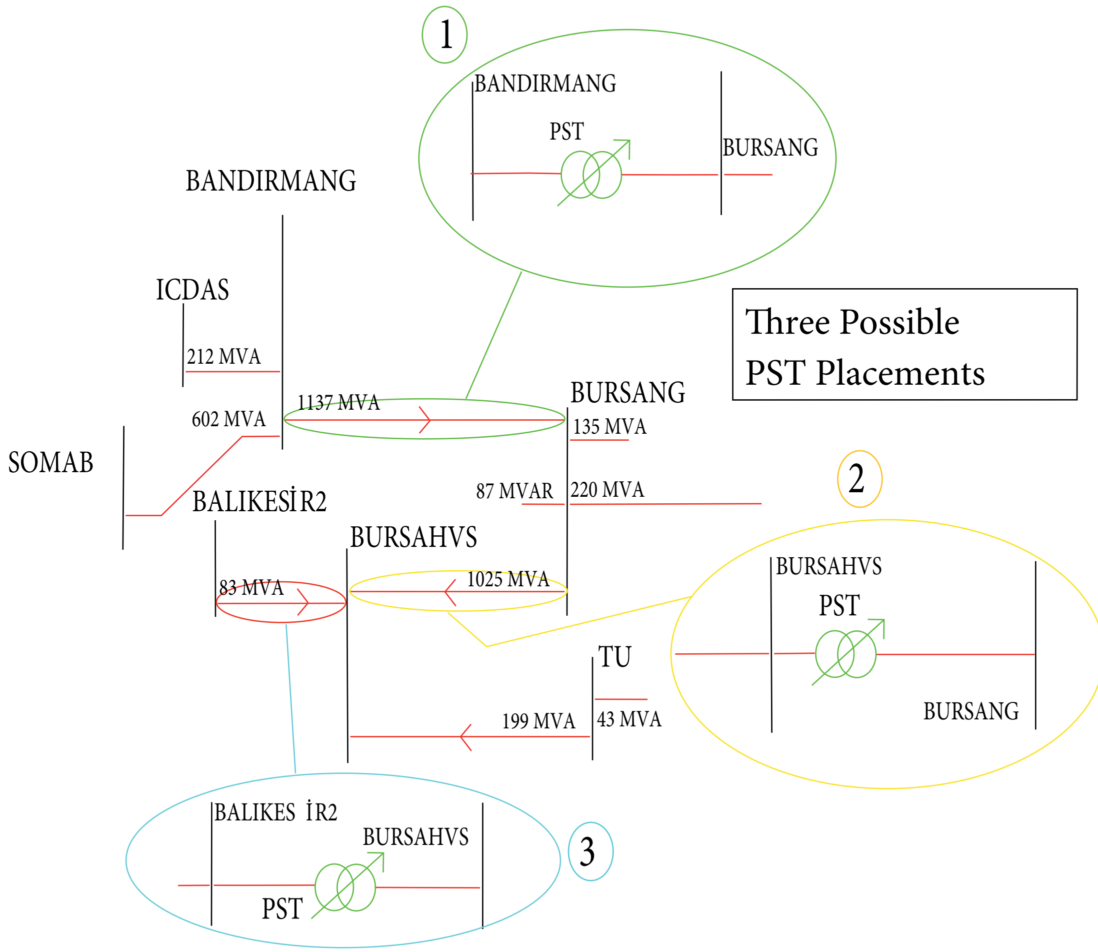


Figure 9. Possible PST placements.

3.2. Mathematical model

In this paper, we aim to provide N-1 security and to reduce power losses which are caused by PST. In order to reduce the calculation burden, we first perform N-1 analysis and determine the worst case scenario for real data that is on 01.10.2018 which was explained in Section 3. In the second stage, we apply our mathematical model and improve system performance. Provided that a PST is added to the network, power losses are increased since the power flow is directed to the corridor with high impedance. Therefore, the angle of PST must be carefully adjusted. N-1 security should be provided and active power losses should be minimized. This letter proposes a mathematical model to suitably determine the angle of PST which is added to Bandırma NG–Bursa NG ETL in order to minimize the active power losses that are caused by PST. This mathematical model is valid only if the wind power generation of the west of the Turkish transmission system is low because it does not need to add PST if wind power generation is high. Furthermore, we must specify that the overload level of AUT can change if it is performed on a different topology in 154 kV voltage level and for this reason, power losses that are caused by PST may increase as well. The worst case in terms of N-1 analysis for 400 kV voltage level in the related region is that Bekirli TPP–Çan-2 TPP ETL is out of service. The worst case in terms of N-1 analysis for 154 kV voltage level in the related region is the opening of the 400 kV Bursa NG–Bursa Industry HVS ETL because Bursa NG Autotransformers are overloaded if Bursa NG–Bursa Industry HVS ETL is out of service. In our mathematical model, active power losses are minimized by considering this constraint.

Table 3. Some power flows (in % rating) in base case and n-1 case where PST is placed.

Power flow	400 kV line with PST					
	Bandırma NG–Bursa NG		Bursa NG–Bursa Industry		Bursa Industry–Balıkesir2	
	Base	N-1	Base	N-1	Base	N-1
Bandırma NG–Bursa NG	13.1	34.2*	50.1	74.4*	63.2	86.0*
Bursa NG–Bursa Industry HVS	62.5	106.1*	23.1	16.1*	64.4	104.6*
Bursa Industry HVS–Balıkesir-2 HVS	27.3	10.9*	49.6	14.3*	72.9	42.2*
Bekirli TPP–Gelibolu-2 HVS–1-2	64.4	83.8*	46.1	65.1*	45.3	62.4*
Cenal TPP–Gelibolu-2 HVS–1-2	59.6	65*	47.6	52.5*	45.8	50.1*
Bursa NG–Adapazarı HVS	12.6	17.2*	43.0	41.0*	20.9	17.7*
Bursa NG–Kocaeli HVS	7.9	12.8*	54.7	51.0*	30.9	26.0*
Tutes Şalt HVS–Bursa Industry HVS	12.6	13.9*	46.7	44.9*	35.8	42.1*
Bursa NG 400/154 kV AutoTransformer	77.2	101.2**	136.0	141.6*	95.7	120.3**
154 kV Bursa NG–Otosansit HVS	75.8	106.0**	141	150.7*	87.3	118.7**
* : 400 kV Bekirli TPP–Can-2 TPP ETL does not work in the N-1 case						
** : 400 kV Bursa NG–Bursa Industry HVS ETL does not work in the N-1 case						

The objective function that is expressed in Eq. 5 is to minimize the active power losses caused by the PST in the Turkish transmission network:

$$minimum \qquad \sum_{l=1}^{N_l} P_l. \tag{5}$$

N_b is the total bus number, N_l is the number of transmission line and P_l is the real power losses. The problem constraints are:

$$P_i - jQ_i = |V_i| \underline{/-\delta_i} \sum_{k=1}^{N} |V_k||Y_{ij}| \underline{/\theta_{ik} + \delta_k} \qquad i \in N, \tag{6}$$

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & 0 \\ 0 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix}, \tag{7}$$

$$\alpha^{min} \leq \alpha \leq \alpha^{max}, \tag{8}$$

$$S_{PST} \leq \ S_{PST}^{max}, \tag{9}$$

$$V_i^{min} \leq V_i \leq \ V_i^{max} \quad i = 1, 2, ..., N_b, \tag{10}$$

$$S_{BNGAT} \leq 1.1 * S_i^{max}, \tag{11}$$

$$S_i \leq \ S_i^{max} \quad i = 1, 2, ..., N_l, \tag{12}$$

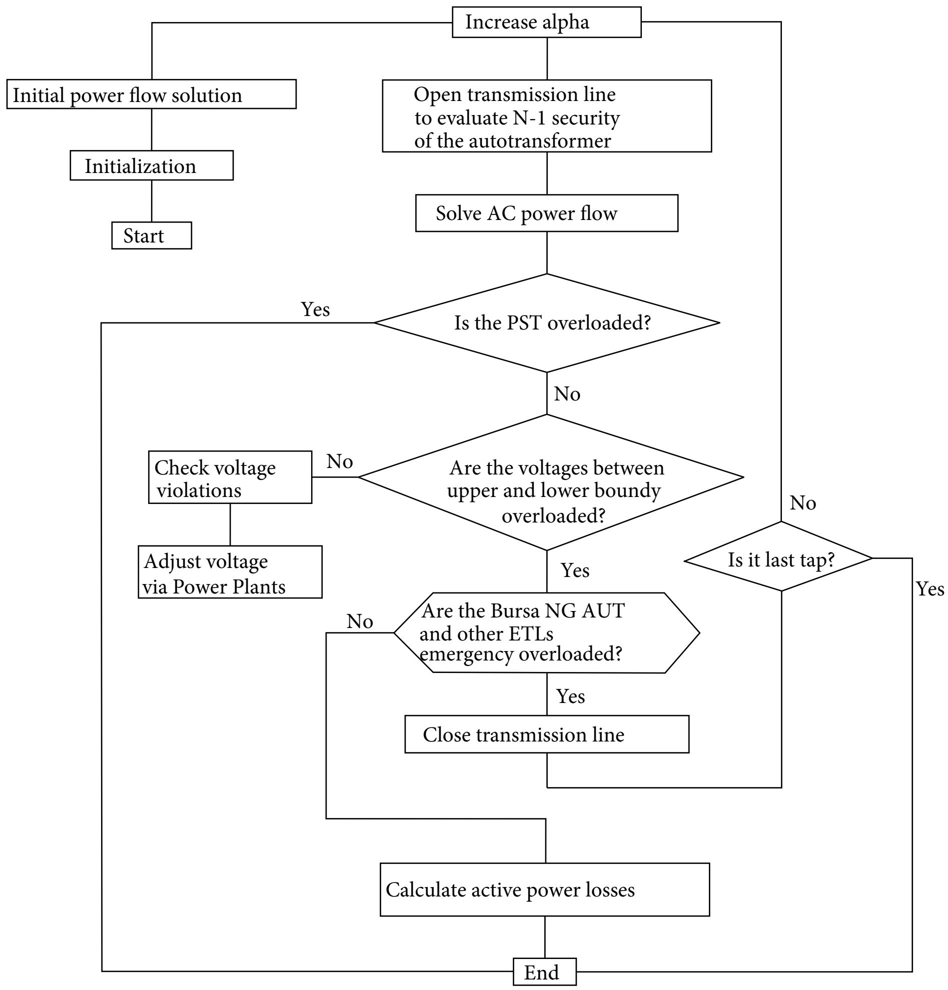


Figure 10. The process of the mathematical model.

The process of the mathematical model is shown in Figure 10. In the initialization section, case data that will be used for the algorithm is run via Python interpreter in PSSE simulation program. The initial AC power flow solution is performed through the fast decoupled Newton–Raphson (FDNR) method. Eqs. (6) and (7) represent AC power flow formulation with the FDNR method. The next step is that the alpha angle is increased one tap. The reactance of the PST will vary quadratically as the angle changes. In the first tap of PST, N-1 security could not be ensured since the AUT of Bursa NG HVS is overloaded. In this step, our aim is that the angle of PST will be increased gradually in order to provide N-1 security. If the angle of PST is adjusted to the last tap, it is clear that N-1 security is provided but in this case, the power losses will increase. Therefore, we increase the angle of PST step by step until N-1 security is provided because we want to restrict the angle because it enhances the power losses. As stated previously, we must provide N-1 security of the transmission system; therefore, the Bursa Industry HVS–Bursa NG ETL, which is the critical transmission line that is determined before, is opened for evaluating the security after the increase in the alpha step. When the angle of PST is increased or decreased, the power flow over the PST is increased or decreased as well. Thus, we have added constraints (Eqs. (8) and (9)) which ensure that the angle and apparent power of PST cannot exceed its limits. The voltage level of busbars should be considered in this step because the reactive power flow

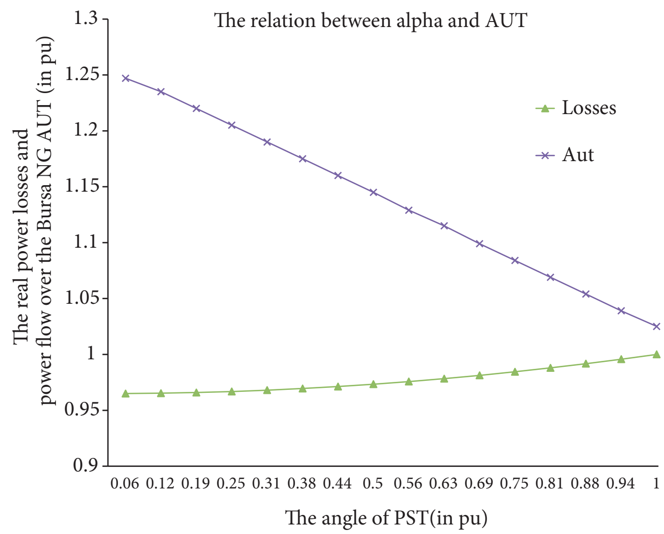


Figure 11. Changing of power losses and autotransformer loading due to angle of PST.

in the transmission system may change; hence, we have added Eq. (10) in order to ensure that the voltage of busbars cannot exceed its limits. After voltages are checked, we should ensure that power flow over the AUT in Bursa NG and other transmission lines are within boundaries. Therefore, we have the added constraints, Eqs. (11) and (12), for providing security. According to Eq. (11), the apparent power of Bursa NG Autotransformer is restricted by the upper limit. Constraint in Eq. (12) ensures that the apparent power of the transmission lines cannot exceed its limit. The loop continues until the emergency overloads are removed. Finally, we have calculated the active power losses in the transmission system because as mentioned before, one of our goals is that the algorithm can reduce the power losses due to the angle and reactance of PST.

To summarize, the AUT in Bursa NG has overloaded at the first tap of PST in the contingency. As long as the tap of PST is increased, the power flow over AUT is decreased but the losses rise. Therefore, if the power flow of AUT is loaded within its limit, the increment of alpha is ceased for restricting the losses and in this way, a suitable angle of PST has been determined.

4. Results and discussion

While the integration of renewable energy sources in the grid has been increasing, there are limited updates in the network. Depending on the level of production in the wind power plants, the power flows in Corridor-1 and Corridor-2 can change considerably. Therefore, in order to cope up with the dynamic change of renewable energy integration into the network, a new corridor should be established or existing corridors should be used effectively.

The python can easily simulate power system problems through power system simulation programs, hence the design and test of our mathematical model can be achieved with ease. The proposed mathematical model is implemented using PSS/E with the Eclipse-Python and tested on the Turkey power grid. Initially, the PST angle is maximum at 24 degree and the real power losses in the system are 779.5 MW. The mathematical model was performed and Figure 11 was created. The new real power losses in the Turkish system are 761.5 MW at 16.5 degree PST angle. The results of applying the mathematical model to the Turkey power grid demonstrate the effectiveness of the proposed method to decrease real power losses. These losses comprise the whole of

```
# Create Subsystems
psspy.bsys(0,0,[ 0.4, 380.],0,[],0,[],0,[],1,[1])                    #380 kV subsystem
psspy.bsys(1,0,[ 0.4, 380.],0,[],0,[],0,[],2,[1,2])                  #154,380 kV subsystem
psspy.bsys(2,0,[ 0.4, 380.],0,[],1,[123410],0,[],0,[])               #PST bus

# Number of Power Flow
ierr, flow_number = psspy.aflowcount(1,1,1,2)
#Bus Count
ierr, buses = psspy.abuscount(1,1)
#Bus Name
ierr, bus_name = psspy.abuschar(1,1,'NAME')
#From Bus Name
ierr, from_bus_name = psspy.aflowchar(1,1,1,2,'FROMNAME')
#To Bus Name
ierr, to_bus_name = psspy.aflowchar(1,1,1,2,'TONAME')
fr=from_bus_name[0]
to=to_bus_name[0]

#Algorithm
I_n = (1400*10**3)/(math.sqrt(3)*380)      #Nominal current of PST
alpha = 0                                  #PST degree
tap = 0                                    #Tap of PST
reac_eq = 0.0925                           #PST Reactance
total_tap = 16
print(" Angle of PST: %1.f "%(alpha))
print(" Reactance of PST: %1.f "%(reac_eq))

for i in range (total_tap+1):
     # Solve Power Flow + Flat Start (Fixed Slope Decoupled Newton Raphson)
    psspy.fdns([0,0,0,0,0,1,0,0])
    #Change reactance and angle of PST
    psspy.two_winding_chng_4(123410,220011,r"""1""",[_i,_i,_i,_i,_i,_i,_i,_i,_i,_i,_i,_i,_i,_i,_i],[_f,reac_eq,_f,_
    f,_f,alpha,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f],[r"""PST""",r"""Yy0"""])
    # Solve Power Flow (Fixed Slope Decoupled Netwon Raphson)
    psspy.fdns([0,0,0,0,0,0,0,0])

    # OPEN BURSA NG - BURSA HVS ETL FOR EVALUATİNG N-1 SECURİTY
    psspy.branch_chng(220010,220110,r"""1""",[0,_i,_i,_i,_i,_i],[_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f])
    # Solve Power Flow (Fixed Slope Decoupled Newton Raphson)
    psspy.fdns([0,0,0,0,0,0,0,0])
    # Loading of PST
    ierr, Loading_PST = psspy.brnmsc(123410,314911,'1','PCTMVC')
    if Loading_PST>100:
        print("PST Loading: %1.2f "%(Loading_PST))
        break
    # Voltage Check
    ierr, bus_voltage = psspy.abusreal(1,1,'PU')
    bn=bus_name[0]
    bv=bus_voltage[0]

    for ii in range(buses):
    if bv[ii]>1.1:
        print("Voltage Limit Checking")
        print(str(bn[ii]) + str(bv[ii]))

    if bv[ii]<0.90:
        print("Voltage Limit Checking")
        print(str(bn[ii]) + str(bv[ii]))
```

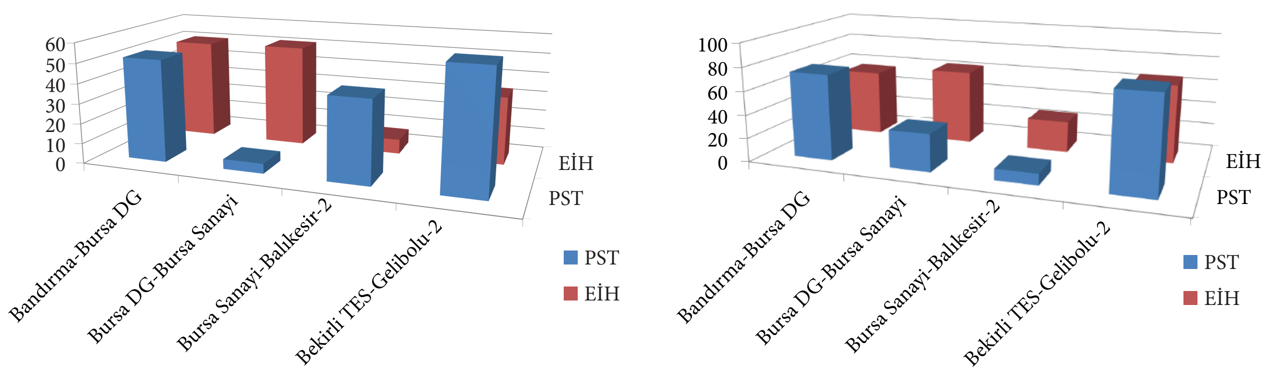
Figure 12. Python code for our algorithm - Part-I.

```
        # Loading of Branch
        ierr, percent_load = psspy.brnmsc(220010,220021,'1','PCTMVC')
        print("Loading of Bursa NG AutoTransformer: %1.2f "%(percent_load))
        # Check Loading Amounts:
        overload_lines = []
        count = 0
        ierr, loading_rate = psspy.aflowreal(1,1,1,2, 'PCTMVARATEC')
        l=loading_rate[0]
        for iii in range(flow_number):
            if l[iii] >= 120:
                print("There is an emergency overload")
                print(str(fr[iii]) + str(to[iii]) + str(l[iii]))
                l_list = [str(l[iii])]
                overload_lines += l_list
        for iiii in range(len(overload_lines)):
            if overload_lines[iiii] <= 120 : #count overloads that are lower than emergency overload
                count += 1
        tap = tap + 1
        alpha = tap*1.5
        reac_eq = (tap**2)*(1.07)*(10**(-4))+(tap*1.3*(10**(-4)))+0.0925
        Xpstpu = reac_eq/14

        ierr, bus_angle = psspy.abusreal(2, 1, 'ANGLE')
        ierr, PST_load_amper = psspy.brnmsc(123410,220011,'1','AMPS')

        #Angle deviation in radian is caused by load dependence
        dev_alphar = math.atan(((PST_load_amper/I_n)*Xpstpu*math.cos(float(bus_angle[0][0])))/
        (1+((PST_load_amper/I_n)*Xpstpu*math.sin(float(bus_angle[0][0])))))

        #Angle deviation in degree is caused by load dependence
        dev_alphad = (dev_alphar*180)/math.pi
        alpha = alpha - dev_alphad

        print("Alpha: %1.5f, Angle deviation: %1.5f, PST load(amper): %1.5f , Tap of PST: %1.f, Reactance: %1.5f
        "%(alpha, dev_alphad, PST_load_amper, tap, reac_eq))

        #Close Transmission Line
        psspy.branch_chng(220010,220110,r"""1""",[1,_i,_i,_i,_i,_i],[_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f])
        #Solve Power Flow (Fixed Slope Decoupled Newton Raphson)
        psspy.fdns([0,0,0,0,0,0,0,0])
        x = psspy.solved()
        if x == 0:
            print(' Met Convergence Tolerance ')
            ierr, system_losses = psspy.systot('LOSS')
            print("Active Power Losses: %1.2f "%(system_losses.real))
            print("------------------------------------------------------------")
        else:
            print(' Blown up ')
'''
In the critical N-1 situation that is determined before, if the number of overloaded lines that is lower than emergency
overload equal the number of all lines that are overloading and the loading of Bursa NG autotransformer is lower than
%110, the algorithm will be finished.
'''
        if percent_load < 110 and count == len(overload_lines):
    #we want to ensure that whole overloads in transmission lines are lower than the emergency overload
            break
        else:
            continue
```

Figure 13. Python code for our algorithm - Part-II.

Turkish transmission system losses with respect to real data that is from 01.10.2018 which was explained in Section 3. The python program which represents our algorithm is described in Figures 12 and 13.

A new transmission line can be made parallel to the overloaded ETL instead of the PST considered in this study. However, the feasibility of this method is discussed because the related route is in the province of Bursa. Alternatively, a direct line can be drawn from Bandırma to Bursa. Figures 14a and 14b show the comparison of the new line and the PST for the base case and the N-1 case. As can be seen, overloading can be prevented by creating a parallel corridor. Normally, the active power loss of the Turkey transmission system on 10.01.2018 has been calculated as 745.5 MW and if a Bandırma NG–Bursa Industry transmission line is added, the active power loss will be 727.4 MW. Provided that PST is added in the transmission system, the active power loss will change via the tap which changes the angle of PST. In this situation, the active power loss will be 748.9 MW in the first tap, will be 761.4 MW in tap eleven which is chosen as the most suitable angle and will be 779.5 MW in the last tap.



(a) Base case. (b) N-1 case.

Figure 14. Comparison of new line and PST (in %).

When the power flows are examined, it is seen that the transfer capacity in Corridor-2 cannot be used effectively. Thus, increasing the transfer capacity of existing Corridor-2 is the only choice before installing a new ETL. Therefore, the problem can be solved with less cost and time. To prove that, the capacity of Corridor-2 has been increased with PST without installing a new ETL. Base case and N-1 case loads of 400 kV Bursa NGCCPP–Bursa Industry ETL was in the interval limit by using Corridor-2 when there was no wind production.

5. Conclusion

With recent changes in Turkey's power system, wind energy has become very important because of the fluctuating generation. The grid operators are making a serious effort for maintaining their system secure. The variable energy flows and lack of energy transmission line investment require new solutions. One of these new solutions can be to use PST as we did in this paper. This paper presents a mathematical model based on linear programming for minimization of real power losses that are caused by the PST. Firstly, the location of PST is determined with the aim of alleviating congestion and ensuring N-1 security criterion. After the location of the PST is determined, the worst N-1 cases on 01.10.2018 at 9 AM are selected to reduce computational complexity. Secondly, the angle of PST is properly determined through a linear mathematical model which has been presented in this paper. The results indicate that the PST angle that is adjusted properly can reduce the cost.

PST is a convenient way of using the transfer capacity of existing ETLs instead of adding extra ETLs. Although the investment cost of a conventional PST is high, the maintenance costs are very low. Therefore, using PST instead of installing a new ETL can provide more benefits in terms of time and cost. However, the economic side of PST investment has to be taken into consideration. Because the investment cost of the PST is very high at bulk power. Establishing a new line with an appropriate route can be an alternative to PST with a lower cost. PST can provide more advantages when the areas to be expropriated, investment and operating costs, and project completion times are taken into consideration.

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