OPTIMAL PLACEMENT OF PHASE-SHIFTING TRANSFORMER FOR ACTIVE POWER FLOW CONTROL USING GENETIC ALGORITHMS

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In this paper, the authors propose a methodology for optimal placement of a phase shifting transformer (PST) in a power system to improve the static stability reserves. A genetic algorithms (GA) based optimization model was developed to determine the best location (PST is installed in series with a transmission line) and the tap position, then, depending on the solution resulted, the PST rating is chosen. An adapted version of the GA tool from Matlab was used, while all other functions were coded by the authors. The simulations were performed on a modified version of the CIGRE Nordic32 test power system.

Keywords: phase shifting transformer, genetic algorithms, power system security

1. Introduction

The power systems are currently facing major challenges following the development of the electricity market and the increasing share of generation from intermittent renewable energy sources. In interconnected power systems, the system operators have to take adequate countermeasures to unexpected events, which may lead to network overloading on some corridors [1], [2], [3].

The straightforward solution to alleviate the network congestions is to construct new transmission lines, solution difficult to implement due to socio-ecological concerns about new overhead lines and the prohibitive costs for land utilization. Therefore, the best available solution is to install power flow controllers in order to enhance the power transmission capability of the already existing lines [4]. The first choice is the phase-shifting transformer, as it is the cheapest power controller and performs satisfactorily under steady-state conditions.

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Various operating problems are experienced by power systems across Europe due to the development of wind generation especially in the North Sea. For instance, since large loads are located in South Germany, the power produced by offshore wind farms does not follow a straight line but flows on the lower impedance path through the Polish and Czech power systems. A phase shifter was installed in 2005 in the 400-kV substation of Nosovice (Czech Republic) to control the active power flows between the Czech and Polish power systems [5]. Installation of phase shifters is planned in the coming years on the two connections between the Polish power system and 50 Hertz (one of the four German TSOs) that are Mikulowa (PL) – Hagenwerder (DE) 400 kV and Krajnik (PL) – Vierraden (DE) 220 kV transmission lines. Both are double-circuit lines, and PSTs will be installed on every transmission line circuit, once the latter is switched to 400 kV [5], [6], [7].

2. The theory of phase shifting transformers

The phase shifting transformer (PST) is a particular transformer type that is connected in series with an electrical line and has the role to control the active power flow. Let us assume that the line is connected between any nodes *i* and *j*. In order to connect the PST in series with the electrical line, an additional node *k* is created. Therefore, connecting the PST between the nodes *i* and *k*, the line will then be connected between the nodes *k* and *j*. The one-line diagram of these representations is illustrated in Figs. 1*a* and 1*b*.

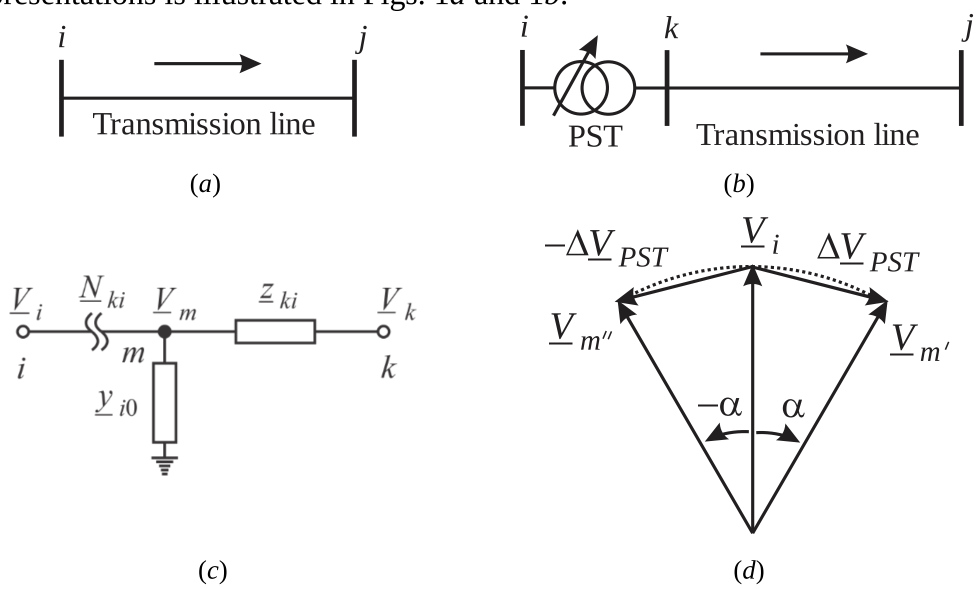

Fig. 1. (*a*) One-line diagram of an electrical line; (*b*) One-line diagram of a PST installed in series with an electrical line; (*c*) the equivalent Γ circuit of a transformer with a complex turns ratio for PST modelling (*d*) the PST voltage phasor diagram [4], [8].

The PST is modelled using the Γ equivalent circuit (Fig. 1*c*), with complex transformer turns ratio, $\underline{N}_{ki}$, given by

$$\underline{N}_{ki} = \frac{\underline{V}_m}{\underline{V}_i} = N_{ki} \cdot e^{\pm j\alpha} \tag{1}$$

In the present work, only the symmetrical PST is considered, which assumes that the output voltage phasor $\underline{V}_m$ is shifted by an angle α with respect to the input voltage phasor $\underline{V}_i$, while maintaining constant the magnitude (Fig. 1*d*). Under these circumstances we have assumed in equation (1) that $N_{ki} = 1$, and the inserted voltage is $\Delta\underline{V}_{PST}$.

The PST is also modelled by a series impedance $\underline{z}_{ik}$, that causes a small voltage to drop between nodes *i* and *k*. For this reason, the magnitude of the voltage phasor $\underline{V}_k$ is not equal to the magnitude of the voltage phasor $\underline{V}_i$.

The PST controls the phase angle shift α by changing the actual operating tap position. For the PST considered in this study the middle tap position is zero, while the operating tap can be selected between the minimum, $n_t^{\min}$, and maximum, $n_t^{\max}$, positions. The phase angle shift α is zero when the PST is set on the middle tap, and it changes by one degree when switched between two consecutive tap positions.

The PST controls the active power flow through the electrical line by controlling the phase angle shift ±α. The apparent power flow through the PST is determined using the Γ equivalent circuit from Fig. 1*c*, that is:

$$\underline{S}_{ik} = V_i^2 N_{ki}^2 \underline{y}_{i0}^* + \underline{V}_i \left[\left(\underline{V}_k - \underline{N}_{ki} \underline{V}_i \right) \cdot \underline{Y}_{ik} \right]^* \tag{2}$$

$$\underline{S}_{ki} = \underline{V}_k \left[\left(\underline{V}_i - \frac{\underline{V}_k}{\underline{N}_{ki}} \right) \cdot \underline{Y}_{ki} \right]^* \tag{3}$$

where $\underline{Y}_{ik}$ and $\underline{Y}_{ki}$ are the corresponding terms that form the nodal admittance matrix, and $\underline{y}_{i0}$ is the transformer shunt admittance.

3. Formulation of the optimization problem

Let us consider an electrical power system consisting of n_N nodes and n_B branches, out of which n_L are electrical lines and n_T are two-winding transformers. 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 aim of our work is to determine the optimal location and size of the PST. For this purpose, we have developed an optimization model based on genetic algorithms, aiming at minimizing the branch loadings all over the power system, while maintaining the nodal voltages and branch loadings within their admissible limits. The control variables are grouped into a vector

$$x = \begin{bmatrix} x_1 & x_2 \end{bmatrix} \quad (4)$$

where x_1 is the PST location (the index of the electrical line that the PST will be inserted on) and x_2 is the actual operating tap position of the PST. It should be mentioned that both variables x_1 and x_2 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 $P_L(x)$ [9], [10]. The optimization problem is thereby formulated as

$$\min F(x) = \left[\sum_{br=1}^{n_B} \gamma_{br}^2(x) \right] \cdot P_V(x) \cdot P_L(x) \quad (5)$$

subject to:

$$\begin{cases} 1 \le x_1 \le n_L^{\max} \\ n_t^{\min} \le x_2 \le n_t^{\max} \end{cases} \quad (6)$$

In order to reduce the computation time, a network pre-analysis is performed while the worst scenarios are identified. Therefore, the candidate line for the PST position, x_1, is chosen from a list of $n_L^{\max}$ selected lines. The PST tap position x_2 is set to take any integer value between $n_t^{\min}$ and $n_t^{\max}$.

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

$$\gamma_{br} = \frac{S_{br}(x)}{S_{br}^{adm}} \quad (7)$$

In equation (7), when two parallel line circuits or two parallel transformers form the branch, the total rating of the branch is considered.

The penalty functions $P_V(x)$ and $P_L(x)$ from equation (5) have the purpose of increasing the value of the objective function $F(x)$ if the static security operating conditions are not satisfied.

The penalty function $P_V(x)$ penalizes the x candidate solution if there is at least one nodal voltage that exceeds the admissible upper, $V_k^{\max}$, or lower, $V_k^{\min}$, voltage limits.

$$P_V(x) = \begin{cases} 1 \quad \text{if } V_k^{\min} \le V_k \le V_k^{\max} \ , \ \forall\ k = \overline{1, n_N} \\ 10 \text{ otherwise} \end{cases} \tag{8}$$

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, γ_{br}^{adm}. For security reasons, as also used in practice, the threshold γ_{br}^{adm} is lower than 100% [10].

$$P_L(x) = \begin{cases} 1 \text{ if } \gamma_{br} \le \gamma_{br}^{adm} \ \forall\ br = \overline{1, n_B} \\ \prod_{br \in \gamma} 2^{\gamma_{br}} \ \text{ where } \gamma = \left\{ br \middle| \gamma_{br} \ge \gamma_{br}^{adm} \right\} \text{ otherwise} \end{cases} \tag{9}$$

4. The simulation algorithm

In order to solve the optimization problem, a genetic algorithm (GA) was developed. The GA are evolutionary calculation methods that mimic the natural evolution process and genetics [11], [12]. The steps performed are as follows [13]:

Step 1. Generate an initial population composed of randomly created *individuals*
Step 2. Create a new *generation*:
- 2.1. *Evaluate* all the individuals in the current population
- 2.2. *Select* the individuals that will be the “parents” for the future generation
- 2.3. The best individuals will pass over unmodified in the next generation
- 2.4. Create children using *crossover* and *mutation*
- 2.5. Replace the parents with the generated children in order to form the *new population*

Step 3. Repeat the second step until a stopping criterion is met

All the results presented in this paper are generated in Matlab, using a set of functions and scripts created by the authors, and the Matlab genetic algorithm toolbox, namely the default *ga* function.

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 $x = [x_1 \ \ x_2]$. The flowchart for the evaluation of the objective function is shown in Fig. 2.

The power system data is first read. Then, the settings (PST position and tap) for the current individual are applied to adjust the power system data using the function Add_{PST} (x_1, x_2). For this individual, the load flow is calculated by using a function f_{LF}, which employs the Newton-Raphson method. The objective function value y_{obj} is then determined, while the two penalty functions P_V and P_L described in equations (9) and (10) are applied. In the case of load flow calculation divergence, an additional penalty function is applied, which consists in multiplying the objective function value by 10^4. Finally, the algorithm returns the value y_{obj} for the current individual x.

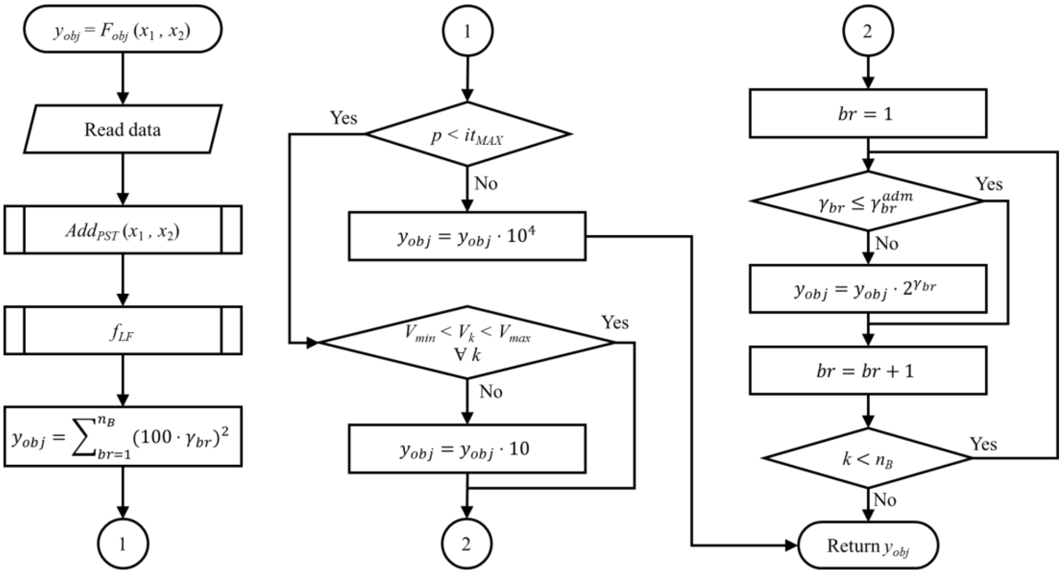

Fig. 2. The flowchart for evaluation of the objective function $F_{obj}(x_1\ x_2)$.

Another customization added by the authors in the genetic algorithm is a new mutation function. The mutation operator is responsible for population diversity; therefore, it ensures that the GA does not get jammed on a local minimum of the objective function. In the Matlab GA toolbox, several mutation functions are implemented, but in this particular case a more aggressive mutation is required in order to create a diversified population. For this reason, the authors have created a mutation function that generates two categories of children mutation. The first category consists of children of the best individuals with only one gene randomly modified, while the second consists of randomly generated individuals.

5. Case study and results

Description of the CIGRE Nordic32 test system

The case study presents the optimal PST placement in the CIGRE Nordic32 test power system (Fig. 3), aiming at demonstrating that in some specific cases construction of new transmission lines can be avoided. This test system was chosen because it is a representation of a real power system (Swedish power system) [14], and its operating conditions reflects some limitations in terms of voltage level and network loading [15].

The system consists of 32 nodes, out of which 12 are PQ nodes and the other 20 are PV type nodes (at one bus a synchronous compensator is connected). The system is divided into 4 zones: North, South, Central and External. The Nordic32 system includes three voltage levels: 400 kV (19 buses), 220 kV (2 buses) and 130 kV (11 buses). The system also consists of 37 transmission lines (27 at 400 kV, one at 220 kV, and 9 lines at 130 kV) and 6 transformers.

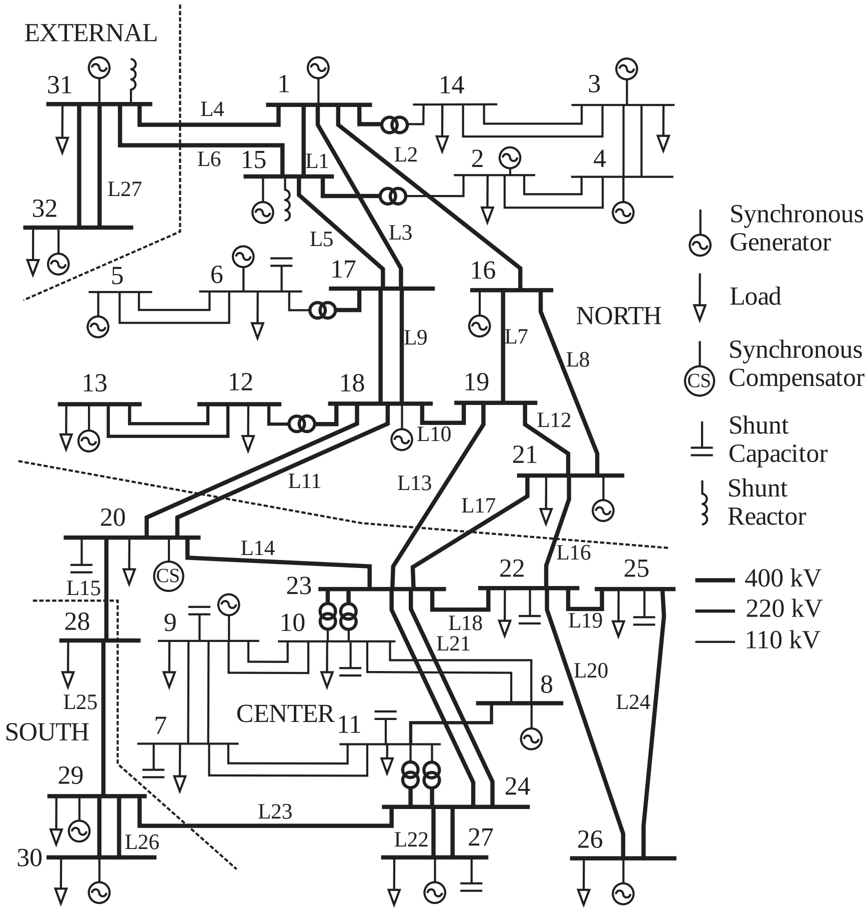

Fig. 3. Equivalent one-line diagram of the CIGRE Nordic32 power system [14].

Series compensation devices are installed on all the four interconnection transmission lines between the North and Central zones. Also, 11 shunt compensation devices are installed, out of which 9 capacitor banks and 2 reactors.

Scenario assumptions

Two different generation-load scenarios have been defined:

S0) *The base case scenario*, characterized by an important power flow from the Northern zone (which generates an important amount of active power) towards the Southern and Central zones where important loads are concentrated. In this scenario, no network overloading is identified.

S1) *The heavy load scenario*, developed by the authors from the base case scenario. In order to increase the active power flow on the Northern-Central interconnection transmission lines, the load was increased in the Southern and Central zones, while the generated active power was increased only in the Northern.

Variables setting

Considering the configuration of the Nordic32 test power system, the candidate locations for installing the PST are the 400 kV transmission lines only. As shown in Fig. 3, there are 27 such lines, and thus the variable x_1 will take values between 1 and 27.

The range for the variable x_2 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. Assuming that the switching between two consecutive tap positions will result in the variation of the phase angle shift α by 1°, the PST will be able to set the phase angle shift α between the –30° and +30°.

In order to limit the transmission lines loading below a threshold lower than 100%, γ_{br}^{adm} from the expression of the penalty function P_L from equation (10) is set to 75%. This threshold was imposed in order to achieve at least one solution in the case of scenario S0. In consequence, the GA will determine a solution for which all the line loadings are below γ_{br}^{adm} = 75%, thus improving the static security of the power system.

The PST is dimensioned in terms of the rating of the transmission line that result as optimal solution. Thus, the MVA rating of the PST will be higher than the line rating, while its value is chosen from a list of standard data. If a double-circuit line will result as the optimal solution, then two parallel identical PSTs are considered. Additionally, the PST series impedance is calculated accordingly.

Simulation results

Scenario S0. The optimal solution for this scenario is $x^* = [x_1^* = 10, x_2^* = 14]$, for which the objective function value is y_{obj}^* = 69.669. The electrical line corresponding to the index x_1^* = 10 is the line connected between buses 18 and 19 (Fig. 3).

The load flow results, for both the initial case – without the PST – and the case with the PST installed according to the optimal solution, are presented in Fig. 4. Note that this Fig. illustrates only the 400 kV buses and transmission lines. The main purpose of this specific graphical representation is to facilitate highlighting the differences created after the PST is introduced. For this purpose, the textboxes attached to the buses contain the bus number and the bus voltages (in p.u.); the first voltage value corresponds to the case without PST, and the second value is for the case with PST. Also, the values attached to the transmission lines represent the line loading (in percentage) before (the left side value) and after (the right-side value) installation of the PST.

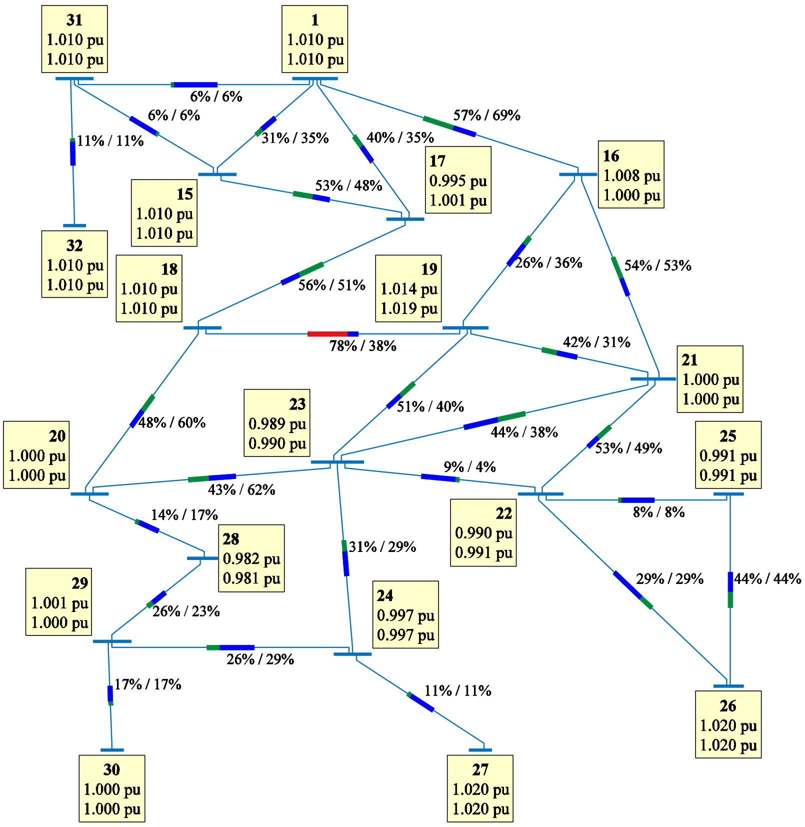

Fig. 4. Comparison of the load flow results for the 400-kV network in the S0 scenario, before and after installation of the PST.

It can be seen that the PST is installed in series with the heaviest loaded line, and that it reduces this line loading from 78% to 37%. This will result in the increase in the active power losses by 3.3%.

The influence of the PST on the bus voltages is very low since the voltage was changed for seven buses only, the greatest difference being 0.008 p.u. at bus 16. This can be explained by the fact that the Nordic32 network is provided with many generators, capable of controlling the voltage level.

Scenario S1. The optimal solution is $x^* = [\,x_1^* = 10,\; x_2^* = 23]$, for which the objective function value is y_{obj}^* = 88.450. As in the previous scenario, the PST is connected in series with the line 18-19. Fig. 5 illustrates a graphical comparison between the load flow results before and after the PST installation, using the same legend as in Fig. 4.

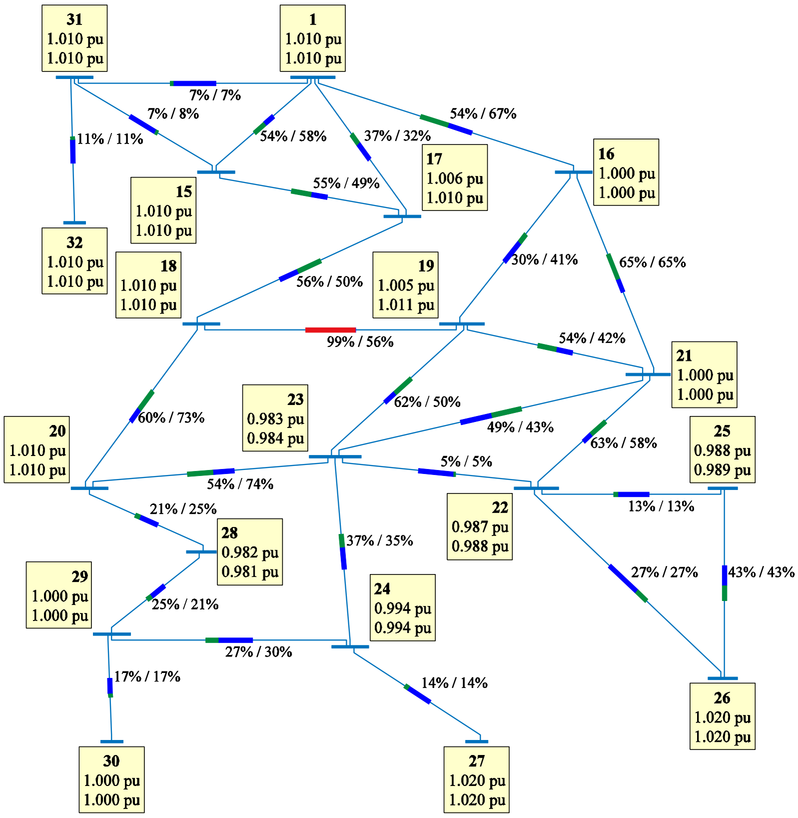

Fig. 5. Comparison of the load flow results for the 400-kV network in the S1 scenario, before and after installation of the PST

In this case, it can be noticed that the PST is installed in series with the heaviest loaded transmission line (very close to its MVA rating). The PST reduces the load on the controlled line from 99% to 56% while all the other transmission lines are loaded below 75%. Also, the PST influence on the nodal voltages is again reduced, the largest difference being 0.006 p.u. at bus 19 and the active power losses increase by 6.5%.

The PST Characteristics. The PST is considered to be installed in series with the transmission line L10 (the optimal location found on both scenarios) and its active power (P_{PST}) –tap position (n_{tap}) characteristics are generated by repeating the load flow calculation for every tap. Fig. 6 shows the characteristics for the two scenarios. It can be observed that the L10 line MVA rating is exceeded for taps lower than –14 in S0, respectively –5 in S1, whereas for tap positions greater than 24 the load flow calculation is no longer convergent.

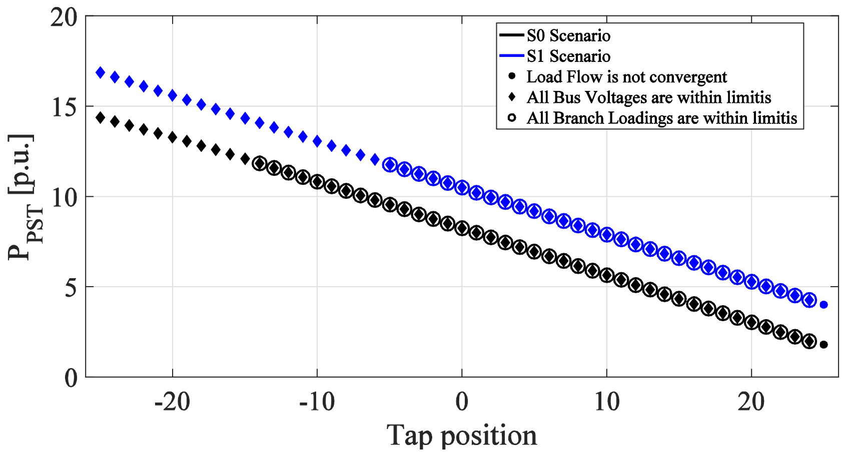

Fig. 6. PST active power – operating tap characteristics for the two considered scenarios.

6. Conclusions

The purpose of this paper was to show the opportunity of using a phase-shifting transformer to alleviate the risk for network overloading. A study has been done on the CIGRE Nordic 32 network to explain the effectiveness of the PST device for particular cases. For this purpose, we have developed a genetic algorithm based mathematical model to identify the optimal location and the optimal PST characteristics, while meeting the network security constraints.

Based on the results achieved by simulation, the following conclusions have been drawn:

- 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.
- For most of the PSTs installed in the world, a wide range of control is considered by using a large number of taps for both increasing and decreasing directions. Since the PST is a mechanical device, the tap position should be set to deal with many scenarios. For this reason, in reality only few taps are used.
- 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.

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