# Phase Shifting Transformers in an Efficient Power Flow Control Method

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**Abstract:** A fast and efficient power flow control method incorporating the automatic adjustment of Phase Shifting Transformers (PSTs) for specified line flows is presented. The effects of a PST are represented by the power-injection model and the corresponding extension of the conventional load flow equations is made. The load flow control by means of PST is modeled by appropriate additional equations. A special fast decoupled algorithm is developed for the solution of the power flow control problem. The high numerical efficiency and simplicity of the fast decoupled algorithm employed is demonstrated on cases of the present state of interconnections in the Balkan Electric Power Systems (EPSs) which are operating as an island with respect to UCPTE.

**Keywords**: Efficient Power Flow Control, Phase Shifting Transformers, Fast Decoupled Algorithm, FACTS

## 1 Introduction

Flexible AC Transmission Systems (FACTS) include a wide range of power electronic controllers which are used to enhance the flexibility of power transmission in Electric Power Systems (EPSs) by, for example, improving the transfer capability of transmission networks, while at the same time, maintaining acceptable levels of reliability and stability [1], [2].

This paper considers the static Phase Shifting Transformer (PST) as a means to control power flow in the EPS without generation rescheduling or topological changes. This is of practical interest nowadays due to the increased loading of EPSs, the consequences of EPS deregulation and open access to transmission grids, as well as due to planning and cost considerations.

In the past, several techniques have been proposed for the adjustment of the phase angle of PST. References [3] to [8] are only few from the long list of published work in this area. In the present paper, which is the continuation of the author's previous papers [9] and [10], we concentrate in presenting an efficient power flow control method, the method for automatic adjustment of a PST aiming to reach the desired line flows. The PST is represented by the well known phase shifter injection model [7]. A simple and reliable fast decoupled load flow algorithm is developed for the numerical solution of the power flow control problem. This fast decoupled load flow has low memory requirements due to the symmetry of the corresponding coefficient matrices. The efficiency of the proposed method is shown in the case of the interconnected EPSs of Balkan countries.

## 2 Formulation of the Power Flow Control Method

### 2.1 General

The general mathematical formulation of the power flow control problem under consideration can be expressed as follows: Find the vector of control variables (i.e. the phase shifter angles φ): **u** which satisfies the following two systems of equations:

$$\mathbf{F}(\mathbf{x},\mathbf{u})=\mathbf{F}^{sp} \qquad (1)$$

$$\mathbf{G}(\mathbf{x},\mathbf{u},\mathbf{d})=0 \qquad (2)$$

with: $\mathbf{u}\in\mathbf{U}$

where **x** is the state vector, **d** is the vector of demand variables, and **U** is the set of permissible values for the vector of control variables (: $-30°\text{electrical}<\varphi<30°\text{el}$). The controlled active power flows on line elements with PST are modeled by equations (1), where $\mathbf{F}^{sp}$ is the vector of specified line flows, while, the power system stationary state is modeled by conventional nodal power flow equations (2).

### 2.2 Phase Shifter Injection Model

In [3,4] the simplified phase shifter injection models (only active power injections) are given, in [5,6,7] the reactive injections are taken into account, but, in all those models the conductance of line elements with PST are neglected. However, if higher accuracy of calculation is required, the conductance of line elements must be taken into account. For these conditions, the following equations represent the effects of PST which is installed in the beginning of the branch «k-m» [11]:

$$P_{ck}=-g_{km}V_k^2\tan^2\varphi-g_{km}V_kV_m\tan\varphi\sin\theta_{km}+b_{km}V_kV_m\tan\varphi\cos\theta_{km} \qquad (3)$$

$$Q_{ck}=g_{km}V_kV_m\tan\varphi\cos\theta_{km}+b_{km}V_k^2\tan^2\varphi+b_{km}V_kV_m\tan\varphi.\sin\theta_{km} \qquad (4)$$

$$P_{cm}=-g_{km}V_kV_m\tan\varphi\sin\theta_{km}-b_{km}V_kV_m\tan\varphi\sin\theta_{km} \qquad (5)$$

$$Q_{cm}=-g_{km}V_kV_m\tan\varphi\cos\theta_{km}+b_{km}V_kV_m\tan\varphi\sin\theta_{km} \qquad (6)$$

where: $k,m\in$ set of all nodes of lines with PST, g,b are the conductance and susceptance respectively of the line elements, φ is the phase shifter angle, θ is the phase-angle difference between voltage phasors.

Thus, the presence of PST on element «k-m» can be simulated by increasing the power injections at the buses «k» and «m», so that generally speaking, the PST injection model retains the symmetry of the $Y_{bus}$ matrix which is very important for the numerical computation as well as memory requirements.

Furthermore, the actual value of real power flow through the line element «k-m» with PST can be expressed as follows:

$$P_{ckm} = g_{km} t^2 V_k^2 - t V_k V_m [g_{km} \cos(\theta_{km}+\varphi) + b_{km} \sin(\theta_{km}+\varphi)] \quad (7)$$

where, same as above, k, m belong to the set of all nodes of lines with PST.

## 2.3 The Power Flow Control Formulation

The Newton-Raphson load flow method [12] is considered as first step, then inspired by subsequent advances [13] the Fast Decoupled Load Flow, contained in standard textbooks [14], is formulated in two matrix equations:

$$[\Delta P/V] = [B'][\Delta\theta] \quad (8)$$

$$[\Delta Q/V] = [B''][\Delta V] \quad (9)$$

where, the matrices B′ and B′′ are real and of order (N-1) and (N-NG) respectively, N is the total number of busbars and NG is the number of generator (or «PV») busbars.

According to the general form of the control problem under consideration herein, given by (1) and (2), and according to the PST injection model in 2.2 above, assuming that a specified number (=NCL) of line flows are controlled by PSTs, we increase the order of the matrix equation (8) by NCL to incorporate the PSTs and satisfy the constraints of the controlled line flows, and arrive at the matrix formulation:

$$[\Delta P/V] = [B_{\theta\varphi}][\Delta\theta, \Delta\varphi]^T \quad (10)$$

$$[\Delta Q/V] = [B''][\Delta V]$$

where the matrix $B_{\theta\varphi}$ is of order (N-1+NCL).

This method of numerical solution is simpler than the recent approach based on Newton-type algorithm [8] and yet the simplifications herein have not compromised the efficiency of the method, i.e. its very good convergence which is demonstrated by the applications.

## 3 Application Cases and Results

The first practical experiences in the application of the developed method have been gained on the case of the synchronous parallel operation of the EPSs of Yugoslavia (YU), Romania (RO), Bulgaria (BG), former Yugoslavian Republic of Macedonia (FYRoM), Greece (GR), and Albania (AL), on the basis of data given in a recent study [15]. Thus, we have analyzed the present state of interconnection in the Balkans which is operating as an «island» with respect to the UCPTE interconnected network.

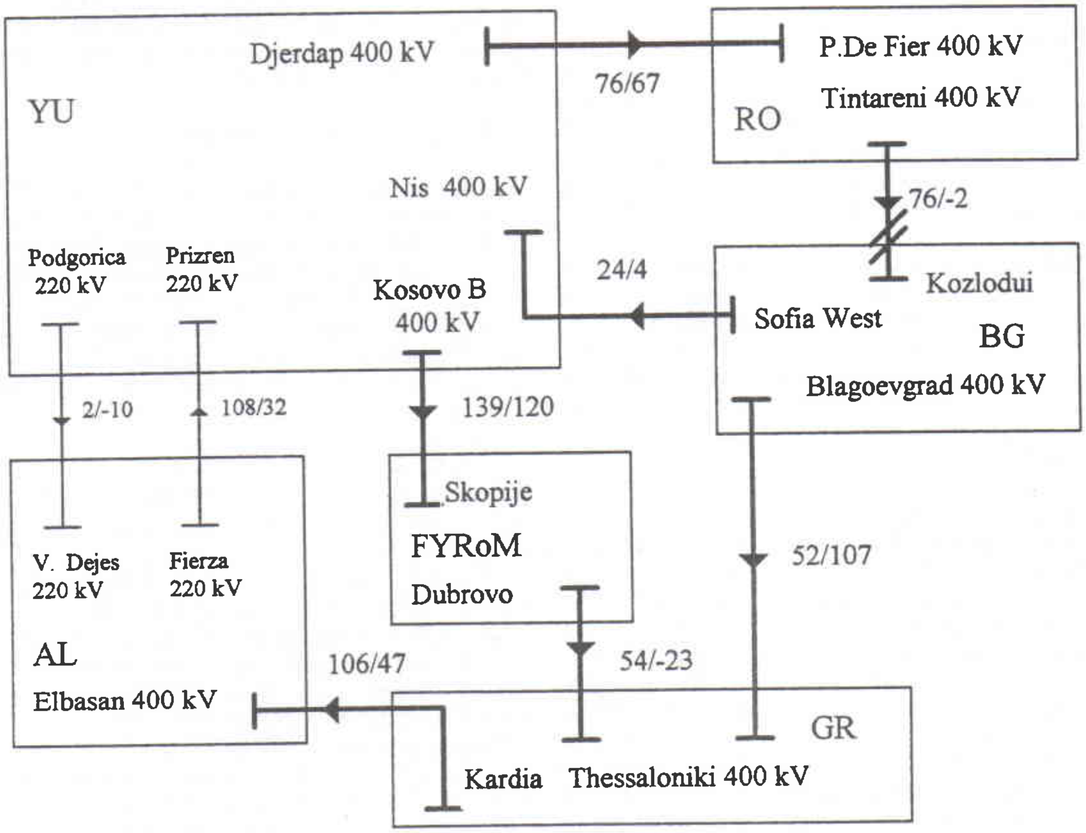

Figure 1: Active and reactive power flows in interconnecting lines

Figure 1 shows the block diagram of the examined interconnected network with active and reactive power flows (in MW/Mvar) indicated on the interconnecting lines, in the case of «zero exchange program» i.e. when there is no programmed power exchange between the interconnected EPSs. In other words, in Fig.1 the active power flows represent the ring power flows.

First, we have considered the elimination of ring power flow GR→AL→YU with PSTs installed on the Albanian side buses of lines Fierza-Prizren (220 kV) and Elbasan-Kardia (400 kV). The specified active power flows are set to zero. Equations (10) converge after only 5 iterations and result in adjusting the phase shifter angles to -8.792°el and 8.981°el respectively. The same elimination of ring power flow GR→AL→YU can be achieved with the use of only the second of the two PSTs, namely the one at beginning of the 400 kV line Elbasan-Kardia, setting the specified active power flows to zero, equations (10) converge after only 5 iterations and result in adjusting the phase shifter angle to 13.427°el. If the elimination of ring power flow YU→RO→BG is sought, then a PST is installed at the beginning of the 400 kV line Djerdap-Portile De Fier and the specified active power flow is set to zero. Equations (10) converge after only 5 iterations and result in adjusting the phase shifter angle to -3.353°el.

Next, consider the case of a scheduled power export of 600 MW from the EPS of Romania to the EPS of Greece. We can redirect this power export at will, using PSTs installed at the beginning of the 400-kV lines Dubrovo-Thessaloniki (see Fig. 1) and Thessaloniki-Blagoevgrad. For example, we can specify the active power flows in these 400-kV lines as 200 MW, and -400 MW respectively, equations (10) converge after only 5 iterations and result in adjusting the phase shifter angles to -3.248°el, and 2.079°el respectively. The same PSTs can redirect power flows in the case of scheduled power export of 800 MW from the EPS of Greece to the EPS of Yugoslavia. For example, we can specify the active power flows in last mentioned 400-kV lines as equal to 300 MW each, equations (10) converge after only 5 iterations and result in adjusting the phase shifter angles to -8.921°el, and 4.691°el respectively.

Finally, consider again the case of scheduled power export of 800 MW from the EPS of Greece to the EPS of Yugoslavia, but with the 400-kV line Thessaloniki-Blagoevgrad tripped. We can redirect this power export at will, using a PST installed at the beginning of the 400-kV line Elbasan-Kardia. For example, we can specify the active power flow in the last mentioned line as equal to -250 MW, equations (10) converge after only 5 iterations and result in adjusting the phase shifter angle to 11.255°el.

In all above cases, the convergence criteria for power-mismatches were:

$$|\Delta P| \leq 0.01\mathrm{MW} \qquad (11)$$
$$|\Delta Q| < 0.05\ \mathrm{Mvar}$$

The total number of busbars are N = 240 of which the generator busbars are NG = 56.

## 4 Conclusions

A novel approach to form an efficient decoupled procedure for the automatic adjustment of PST to achieve specified active power flows through certain lines of meshed power systems has been presented. The initial experiences in the practical application of the developed method in the interconnected network of EPSs of Balkan countries demonstrate the method's simplicity, high speed and reliable convergence characteristic as well as low memory requirements. According to these characteristics, the proposed method appears to be a suitable tool for the evaluation of all relevant technical effects of installation of PST in interconnections of meshed systems. Continuation of research in this direction is deemed worthwhile.

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