

## An Advanced Method for Active Power Flow Control in Electric Power Interconnections

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**Abstract:** This paper presents an advanced method for active power flow control by use of static phase shifting transformer. It is based on non-standard load-flow model, which enables more accurate evaluation of the relevant technical effects of phase shifting transformer installation. For solution of the power flow control problem defined, the special fast decoupled procedure is developed. The high numerical efficiency and simplicity of this procedure has been established on the example of real interconnection formed by the Electric Power System of Serbia and Montenegro, Romania, Bulgaria, Former Yugoslav Republic of Macedonia, Greece and Albania (ex Second UCTE synchronous zone).

**Keywords:** Advanced method, phase shifting transformer, series FACTS controller, power flow control, real interconnection.

### 1 Introduction

An important problem in modern Electric Power Systems (EPSs) is the provision of the necessary level of operational security. In recent years, the increased practical interest to this problem and corresponding new challenges are essentially due to increased loading of EPSs, combined with a process of deregulation in electric power market and restructuring of the power utilities.

Also, the processes above mentioned are very important and topical for all countries in Southeast Europe, as well as for Serbia and Montenegro and its power industry, according to the following facts:

- *Reconnection the Second UCTE synchronous zone with the main part of the UCTE grid.*

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The Second UCTE synchronous zone was disconnected from the main UCTE grid since 1992, due to war consequences in former SFR Yugoslavia. Since then, there are only periodical island operations between the parts of these zones. The present Second UCTE synchronous zone is consisted of the networks of Albania (AL), Bosnia-Herzegovina (eastern part, RS), Bulgaria (BG), FYR Macedonia (MK), Greece (GR), Romania (RO), Serbia and Montenegro (SCG). The reconnection of the Second zone with the main UCTE grid is successfully made in 10 October 2004 [1].

• *Establishment of Regional Electricity Market*

According to the Memorandum of Understanding [2], all the countries from South-east European region agreed upon the constitution of a competitive Regional Electricity Market (REM) in Southeast Europe. The proposed time period for creation of regional electricity market is last up to year 2006.

Open access power systems need accurate transmission capacities evaluation to guarantee secure operation for all transactions. In other words, electric power markets need to know how much power can be transferred between certain points, e.g. to know the real technical limitations of these power exchanges due to the set of various network constrains.

In this context, the evaluation of cross-border transmission capacity [3, 4], as well as the congestion forecast and congestion management have a great practical importance [5, 6].

It is well known that acronym FACTS [7, 8] has been adopted to describe a wide range of power electronic based controllers, which are capable to increase the flexibility of EPS's. In other words, to improve the transfer capability of transmission networks, while, at the same time, maintain acceptable level of reliability and stability. The increased practical interest for these controllers is essentially due to above mentioned increased loading of EPSs, combined with a process of liberalization in electric power market, as well as to the actual trend in forming of acceptable cost of these components.

This paper deals with the static Phase Shifting Transformer (PST), which belongs to category of series FACTS controllers, which have the possibility of controlling power flow in the EPS's. In [9], which related to the European practice, for increasing the transfer capacity on critical lines, e.g. to eliminate the congestions, the application of series FACTS controllers (as so call "soft measures", with relatively small investments) is recommended.

In the past, several techniques have been proposed for the adjustment of phase angle of PST. References [10–15] are only few from the long list of published work in this area. In many papers is pointed out that the application of FACTS controllers is practically made without generation rescheduling, except the minimal changes, caused by the differences in power losses, se appeared by the change in power flow.

However, in conditions of open access electricity market and consequently, evaluation of energy efficiency in transmission systems, where all relevant technical effects are evaluated, and further valorise, arises the important question how to make a more accurate evaluation of relevant technical effects of installation of PST, as a good base for further techno-economical analysis? In other words, it is necessary, inter alia, to make a more accurate evaluation of losses changes, as well as to make a more accurate security assessments, specially in cases of big injection losses (big production unit tripping).

It is evidently that the classical load-flow model (existence one reference node, which at the same time play role of slack bus) for this purpose is not convinced. The main reason for this is the facts that all the changes (including the active power losses changes) are located to the only one generator (slack) node, what are opposites of the real operation practice.

In this paper an efficient power flow control method, e.g. the method for automatic adjustment of a PST to reach the specified line flows is presented. It is based on non-standard load-flow model, which enables more accurate evaluation of the relevant technical effects. The effects of PST are represented by corresponding injection model, with respecting the conductance of elements with PST. For solution of power flow control problem defined, a simple fast and reliable decoupled procedure is developed, with evidentially low memory requirements, according to the symmetry property of corresponding coefficient sub matrices. The efficiency of method developed has been demonstrated on the example of existing electric power interconnection in the Balkans (ex Second UCTE synchronous zone).

## 2 Formulation of Advanced Power Control Method

### 2.1 Generally

The general mathematical formulation of control problem considered is to found control vector  $u$ , which satisfy the following two systems of equations

$$\mathbf{F}(\mathbf{x}, \mathbf{u}) = \mathbf{F}^{SP} \quad (1)$$

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

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

where  $x$  is the state vector,  $u$  is the vector of control variables (i.e. the phase shifter angles  $\phi$ ) in region of permissible values  $U$  ( $-30^\circ < \phi < 30^\circ$ ) and  $d$  is the vector of so called demand variables.

The controlled active power flows on elements with PST are modelled by equations of form (1) (FSP is the vector of specified line flows). The equations of form (2) represent the power system stationary state.

## 2.2 Phase shifter injection model

The simplified phase shifter injection models (only active power injections) are given in [10, 11]. In [12–14], the extension of this model are given i.e. the reactive injections are taken into account, but in all of above mentioned approaches, the conductance of elements with PST are neglected. However, if the high accuracy of calculation is required, the conductance of elements (especially for relatively short lines) must be taken into account. For these conditions, the following equations represent the effects of PST, which is installed, on the beginning of element  $k - m$  [16]

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

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

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

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

$$k, m \in NC$$

where  $NC$  is set of all terminal nodes of lines with PST,  $g_{km}$  and  $b_{km}$  are conductance and susceptance of the element  $k - m$ ,  $\phi$  is phase shifter transformer angle,  $\underline{t}$  is complex tap of PST:  $\underline{t} = te^{j\phi}$ , where  $t = 1/\cos \phi$ ,  $\theta_{km}$  is phase angle difference between voltage phasors  $\underline{V}_k$  and  $\underline{V}_m$ .

Thus, the presence of PST on element  $k - m$  can be simulated by increasing the injections at the terminal buses  $k$  and  $m$ . In other words, the PST injection model retains the symmetry property of  $Y_{bus}$  matrix, which is evidently very important for the practical computation, as well as for memory requirement aspects.

Next, in this context, the actual value of active power flow  $P_{ckm}$  on element (line)  $k - m$  with PST can be expressed as

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

$$k, m \in NC$$

## 2.3 The power flow control formulation

According to the general form of control problem considered, given by equations (1) and (2), and according to the PST injection model given before, the following

balance equations are actual

$$\Delta P_{ci} = P_{ci}^{SP} - P_{ckm} = 0; \quad i \in NCL, \quad k, m \in NC \quad (8)$$

$$\Delta P_i = P_{GOi} - k_{pi} \delta f - P_i = 0, \quad i \in NG \quad (9)$$

$$\Delta Q_i = Q_{GOi} + Q_{GOi} \frac{V_{GOi} - V_{Gi}}{s_{Vi} V_{GOi}} - Q_i, \quad i \in NSV \quad (10)$$

$$\Delta P_i = P_{Gi} - P_{Li}(V_{i,f}) - P_i = 0 \quad (11)$$

$$\Delta Q_i = Q_{Gi} - Q_{Li}(V_{i,f}) - Q_i = 0; \quad i \in N/NC \quad (12)$$

$$\Delta P_i^C = P_L(V_{i,f}) - P_i - P_{ci} = 0 \quad (13)$$

$$\Delta Q_i^C = Q_{Li}(V_{i,f}) - Q_i - Q_{ci} = 0; \quad i \in NC \quad (14)$$

which satisfy the following constraints

$$P_{Gmini} \leq P_{Gi} \leq P_{Gmaxi}, \quad i \in NG \quad (15)$$

$$Q_{Gmini} \leq Q_{Gi} \leq Q_{Gmaxi}, \quad i \in NG \quad (16)$$

where:

$P_{ci}^{SP}$  - specified line flows;

$N$  - total number (set) of all nodes of the interconnected power system;

$NG$  - total number (set) of generator nodes ( $NG \in N$ );

$NSV$  - number (set) of generators with static voltage-reactive power characteristic ( $NSV \in NG$ );

$NL$  - number (set) of load nodes ( $NL \in N$ ;  $NL = N - NG$ );

$NC$  - total number (set) of all terminal nodes of lines with Phase Shifting Transformer;

$NCL$  - total number (set) of controlled line flows;

$P_{GOi}$  - active power of the  $i$ -th generator in the initial steady-state;

$k_{pi}$  - primary frequency control constant of  $i$ -th generator;

$\Delta f = f - f_0$  - deviation of the quasi-stationary value of frequency  $f$  from its initial value  $f_0$ ;

$Q_{GOi}, V_{GOi}$  - reactive power and voltage at the ends of  $i$ -th generator in the initial steady-state;

$s_{Vi}$  - droop of the static voltage-reactive power characteristic of the  $i$ -th generator;

$P_i, Q_i$  - injected active and reactive power;

$P_L(V_{i,f}), Q_L(V_{i,f})$  - load active and reactive power at node  $i$ , as a complex function of the voltage at its end and the quasi-stationary value of the frequency.

It should be noted that in this case, as opposed to the usual approaches, the upper and lower limits of active and reactive power generation are not constant, *a priori* defined quantities, but rather corresponding functions of relevant state variables [17, 18].

Thus, the power flow control formulation includes nonlinear algebraic equations with *two groups* of following unknown variables:

- vector of control variables -  $\phi$  of dimension  $NCL$
- state vector which contains two subvectors -  $\theta$  and  $V$  of dimensions  $(N - 1)$  and  $(NSV + NL)$  respectively, and *scalar*  $f$ .

In other words, we look for the *control vector*  $\phi$  (within of above mentioned permissible values) in such way that the specified controlled line flows (8) and the load flow equations (9)-(14) are satisfied., strictly respecting the constraints (15) and (16).

According to the approach given in [19], the extension of control model is made, introducing the evaluation of effects of primary frequency control (equations (9)) and primary voltage control (equations (11)).

## 2.4 Solution method

The first step in the development the solution method is the application of the Newton-Rhapson method [20], on the balance equations (8)-(14). Next, inspired by [21], in forming the Jacobian matrix, the similarly justified assumptions and simplifications, resulting from the “physical” nature of the problem, are introduced. Thus, we obtained the following two decoupled linearized systems of equations (naturally, only during one iteration), which are solved successively in accordance with the sub iteration indices  $k$  and  $l$

$$\begin{bmatrix} \Delta P^c \\ \frac{V}{\Delta P^c} \\ \frac{V}{\Delta P^c} \\ \frac{V}{\Delta P^c} \\ \frac{V}{V} \end{bmatrix}^{(k)} = \begin{bmatrix} \mathbf{B}' & \mathbf{B}'_{p\Theta} & \mathbf{F} \\ \mathbf{B}'_{p\Theta} & \mathbf{B}'_{\Phi} & \mathbf{0} \\ \mathbf{B}_r & \mathbf{0} & \Delta(\Delta f) \end{bmatrix} \begin{bmatrix} \Delta \Theta \\ \Delta \Phi \\ \Delta(\Delta f) \end{bmatrix}^{(k+l)} \quad (17)$$

$$\frac{\Delta Q^c}{V}^{(l)} = \mathbf{B}'' \Delta V^{(l+1)} \quad (18)$$

The elements of the all coefficient submatrices  $B'$ ,  $B'_{p\phi}$ ,  $B'_{p\Theta}$ ,  $B'_{\phi}$ ,  $F$ ,  $F_r$  and  $B''$  have the constant values for a given network topology. Submatrices  $B'_{p\theta}$ ,  $B'_{p\phi}$  i  $B'_{\phi}$ , of dimension  $(NCL) \times (N - 1)$ ,  $(N - 1) \times (NCL)$  and  $(NCL) \times (NCL)$ , respectively,

have the following elements

$$\begin{aligned}
 b'_{p\phi ki} &= \frac{1}{x_{km}} & b_{p\Theta mi} &= -\frac{1}{x_{km}} \\
 b'_{p\phi mi} &= -\frac{1}{x_{km}} & b'_{\pi ki} &= \frac{1}{x_{km}} \\
 b'_{p\Theta ki} &= \frac{1}{x_{km}} & & i \in NCL, \quad k, m \in NC
 \end{aligned} \tag{19}$$

where  $x_{km}$  is reactance of the element  $k - m$ .

Next, submatrice  $\mathbf{F}$ , of dimension  $(N - 1) \times 1$  has the following elements

$$\mathbf{F}_i = \begin{cases} K_{pi} & \text{for } i \in NG \\ 0 & \text{for } i \in NL \end{cases} \tag{20}$$

The square submatrice  $\mathbf{B}'$ , of dimension  $(N - 1)$  is identical to the corresponding submatrice in the fast decoupled load flow method [21]. Also, the square submatrice  $\mathbf{B}''$ , of dimension  $(NSV + NL)$ , is identical to the corresponding submatrice in above mentioned method. Only differences are in diagonal elements which correspond to the generators with static voltage-reactive power characteristic (extension for quantity  $Q_{Goi}/(sV_i V_{Goi}^2)$ ).

It should be pointed out, in relation to the approach given in [19], which is based on classical load-flow model, now exist submatrices  $\mathbf{F}$  and  $\mathbf{F}_r$ , which correspond to the quasi-stationary value of frequency  $f$ . Index  $r$  indicates the reference node (chosen arbitrarily), which has the fixed value of angle (usually zero value). However, opposite to the classical load-flow model, where the referent node (introduced due to the same reason elimination of singularity) is at the same time a slack bus, all nodes play role of slack node. In other words, in restore of new steady-state, participate all generator nodes (according to their primary frequency control constants) and all load nodes (according to their complex function of the voltage at its end and the quasi-stationary value of the frequency). This characteristic of advanced method proposed is essential, because enables more accurate evaluation of the relevant technical effects of installation of PST.

Evidently, the solution method developed is simpler than the recent approach based on Newton type algorithm [15], but all the justified simplifications which are introduced in forming the corresponding coefficient matrices have not disturb its efficiency, e.g. its very good convergence, which will be demonstrate in next part of this paper.

### 3 Practical Application of Advanced Method

The first practical experiences in the application of the method developed have been gained on an example of the synchronous parallel operation of the EPS's of Serbia and Montenegro (SCG), Romania (RO), Bulgaria (BG), former Yugoslav Republic of Macedonia (MK), Greece (GR) and Albania (AL) (ex Second UCTE synchronous zone).

All 400 kV and 220 kV networks of SCG (including 110 kV network), RO, BG, MK were modelled, as well as the complete 220 kV network of AL. The EPS of GR was represented by a corresponding equivalent at the 400 kV and 150 kV levels, with the exception of the Northern part, which was modelled in detail. Thus, the real electric power interconnection with 1059 nodes (175 generators and 1413 elements) is modelled.

A good illustration of the convergence characteristics of proposed method is presented in Table 1 which relates to the case when the PST are installed on the beginning of 400 kV interconnecting lines Blagoevgrad (BG) - Thessaloniki (GR) ( $\Delta\phi 1$ ) and Skopje (MK) - KosovoB (SCG) ( $\Delta\phi 2$ ), with 400 MW and -300 MW specified active powers, respectively. This table gives the maximum power mismatches ( $\max |\Delta P|$  and  $\max |\Delta Q|$ ) and correction of frequency change ( $\Delta(\Delta f)$ ) during the iterative procedure of solving the equations (17) and (18), as well as the corrections of phase shifter angle of PST installed on before mentioned interconnecting lines.

From this table, it should be seen that after only 6 iterations, the demanded values of PST angles ( $22.426$  and  $-15.516^\circ$ ) for specified power flows are obtained. Thus, the initial experiences in the practical application of the developed method, which were gained on an example of real electric power interconnection, demonstrate simplicity and fast and reliable convergence characteristic with evidently low memory requirements.

Table 1. Maximum power mismatches, corrections of phase shifter angles and correction of frequency change during the iterative procedure

Number of iterations	$\max  \Delta P $ (MW)	$\max  \Delta Q $ (Mvar)	$\Delta\phi 1$ ( $^\circ$ )	$\Delta\phi 2$ ( $^\circ$ )	$\Delta(\Delta f)$ ( $10^{-4}$ Hz)
1	161.810	88.477	22.56	-14.95	3.8
2	35.844	14.628	-0.40	-0.38	-8.8
3	3.259	1.204	0.28	-0.18	2.1
4	1.135	0.500	-0.04	0.01	-0.2
5	0.209	0.250	0.02	-0.01	0.1
6	0.076	0.098	0.00	0.00	0.0

Table 2 gives the comparison between the results obtained by the method pre-



sented (upper index  $n$ ) and method, which is based on classical load-flow model [19]. Those results relate to the case when the EES of Greece imports 700 MW from EPS's Serbia and Montenegro (350 MW) and Romania (350 MW), and SPST are installed on the beginning of 400 kV interconnecting lines Blagoevgrad (BG) - Thessaloniki (GR) and Skopje (MK) - KosovoB (SCG).

This table gives the ratios of changes (according to the state without this controllers), of total active ( $\Delta P_g$ ) and reactive ( $\Delta Q_g$ ) power losses and ratios of obtained values of phase shifter angle of PST  $\phi_1$  and  $\phi_2$  for four variants of specified active power flow on above mentioned interconnecting lines. In variant A, on first line is specified 500 MW, and on second  $-200$  MW, in variant B, 400 MW and  $-300$  MW, in variant C, 300 MW and  $-400$  MW and, finally in variant D, 200 MW and  $-500$  MW.

Table 2. Comparison between the results obtained by the method presented (upper index  $n$ ) and method, which is based on classical load-flow model

Variant	$\frac{\Delta P_g^n}{\Delta P_g}$	$\frac{\Delta Q_g^n}{\Delta Q_g}$	$\frac{\phi_1^n}{\phi_1}$	$\frac{\phi_2^n}{\phi_2}$
A	0.871	0.989	1.160	0.950
B	1.009	0.950	0.743	0.930
C	0.777	1.026	0.930	0.823
D	0.924	1.018	0.952	1.590

According to the given results, it should be seen the significant differences, especially between the reached values of phase shifter transformer angle. Therefore, if the more accurate determination of values of phase shifter angle for specified active power flow, is requirement, the application of approach, based on non-standard load-flow model, which is near to the real operation practice, is necessary.

The differences in obtained results of steady-state security analysis are more, especially in cases of big injection losses (e.g. big production unit tripping), according to the above mentioned reason at classical load-flow model (existence one reference node, which at the same time play role of slack bus). Naturally, that was expected, because in the approach, which is based on non-standard load-flow model, in restore of new, post-dynamic quasi-stationary state participate all generator nodes (according to their primary frequency control constants) and all load nodes (according to their functions of voltage and frequency), what corresponds to the real operation practice.

## 4 Conclusions

A possible way to form an efficient method for the automatic adjustment of a PST, for specified active power flows through certain lines of electric power interconnec-

tion, has been presented. It is based on non-standard load-flow model, in which, opposite to the classical load-flow model, where the referent node is at the same time a slack bus, all nodes play role of slack node. In other words, in restore of new steady-state, participate all generator nodes (according to their primary frequency control constants) and all load nodes (according to their complex function of the voltage at its end and the quasi-stationary value of the frequency). This characteristic of advanced method proposed is essential, because enables more accurate evaluation of the relevant technical effects of installation of PST.

Apart from its simplicity and evidentially low memory requirements, according to the symmetry property of corresponding coefficient sub matrices, the method developed is also characterized by fast and reliable convergence characteristics, which were demonstrated on the example of the presently existing electric power interconnection in the Balkans. According to these properties, the developed method would be a useful tool for evaluation of all relevant technical effects of installation of PST in real electric power interconnection as a good base for further techno-economical analysis.

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