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An Efficient Decoupled Power Flow Control Method by use of Phase Shifting Transformers

Dragan P. Popović

Abstract: This paper presents an efficient fast decoupled power flow control method, e.g. method for automatic adjustment of a phase shifting transformers (PST) for specified line flows. The effects of a PST are represented by injection model and the corresponding extension of conventional load flow equations is made. Furthermore, the load flow control by means of PST is modeled by additional equations. 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 power system of Serbia and Montenegro, Romania, Bulgaria, Former Yugoslav Republic of Macedonia, Greece and Albania (Second UCTE synchronous zone).

Keywords: Phase shifting transformer, FACTS, power flow control, method, Second UCTE synchronous zone.

1 Introduction

An important problem in modern electric power systems (EPS's) 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 EPS's, combined with a process of deregulation in electric power market and restructuring of the power utilities. 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.

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The author is with Nikola Tesla Institute, Belgrade, Koste Glavinića 8a, Serbia and Montenegro (e-mail: dpopovic@ieent.org).

It is well known that acronym FACTS [1, 2] has been adopted to describe a wide range of power electronic based controllers, which are capable to increase the flexibility of electric power systems (EPSs).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 EPS's, 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 belong to category of series FACTS controllers, which have the possibility of controlling power flow in the EPS without generation rescheduling or topological changes.

In the past, several techniques have been proposed for the adjustment of phase angle of PST. References [3]-[8] are only few from the long list of published work in this area.

In this paper we concentrate on giving an efficient power flow control method, e.g. the method for automatic adjustment of a PST to reach the specified line flows. 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 matrices. The efficiency of method developed has been demonstrated on the example of existing electric power interconnection in the Balkans (Second UCTE synchronous zone).

2 Formulation of Power Flow Control Method

2.1 Generally

The general mathematical formulation of control problem considered is: Found vector $\boldsymbol{u}$ which satisfy the following two systems of equations

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

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

$$\boldsymbol{u} \in \boldsymbol{U}$$

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

The controlled active power flows on elements with PST are modelled by equations of form (1) ($\boldsymbol{F}^{SP}$ is the vector of specified line flows), and power system stationary state is modelled by conventional nodal power flow equations of form (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 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 "$k-m$" [9]

$$\begin{aligned}
P_{ck} &= -g_{km}V_k^2\tan^2\phi - g_{km}V_kV_m\tan\phi\sin\theta_{km} + b_{km}V_kV_m\tan\phi\cos\theta_{km} && (3)\\
Q_{ck} &= g_{km}V_k\tan\phi\cos\theta_{km} + b_{km}V_k^2\tan^2\phi + b_{km}V_kV_m\tan\phi\sin\theta_{km} && (4)\\
P_{cm} &= -g_{km}V_kV_m\tan\phi\sin\theta_{km} - b_{km}V_kV_m\tan\phi\sin\theta_{km} && (5)\\
Q_{cm} &= -g_{km}V_kV_m\tan\phi\cos\theta_{km} + b_{km}V_kV_m\tan\phi\sin\theta_{km} && (6)\\
k,m &\in NC
\end{aligned}$$

where NC is set of all terminal nodes of lines with PST, g_{km} and b_{km} are conductance and susceptanse of the element "$k-m$", ϕ is phase shifter transformer angle, $\underline{t}$ is complex tap of PST: $\underline{t} = t\exp(j\phi)$, where $t = 1/\cos\phi$, θ_{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 termal 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 computational, 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:

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

for $k,m \in NC$.

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:

$$\begin{aligned} \Delta P_{ci} &= P_{ci}^{SP} - P_{ckm} = 0, \quad i \in NCL, \quad k,m \in NC, & (8)\\ \Delta P_i &= P_{Gi} - P_{Li}(V_i) - P_i = 0, & (9)\\ \Delta Q_i &= Q_{Gi} - Q_{Li}(V_i) - Q_i = 0, \quad i \in N/NC, & (10)\\ \Delta P_i^C &= P_{Gi} + P_{ci} - P_{Li}(V_i) - P_i = 0, & (11)\\ \Delta Q_i^C &= Q_{Gi} + Q_{ci} - Q_{Li}(V_i) - Q_i = 0, \quad i \in NC, & (12) \end{aligned}$$

where N is number, i.e. designation of the set of all nodes of power systems; NCL is number, i.e. designation of the set of controlled line flows; P_{ci}^{SP} is specified line flows; P_{Gi} and Q_{Gi} are generator active and reactive power; $P_L(V_i)$ and $Q_L(V_i)$ are load active and reactive power, as a complex function of the voltage; P_i and Q_i are injected active and reactive power.

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

- state vector which contains vectors - $\boldsymbol{\theta}$ and $\boldsymbol{V}$ of dimensions $(N-1)$ and NL respectively (NL - number, i.e. designation of the set of load nodes ($NL = N - NG$); NG - number, i.e. designation of the set of generator nodes),
- vector of control variables - $\boldsymbol{\phi}$ of dimension NCL.

In other words, we look for the control vector $\boldsymbol{\phi}$ (within of above mentioned permissible values) in such way that the load flow equations ((9)-(10) or (11)-(12)) and specified controlled line flows (8) are satisfied.

2.4 Solution method

The first step in the development the solution method is the application of the Newton-Rhapson method [10], on the balance equations (8)-(12). Next, inspired by [11], in forming the Jacobian matris, 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 subiteration indices k and l:

$$\begin{bmatrix} \frac{\Delta P^c}{V} \\ \frac{\Delta P_c}{V} \end{bmatrix}^k = \begin{bmatrix} B' & B'_{P\phi} \\ B'_{P\Theta} & B'_{\phi} \end{bmatrix} \begin{bmatrix} \Delta\Theta \\ \Delta\phi \end{bmatrix}^{k+1} \tag{13}$$

and

$$\left(\frac{\Delta Q^C}{V}\right)^l = B'' \Delta V^{l+1}. \tag{14}$$

The elements of the all coefficient submatricies $\boldsymbol{B}'$, $\mathbf{B}'_{p\phi}$, $\mathbf{B}'_{p\theta}$ $\mathbf{B}'_{\phi}$ and $\mathbf{B}''$ have the constant values for a given network topology. The square submatrices $\mathbf{B}'$ and $\mathbf{B}''$, of dimension $(N-1)$ and NL, respectively, are identical to the corresponding submatrices in the fast decoupled load flow method [11].

Further, $\mathbf{B}'_{p\theta} = \mathbf{B}'^{T}_{p\phi}$ and $\mathbf{B}'_{\phi}$ has only diagonal elements, e.g. the coefficient matrix of system of equations (13) is simetrical. The submatrices $\mathbf{B}'_{p\theta}$, $\mathbf{B}'_{p\phi}$, and $\mathbf{B}'_{\phi}$, of dimension $(NCL)\times(N-1)$, $(N-1)\times(NCL)$ and $(NCL)\times(NCL)$, respectively, have the following elements (V_n represents the rated value voltage):

$$\begin{aligned} B'_{p\phi ki} &= \frac{V_n}{X_{km}}; & B'_{p\phi mi} &= -\frac{V_n}{X_{km}}; \\ B'_{p\Theta ki} &= -\frac{V_n}{X_{km}}; & B'_{p\Theta mi} &= -\frac{V_n}{X_{km}}; \\ B'_{\phi ki} &= \frac{V_n}{X_{km}}; & i &= \in NCL \quad k,m \in NC \end{aligned} \tag{15}$$

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

Evidently, the solution method developed is simpler then the recent approach based on Newton type algorithm [8], 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 Methods

The first practical experiences in the application of the method developed have been gained on an example of the synchronous parallel operation of the EPSs of Serbia and Montenegro (SCG), Romania (RO), Bulgaria (BG), former Yugoslav Republic of Macedonia (FYROM), Greece (GR) and Albania (AL). In other words, the present state of the interconnection in the Balkans(Second UCTE synchronous zone), which is operating as an "island" with respect to the main part of UCTE interconnection, is analyzed.

Figure 1 shows the block diagram of interconnection considered with the active and reactive power flows (MW/Mvar) on interconnecting lines in the case when there is no programmed power interchange between the EPSs ("zero" exchange program), e.g., these powers represent at the same time the ring power flows.

The first case of application of developed method is elimination of the ring flows in direction GR - AL - SCG. For this, PST are installed at the beginning of 220 kV line Fierza (AL) - Prizren (SCG) and 400 kV line Elbasan (AL) - Kardia (GR), with zero specified active powers. Table 1 gives the maximum power mismatches during the iterative procedure of solving the equations (13) and (14), as

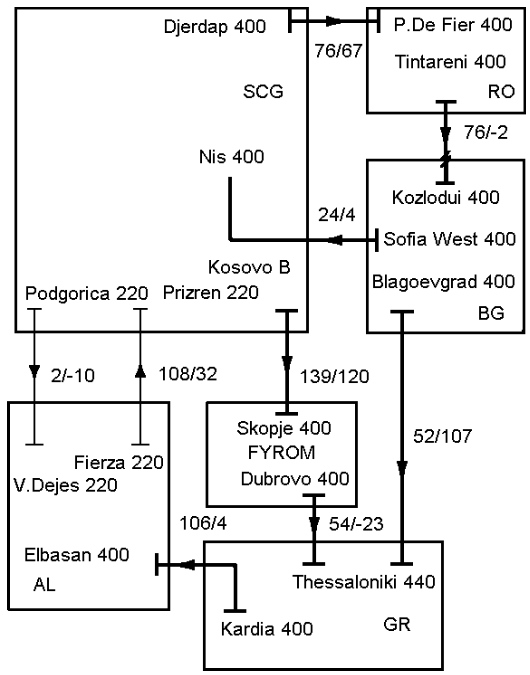

Fig. 1. Active and reactive powers on interconnecting lines for ”zero” exchange program.

well as the corrections of phase shifter angle of PST installed on before mentioned interconnecting lines.

It should be noted that the iterative procedure in all cases considered, had a so-called ”flat” start (1 p.u. voltage magnitude for all PQ buses and zero for voltage angle and phase shifter angle). As a result, after 5 iterations a phase shifter are adjusted automatically (-8.792 and 8.981°el) so as to satisfy a zero specified power flows

Table 1. Maximum power mismatches and corrections of phase shifter angle during the iterative procedure (ring flows evaluation).

No. of iterati on	max $\|\Delta P\|$ (MW)	max $\|\Delta Q\|$ (Mvar)	max $\|\Delta P_c\|$ (MW)	$\Delta\phi_1$ (°el)	$\Delta\phi_2$ (°el)
0	1727.4	4901.7	0.000	–4.453	13.586
1	198.8	262.6	8.891	–4.124	–4.643
2	22.1	14.1	1.904	–0.199	0.042
3	1.7	0.609	0.126	–0.013	–0.007
4	0.116	0.047	0.010	–0.001	0.000
5	0.010	0.031	0.001	–	–

Table 2 relates to the case when the EPS of Greece exports 800 MW to the EPS of Serbia and Montenegro and PST are installed on the beginning of 400 kV lines Dubrovo (FYROM) - Thessaloniki (GR) ($\Delta\phi_1$) and Thessaloniki (GR) - Blagoevgrad (BG) ($\Delta\phi_2$), with -300 and 300 MW specified active powers, respectively. From this table, it should be seen that after only 5 iterations, the demanded values of phase shifter angles (–8.921 and 4.691°el) are obtained.

Table 2. Maximum power mismatches and corrections of phase shifter angle during the iterative procedure (GR exports 800 MW to SCG).

No. of iteration	max $\|\Delta P\|$ (MW)	max $\|\Delta Q\|$ (Mvar)	max $\|\Delta P_c\|$ (MW)	$\Delta\phi_1$ (°el)	$\Delta\phi_2$ (°el)
0	1727.4	4901.7	300	–9.324	7.062
1	199.6	263.2	11.0	0.055	–2.171
2	22.3	14.2	2.9	0.354	–0.209
3	1.8	0.531	0.122	–0.005	0.009
4	0.114	0.031	0.013	0.0009	0.0013
5	0.006	0.016	0.002	–	–

Table 3 relates to the same exchange program (GR - YU 800 MW), but 400 kV line Thessaloniki (GR) - Blagoevgrad (BG) is tripped and 400 kV line Elbasan (AL) - Kardia (GR) has the PST, with -250 MW specified power flow. This case is practically very interesting, because, without of this PST, the line Elbasan (AL) - Kardia (GR) will be loaded with 482 MW, e.g. the only one autotransformer at Elbasan (300 MVA, 400/220 kV) will be overloaded. Thus, with relatively modest value of phase shifter angle (11.255°el), as compared with the possible maximum of existing PSTs, the suitable power flow in postdynamic quasy - stationary state is achieved.

Table 3. Maximum power mismatches and corrections of phase shifter angle during the iterative procedure (GR exports 800 MW to SCG ; line Thessaloniki (GR) - Blagoevgrad (BG) is tripping).

No. of iteration	max $\|\Delta P\|$ (MW)	max $\|\Delta Q\|$ (Mvar)	max $\|\Delta P_c\|$ (MW)	$\Delta\phi_1$ (°el)
0	1727.4	4901.7	250	13.261
1	199.5	263.9	11.9	–2.251
2	22.5	14.3	0.508	0.242
3	1.8	0.547	0.004	–0.001
4	0.119	0.016	0.000	0.001
5	0.006	0.031	0.000	–

Finally, Table 4 gives the number of iterations for desired accuracy of 0.1 MW

Table 4. The number of iterations for desired accuracy of 0.1 MW and 0.1 Mvar and final values of phase shifter angle for specified line flow

Dubrovo (FYROM)-Thessaloniki (GR)		Thessaloniki (GR)-Blagoevgrad (BG)		Number of iterations
P_C^{SP} (MW)	ϕ (°el)	P_C^{SP} (MW)	ϕ (°el)	
–100	9.662	400	–1.736	5
–200	5.790	300	–6.121	5
–200	–4.863	400	8.841	5
–300	–8.921	300	4.691	5
–300	–20.178	400	19.113	6
–400	–13.166	200	0.538	5

and 0.1 Mvar, as well as the final adjustment values of phase shifter angle of PST installed at the beginning of lines 400 kV Dubrovo (FYROM) - Thessaloniki (GR) and Thessaloniki (GR) - Blagoevgrad (BG), for various specified power flows.

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.

4 Conclusions

A possible way to form an efficient decoupled procedure for the automatic adjustment of a phase shifting transformers for specified active power flows through certain lines of power systems has been presented. Apart from its simplicity and evidentially low memory requirements, according to the simetry property of corresponding coefficient 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.

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