Power System Congestion Management using Hybrid Control of PST and Real Power Generations

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ABSTRACT

This paper presents a scheme to solve the congestion problem using hybrid control with phase-shifting transformer (PST) and power generations in power systems. An efficient design of PST and power generation control can improve total transfer capability (TTC) in interconnected systems. This paper deals with an application of optimization technique such as sequential quadratic programming (SQP) for TTC calculation. The optimization method is used to increase power flow of tie line subject to security constraints such as voltage magnitude and real power flow. In order to show the effectiveness of the proposed algorithm, it has been tested on 10 machines 39 buses model systems, and its results are presented.

I. INTRODUCTION

According to the development of flexible AC transmission systems (FACTS) technology, phase-shifting transformer (PST), power flow is controlled by thyristor controlled phase-shifting transformer (TCPST) and Unified power flow controller (UPFC). Most of the electric power in Korea's power system flows from the southern area to Seoul, the capital city in the north. Electrical loads approximately 40% are consumed in the capital area and generation plants are mainly located in the southern portion of the country. Due to this characteristic, transmission congestion is a significant research issue [1]. The transfer of power from the south to the north is anticipated to be increased more and more in the future. Due to the increase in this flow pattern, transmission congestion has the potential to cause a serious voltage stability problem in the power system. During transmission system planning, basic consideration involves securing the power systems for electric power demand levels, various operating points of generation outputs, contingencies and so on. Sufficient transmission capacities are needed to meet the operation condition within the limits in the event of unplanned outages. However, it is hard to provide sufficient transmission capacities overcoming engineering constraints such as thermal capacity limits of transmission lines, disturbances and faults in power systems, and social and economical constraints such as cost, environmental and social problems. Therefore, the possibility of transmission line congestion is ever present.

In the past, many works were studied for the application of FACTS devices and many researches were developed including power flow control based on FACTS devices. Especially, many studies for the application of phase-shifting transformer have emerged to solve total transfer capability (TTC). The modeling of phase shift transformer for the fast-decoupled load flow method is presented. The short circuit for fault analysis is tested [2],[3]. It is also discussed the possibility of improving the transient stability of power systems by installing phase-shifting transformer and not implemented practically as yet [4], [5].

This paper presented a scheme to analyze and solve power system congestion problems by managing power flow of system in emergency states. The scheme for controlling line flow congestion is the hybrid algorithms with phase-shifting transformer (PST) and power generations lower generation costs in power systems. The proposed method is applied to 10 machines 39 buses model system to show its effectiveness.

II. HYBRID CONTROL FOR CONGESTION PROBLEMS

A. Generation Power Output Control

Electric power systems interconnect because the interconnected systems are more reliable as shown in Figure 1, it is a better system to operate, and it may be operate at less cost than if left as separate parts [6].

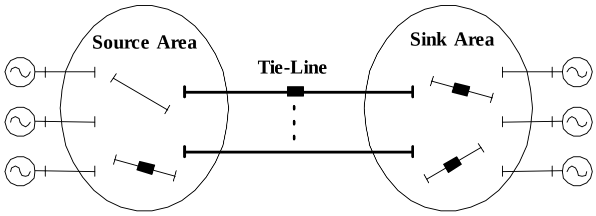

Figure 1. Interconnected system

A load change in sink area is taken care of by all units of source area in the interconnection, not just the unit in the control area where the load change occurred. This fact also makes interconnection more reliable since the loss of a generating unit in one of them can be made up from spinning reserve among units throughout the interconnection. Thus, if a unit is lost in one control area, governing action from units in all connected areas will increase generation outputs to make up the deficit until standby units can be brought on-line. In order to maximize interconnection power flow of tie line connecting source area and sink area we can formulate as follows:

$$\begin{aligned} &Max. \quad \sum_{t \in tie} P_t \\ &S_{ij} \le S_{ij,\max} \\ &P_{GS,\min} \le P_{GS} \le P_{GS,\max} \end{aligned} \tag{1}$$

B. Power Control using PST

Consider a phase-shifting transformer connected between nodes i and j with an ideal turns ratio $T = 1.0\angle\psi^t$ in series with transformer admittance $y^t = |y^t|\angle\alpha^t$ as shown in Figure 2 [3].

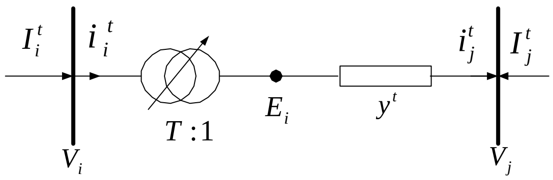

Figure 2. Phase-shifting transformer

$$\begin{aligned} &\frac{V_i}{E_i} = T = \frac{i_j^{*t}}{i_i^{*t}}, \quad E_i = T^* V_i \\ &T^{-1} = T^*, \quad i_j^t = T^* i^t \end{aligned} \tag{2}$$

and

$$\begin{aligned} i_i^t &= T i_j^t = y^t T (T^* V_i - V_j) \\ i_i^t &= y^t (V_i - T V_j) \end{aligned} \tag{3}$$

Using above equations, $I_i^t = i_i^t$ and $I_j^t = -i_j^t$

$$\begin{bmatrix} I_i^t \\ I_j^t \end{bmatrix} = y^t \begin{bmatrix} 1 & -T \\ -T^* & 1 \end{bmatrix} \begin{bmatrix} V_i \\ V_j \end{bmatrix} \tag{4}$$

The off-diagonal elements of the admittance matrix Y for a phase-shifting transformer are not symmetrical, i.e.

$$\begin{aligned} Y_{ij} &= -yT \\ &= (b^t \sin\psi^t - g^t \cos\psi^t) - j(g^t \sin\psi^t + b^t \cos\psi^t) \\ Y_{ji} &= -y^t T^* \\ &= -(b^t \sin\psi^t + g^t \cos\psi^t) + j(g^t \sin\psi^t - b^t \cos\psi^t) \end{aligned} \tag{5}$$

At the ith end of the phase-shifting transformer the apparent MVA, S_i is showed by using eq. (5) as follows:

$$S_i = P_i + jQ_i = V_i I_i^* = y^{t*}(V_i^2 - V_i V_j^* T^*) \tag{6}$$

where $V_i = |V_i|\angle\theta_i, V_j = |V_j|\angle\theta_j$.

Hence the real power flow P_i and P_j of bus i and j can be calculated as follows:

$$\begin{aligned} P_i &= gV_i^2 - V_i V_j y^t \cos(\beta_{ij}) \\ P_j &= gV_i^2 - V_i V_j y^t \cos(-\beta_{ij}) \end{aligned} \tag{7}$$

where $\beta_{ij} = \theta_i - \theta_j - \psi^t - \alpha^t$, the partial derivatives of the real power with respect to the transformer shifting angle for node i and j are as follows respectively:

$$\begin{aligned} &\frac{\partial P_i}{\partial \psi^t} = -V_i V_j y^t \sin(\beta_{ij}) \\ &\Delta\psi^t = \frac{-\Delta P_i}{V_i V_j y^t \sin(\beta_{ij})} \end{aligned} \tag{8}$$

$$\begin{aligned} &\frac{\partial P_j}{\partial \psi^t} = -\frac{\partial P_i}{\partial \psi^t} \\ &\Delta\psi^t = \frac{\Delta P_j}{V_i V_j y^t \sin(\beta_{ij})} \end{aligned} \tag{9}$$

Eq. (8) and (9) are used for adjusting the shifting angle of transformer for either the specified power P_i of the sending end or the specified power P_j of the receiving end.

III. HYBRID CONTROL ALGORITHMS

A. Problem Formulation

In order to maximize interconnection power flow of tie line connecting source area and sink area we can formulate as follows:

Objective:

$$Max. \quad \sum_{t \in tie} P_t \tag{10}$$

Constraints:

Control Variable:

$$\begin{aligned} &P_{GS,\min} \le P_{GS} \le P_{GS,\max} \\ &\psi^t_{i,\min} \le \psi^t_i \le \psi^t_{i,\max} \end{aligned} \tag{11}$$

State Variable:

$$\begin{aligned} &P_{Gi} - P_{Li} - \sum_{j \in i} V_i V_j (G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}) = 0 \\ &Q_{Gi} - Q_{Li} - \sum_{j \in i} V_i V_j (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}) = 0 \\ &S_{ij} \le S_{ij,\max} \\ &V_{i,\min} \le V_i \le V_{i,\max} \\ &S_{ij} \le S_{ij,\max} \end{aligned} \tag{12}$$

where,

λ : increment factor in bus load and generation.

P_{Gi0} : original real power generation at bus i

P_{Li0}, Q_{Li0} : original real and reactive power load at bus i

k_{Gi}, k_{Li} : constants specifying the rate of change in generation and load

P_{Gi}, Q_{Gi} : real and reactive power generation at bus i

P_{Li}, Q_{Li} : real and reactive load demand at bus i, j

$|V_i|, |V_j|$: voltage magnitude at bus i, j

$|V_i|_{\min}, |V_i|_{\max}$: lower and upper limits of voltage magnitude at bus i

$|S_{ij}|$: apparent power flow in line $i-j$

$|S_{ij}|_{\max}$: thermal limit of line $i-j$

$P_{Li} : P_{Li0}(1+\lambda K_{Pi})$

$Q_{Li} : Q_{Li0}(1+\lambda K_{Qi})$

Optimization technique enables Total Transfer Capability(TTC) of two areas to improve by increasing the complex load with uniform power factor at every load in the sink areas and by changing the injected real power at generation buses in the source area and phase-shifting transformer until limits are incurred [6]. The mathematical formulation of TTC using optimization technique can be expressed as eq. (10) – (12). For calculating TTC, the injection real and reactive power at source and sink buses are functions of λ .

B. Sequential Quadratic Programming

Sequential Quadratic Programming (SQP) is the optimization method for the minimization of the maximum of a set of smooth objective functions subject to equality and inequality constraints and simple bounds on the variables [7]. In order to get the optimal solutions SQP generates a point satisfying these constraints by solving a strictly convex quadratic program (QP) using a positive definite estimate H of the Lagrangian. And an Armijo-type arc search or line search (monotone, nonmonotone) are used to compute the direction of descent the objective function. Generalized SQP algorithms are implemented as follows.

Step 1 Initialization

i) Initial value of variables x_0 , step size t_0 and search directions d_0. If x_0 is infeasible for some constraint, substitute a feasible point.

Step 2 Computation of search

i) Compute $d^{\sim}_k$, the solution of the strictly convex QP

ii) Compute the step size $t^{\sim}_k$

Step 3 Updates

i) Update Hessian matrix of Lagrangian using the Powell modification.

ii) Set $x_{k+1} = x_k + t_k d_k + t_k^2 d^{\sim}_k$

iii) Solve the unconstrained QP problem in μ , eq. (13). Increase k by 1.

$$\begin{aligned} \min \Bigg\| &\sum_j \zeta_{k,j} \nabla f_j(x_{k+1}) + \xi_k + \sum_j \lambda_{k,j} \nabla g_j(x_{k+1}) \\ &+ \sum_j \mu_{k,j} \nabla h_j(x_{k+1}) + \sum_j \overline{\mu}_{k,j} \nabla h_j(x_{k+1}) \Bigg\|^2 \end{aligned} \tag{13}$$

where the $\zeta_{k,j}, \xi_k, \mu_{k,j}$ and $\lambda_{k,j}$ are the K-T multipliers associated with QP for the objective functions, variable bounds, equality constraints, and inequality constraints respectively.

IV. NUMERICAL RESULTS

This paper presented the scheme to increase total transfer capability using hybrid control with phase-shifting transformer (PST) and power generation in power systems.
It was applied to IEEE 10 machines 39 buses system for proving the efficiency of the scheme. The model systems are simplified as Figure 3. To investigate the scheme for increasing TTC using hybrid control, the algorithm is executed at Pentium III and the simulation of different cases is implemented as follows:

Case 1: Control of PST (bus 4-14) and Generation output of source area.
Case 2: Control of PST (bus 4-14 and bus 17-16) and Generation output of source area.

Table 1 shows the results of TTC using load increasing factor λ only. The result of SQP is equal to that of repeat power flow (RPF) nearly and SQP can save execution time to calculate TTC. In Table 2, the comparison of TTC with PST control and real power generation control is shown. In Case 1, TTC is calculated by increasing the load of sink area. TTC of RPF is 1007.73 [MW] by restricting the limit of line flow in bus 11 - 6, 400 [MW], while TTC is improved 268.0 [MW] by increasing equal to 1275.73 [MW] through other interconnection line when PST and real power generation are controlled. Also, It is seen that TTC of post-control is improved more than pre-control in each case. It can be found that hybrid control plays an important role increasing interconnection power flow. Especially, in case of Case 2 PST angles are very changed and TTC is improved more than Case 1 because of the control of two PST and real power generation in source area.

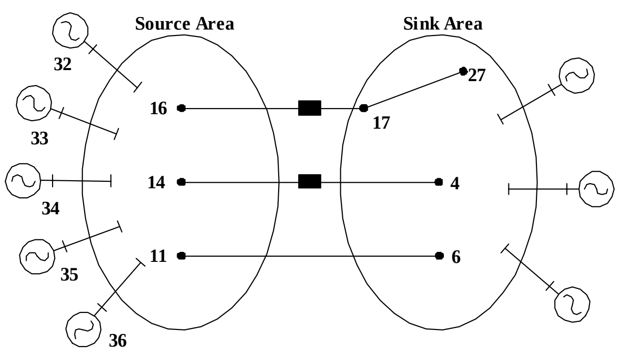

Figure 3. Simplified 10 machines and 39 buses systems

V. CONCLUSION

This paper presents a scheme to solve the congestion problem using hybrid control with phase-shifting transformer (PST) and power generations in power systems.
The proposed scheme can porvide the best placements of the phase-shifting transformers by evaluating total transfer capability in the tie-lines. In order to enhence the congestion problem in the tie-line, the hybrid method to control both phase-shifting transformer (PST) and power generations of the source area is applied. Test results show that the proposed method is reliable compared with RPF method.
Future study is needed to assess available transfer capability (ATC) considering transmission reliability margin (TRM) and capacity benefit margin (CBM).

Table 1. Comparison of TTC using Load Increasing Factor

	RPF	SQP
TTC [MW]	1007.734	1007.736
CPU Time [sec.]	39	5

Table 2. Simulation Results

		PST / angle [deg]	Real Power of Generation Control Buses [MW]	TTC [MW]
			32, 33, 34, 35, 36	
RPF or SQP		-	-	1007.73
Post-Control of PST and Real Power Generation [MW]	Case 1	Bus 4 - 14 control angle □ 1°	618.9, 850.0, 688.0, 1082.8, 485.7	1275.73
	Case 2	Bus 4 – 14 and Bus 17 – 16 control angle □ 1.80° and 4.23°	748.2, 727.8, 604.0, 1121.6, 527.4	1286.0

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