OPTIMAL POWER FLOW INCORPORATING FACTS DEVICES USING PARTICLE SWARM OPTIMIZATION

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ABSTRACT

Three types of FACTS devices, static var compensation (SVC), thyristor controlled series capacitor (TCSC), and thyristor controlled phase shifter (TCPS), are incorporated in the optimal power flow (OPF) problem in this paper. Those FACTS devices add new control variables and power flow constraints to the OPF. All of that have been taken care of in the new developed OPF formulation. Particle Swarm Optimization (PSO), a new evolutionary optimization technique, has been employed for solving this OPF problem. IEEE-30 bus test system is used to validate the approach.

1. INTRODUCTION

Optimal power flow (OPF) started, as one of the challenging needs for economic power system operations, in the early sixties. Its usages have been widened since then to cover many power system applications ranging from preliminary planning to reliable operation. Enormous efforts have been spent for improving OPF to make it of great help for all sorts of power system engineering [1-9].

The importance of incorporating FACTS devices in OPF cannot be over emphasized [3,5]. This importance can be realized when looking to the benefits offered by FACTS devices, the good coordination needs between them, and the need for relaxing the operating limits that stop the OPF objective optimization. Knowing, over that, that OPF is one of the major computation tools assisting in FACTS devices coordination while FACTS devices them self can relax the operating limits at the same times [3-6]. This interconnection between FACTS devices and OPF is quit enough to justify the great demand to incorporate FACTS devices in OPF problem.

OPF is a non-linear problem and can be non-convex in some cases. Moreover, incorporating FACTS devices complicates the problem further. Such complicated problem needs a well-efficient optimization technique for solving. *Particle Swarm Optimization* is such efficient technique borrowed for this task [9].

This paper is organized as follows. Part 2 suggests the FACTS devices modeling for load flow studies and builds the formulation of OPF with FACTS. Part 3 is devoted for the solution methodology where the optimization technique is explained. IEEE-30 bus test system is used for the case studies in part 4 and then the paper is concluded.

2. OPF FORMULATION WITH FACTS DEVICES

2.1. FACTS modeling for power flow studies

2.1.1. Static var compensation (SVC)

From an operation point of view, the SVC can be seen as a variable shunt susceptance. Therefore, we choose to model the SVC as a total variable susceptance between certain limits as shown in figure (1). The effect of this on load flow can be taken care of in building the Y-Bus matrix [8].

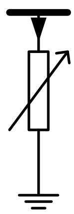

Figure (1) SVC model for power flow studies

2.1.2.Tthyristor controlled series compensation (TCSC)

The effect of TCSC on power system can be seen as a controllable reactance x_c inserted in the related transmission line as shown in figure (2) [4].

Figure (2) TCSC model in power flow calculation

2.1.3. Thyristor controlled phase shifter (TCPS)

The effect of the phase shifter can be seen to be equivalent to an ideal transformer with complex taps as shown in Figure (3).

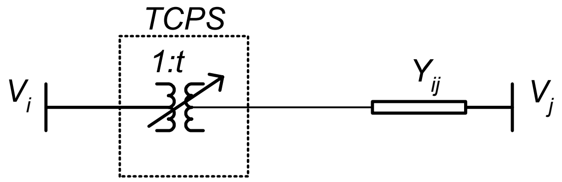

Figure (3) TCPS model in power flow calculation

The modification takes place to the Y-Bus matrix is as follows [7]:

$$Y_{Bus} = \begin{pmatrix} t^2 Y_{ii} & -t\, Y_{ij}\, e^{-j\Phi} \\ -t\, Y_{ij}\, e^{-j\Phi} & Y_{jj} \end{pmatrix} \quad (1)$$

2.2. OPF Formulation

The OPF problem seeks to optimize the steady state performance of a power system in terms of an objective function while satisfying several equality and inequality constraints. OPF in its general form is expressed as follows:

$$Min \quad J(x,u) \quad (2)$$

$$Subject\ to:$$

$$g(x,u) = 0 \quad (3)$$

$$h(x,u) \le 0 \quad (4)$$

Where $\boldsymbol{x}$ is the vector of state variables. This includes the slack bus power P_{G1}, load bus voltage V_L, generator reactive power output Q_G, and transmission line loadings S_l. Hence, $\boldsymbol{x}$ can be expressed as

$$x^T = [P_{G_1}, V_{L_1}, ..., V_{L_{NL}}, Q_{G_1}, Q_{G_{NG}}, S_{l_1}, ..., S_{l_{nl}}] \quad (5)$$

Where *NL*, *NG*, and *nl* are number of load buses, number of generators, and number of transmission lines, respectively.

$\boldsymbol{u}$ is the vector of control parameters (independent variables). It consists of generator voltages V_G, generator real power outputs P_G except the slack bus P_{G1}, transformer tap settings *T*, and FACTS devices control parameters. FACTS devices control parameters in our case consists of the SVC susceptances *B*, TCSC reactances x_c, TCPS angles Φ. Hence, $\boldsymbol{u}$ can be expressed as

$$u^T = [V_{G_1}, ..., V_{G_{NG}}, P_{G_2}, ..., P_{G_{NG}}, T_1, ..., T_{NT}, B_1, ..., B_{NSH}, x_{c1}, ..., x_{CNSC}, \Phi_1, ..., \Phi_{NPS}] \quad (6)$$

Where *NT, NSH, NSC*, and *NPS* are number of regulating transformers, number of SVCs, number of TCSCs, and number of TCPSs, respectively.

Objective:
$\boldsymbol{J}$ is the objective function to be minimize, which is here the fuel cost.

Constraints:
The functions *g* and *h* are the equality and inequality constraints to be satisfied while searching for the optimal solution.

a) Equality constraints

The function *g* represents the equality constraints that are the power flow equations corresponding to both real and reactive power balance equations, which can be written as:

$$P_{G_i} - P_{D_i} = \sum_{j=1}^{NB} V_i V_j Y_{ij}(FACTS) \cos(\theta_{ij}(FACTS) + \delta_j - \delta_i) = 0 \quad ; \forall\, i \in NB \quad (7)$$

$$Q_{G_i} - Q_{D_i} = \sum_{j=1}^{NB} V_i V_j Y_{ij}(FACTS) \sin(\theta_{ij}(FACTS) + \delta_j - \delta_i) = 0 \quad ; \forall\, i \in NB \quad (8)$$

Where:
NB is the number of buses;
P_{Gi} and Q_{Gi} are active and reactive power generations at bus *i*;
P_{Di} and Q_{Di} are active and reactive power demands at bus *i*;
V_i and δ_i are voltage magnitude and angle at bus *i;*
$Y_{ij}(FACTS)$ and $\theta_{ji}(FACTS)$ are magnitude and phase angle of elements in Y-bus matrix where the effects of FACTS have been taken into consideration.

b) Inequality constraints

$\boldsymbol{h}$ is the system inequality operation constraints that include:

i) Generation constraints: Generator voltages, real power outputs, and reactive power outputs are restricted by their lower and upper limits as follows:

$$V_{G_i}^{\min} \le V_{G_i} \le V_{G_i}^{\max}, \quad i = 1,....., NG \quad (9)$$

$$P_{G_i}^{\min} \le P_{G_i} \le P_{G_i}^{\max}, \quad i = 1,....., NG \quad (10)$$

$$Q_{G_i}^{\min} \le Q_{G_i} \le Q_{G_i}^{\max}, \quad i = 1,....., NG \quad (11)$$

ii) Transformer constraints: Transformer tap settings are bounded as follows:

$$T_i^{\min} \le T_i \le T_i^{\max}, \quad i = 1,....., NT \quad (12)$$

iii) Security constraints: These include the constraints of voltages at load buses and transmission lines loadings as follows

$$V_{L_i}^{\min} \le V_{L_i} \le V_{L_i}^{\max}, \quad i = 1,....., NL \quad (13)$$

$$S_l \le S_{l_i}^{\max}, \quad i = 1,....., nl \quad (14)$$

iv) FACTS devices constraints: SVC, TCSC, and TCPS settings are bounded as follows:

$$B_i^{\min} \le B_i \le B_i^{\max}, \quad i = 1,......, NSVC \quad (15)$$

$$x_{c_i}^{\min} \le x_{c_i} \le x_{c_i}^{\max}, \quad i = 1,......, NTCSC \quad (16)$$

$$\Phi_i^{\min} \le \Phi_i \le \Phi_i^{\max}, \quad i = 1,......, NTCPS \quad (17)$$

3. PARTICLE SWARM OPTIMIZATION

3.1. Overview

Particle swarm optimization (PSO) is similar to other evolutionary computation techniques in conducting searching for optima using an initial population of individuals. The individuals of this initial population are then updated according to some kind of process such that they are moved to a better solution area. The four well-known evolutionary algorithms, namely, genetic algorithm, evolutionary programming, evolutionary strategies, and genetic programming are motivated by evolutionary seen in nature. They borrow the principle of competition and survival of the fittest from there. PSO, on the other hand, is motivated form the simulation of social behavior. It borrows the principle of cooperation and competition among the individual themselves.

3.2. PSO Algorithm

In PSO system, each individual adjusts its flying in a multi-dimensional search space according to its own flying experience and its companions flying experience. Each individual is referred to as a "particle" which represents a candidate solution to the problem. Each particle is treated as a point in a *D*-dimensional space. The i^{th} particle is represented as $X_i=(x_{i1}, x_{i2}, x_{i3}, ...,x_{iD})$. The best previous position (giving the best fitness value) of any particle is recorded and represented as $P_l=(P_{i1},P_{i2},P_{i3}, ...,P_{iD})$. The index of the best particle among all the particles in the population is represented by the symbol g. The rate of the position change (velocity) for particle *i* is represented as $V_i=(V_{i1}, V_{i2}, V_{i3}, ...,V_{iD})$. The particles are manipulated according to the following equation [10]:

$$V_{id} = V_{id} + c_1 r_1 (P_{id} - X_{id}) + c_2 r_2 (P_{gd} - X_{id}) \quad ; (19)$$

$$X_{id} = X_{id} + V_{id}; \quad (20)$$

where c_1 and c_2 are positive constants and r_1 and r_2 are uniformly distributed random numbers in [0,1].

4. CASE STUDIES

The IEEE-30 bus system has been used to test the effectiveness of the proposed approach. Three cases have been studied. Case I was the conventional OPF without FACTS devices where the control variables are the generator voltages and the transformer tap settings. In case II, five SVCs have been installed at buses 17, 20, 21, 23, and 24. In case 3, two TCSCs have been installed at branches 4 and 24 together with two TCPSs at branches 4 and 8. Reference [2] claimed that those are the near optimal places. The three cases were studied from the fuel cost minimization objective *J*, i.e.

$$J = \sum_{i}^{NG} f_i (\$ / h) \quad (21)$$

where f_i is the fuel cost curve of the i^{th} generator and it is represented by the following quadratic function:

$$f_i = a_i + b_i P_{G_i} + c P_{G_i}^2 \ (\$ / h) \quad (22)$$

where a_i, b_i, and c_i are the cost coefficients of the i^{th} generator. The values of these coefficients are given in Table 1.

Table 1
Generation cost coefficients

	G_1	G_2	G_3	G_8	G_{11}	G_{13}
a	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
b	*200*	*175*	*100*	*325*	*300*	*300*
c	*37.5*	*175*	*625*	*83.4*	*250*	*250*

Table 2 gives the minimum and maximum limits on the control variables used in each case. Also, it shows the optimal settings of those control variables for each case and the corresponding fuel cost.

As can be expected, case II and III got lower production cost than case I. This is obvious since the solution space in both cases is wider than that in case I. For a complete comparison, the summation of voltage deviation from 1.0 p.u. resulted in each case is given in the table.

Table 2
Optimal settings of control variables

	Min	Max	Case1	Case2	Case3
P_1	.50	2.00	1.7466	1.7490	1.7472
P_2	.20	0.80	0.4844	0.4864	0.4851
P_5	.15	0.50	0.2392	0.2392	0.2380
P_8	.10	0.32	0.2129	0.2111	0.2106
P_{11}	.10	0.30	0.1200	0.1168	0.1210
P_{13}	.12	0.40	0.1200	0.1206	0.1200
V_1	.95	1.10	1.0819	1.0802	1.0811
V_2	.95	1.10	1.0619	1.0613	1.0618
V_5	.95	1.10	1.0347	1.0294	1.0314
V_8	.95	1.10	1.0375	1.0344	1.0391
V_{11}	.95	1.10	1.0517	1.0272	1.0617
V_{13}	.95	1.10	1.0651	1.0605	1.0715
T_{11}	.90	1.10	1.0163	1.0211	1.0040
T_{12}	.90	1.10	0.9937	1.0295	0.9918
T_{15}	.90	1.10	0.9998	1.0269	0.9955
T_{36}	.90	1.10	0.9732	0.9794	0.9686
Q_{17}	-.02	0.05	-	0.0274	-
Q_{20}	-.02	0.05	-	0.0164	-
Q_{21}	-.02	0.05		0.0381	
Q_{23}	-.02	0.05	-	0.0332	-
Q_{24}	-.02	0.05	-	0.0380	-
$TCSC_4$*	0.0	50%	-	-	0.1687
$TCSC_{24}$*	0.0	50%	-	-	0.2902
$TCPS_4$**	-0.1	0.1	-	-	-0.0272
$TCPS_8$**	-0.1	0.1	-	-	-0.0336
Cost ($/H)			801.408	801.308	800.931
$\sum$ *vol. deviation*			0.911	0.742	1.070

* *% of* X_L

** *in radian*

5. CONCLUSION

In this paper, a novel particle swarm optimization approach has been implemented to minimize the generator fuel cost in OPF with FACTS devices. SVC, TCSC, and TCPS were the FACTS devices under this study. Location of the FACTS devices is an important facto in OPF and one may gain more saving in fuel cost if he tries a more optimal location.

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