

An IPM-APSO based hybrid method for multiple objective minimizations using TCPS

M. Balasubba Reddy, Y. P. Obulesh, S. Sivanaga Raju

Abstract: This paper presents an Interior Point Method (IPM) and variant of Particle Swarm Optimization (APSO) based hybrid method to solve optimal power flow in power system incorporating Flexible AC Transmission Systems (FACTS) such as Thyristor Controlled Phase Shifter (TCPS) for minimization of multiple objectives. The proposed IPM-APSO algorithm identifies the optimal values of generator active-power output and the adjustment of reactive power control devices. The proposed optimization process with IPM-APSO is presented with case study example using IEEE 30-bus test system to demonstrate its applicability. The results are presented to show the feasibility and potential of this new approach.

Index Terms: Optimal power flow, Adaptive Particle Swarm Optimization, Flexible AC Transmission, and TCPS

I. INTRODUCTION

The future growth of power system will rely more on increasing capability of already existing transmission systems, rather than on building new transmission lines and power stations, for economic and environmental reasons. Due to deregulation of electricity markets, the need for new power flow controllers capable of increasing transmission capability and controlling power flows through predefined corridors will certainly increase. Ideally, these new controllers should be able to control voltage levels and flow of active and reactive power on transmission lines to allow for their secure loading, to full thermal capability in some cases, with no reduction of system stability security margins [1].

To meet the load demand in a power system and satisfy the stability and reliability criteria, the existing transmission lines must be utilized more efficiently. It provides an economically and technically attractive solution to power system security problem by use of some efficient controls, such as controllable series capacitors, phase shifters, and load shedding, etc., [2]– [6]. Several techniques have been proposed in the past for the adjustment of phase shifter or the adjustment of controllable series capacitor to alleviate line overloads [5], [6].

The main method uses the model of series capacitor or phase shifter in power flow program without generation rescheduling. It is possible to alleviate power flow violation

and enhance power system security in an electrical power system by use of phase shifter without optimal generation rescheduling. However, it is well known that the phase shifter adjustment under given contingencies may fail to yield convergence. Thus, optimal power flow (OPF) with phase shifter is a good choice.

The goal of optimal power flow is to determine optimal control variables and quantities for efficient power system planning and operation. Several optimization techniques have been proposed to handle the OPF problem [7]–[9]. Recently, the research in OPF such as interior point (IP) using new optimization techniques, has been gaining wider attention in power system operation [10], [11]. The interior point method is faster and more reliable for achieving feasibility and convergence. Due to the limitation of IP, the model of discrete variable such as phase shifter has not been investigated in the common OPF.

Heuristic algorithms, such as genetic algorithms (GA) [12] and evolutionary programming [13], have been recently proposed for solving the OPF problem. The results reported were promising and encouraging for further research in this direction. Unfortunately, recent research has identified some deficiencies in GA performance [14]. This degradation in efficiency is apparent in applications with highly epistatic objective functions, i.e. where the parameters being optimized are highly correlated. In addition, the premature convergence of GA degrades its performance and reduces its search capability.

Recently, a new evolutionary computation technique, called particle swarm optimization (PSO), has been proposed and introduced [15–18]. This technique combines social psychology principles in socio-cognition human agents and evolutionary computations. PSO has been motivated by the behavior of organisms such as fish schooling and bird flocking. Generally, PSO is characterized as simple in concept, easy to implement, and computationally efficient. Unlike the other heuristic techniques, PSO has a flexible and well-balanced mechanism to enhance and adapt to the global and local exploration abilities.

This paper presents an IPM-APSO (Adaptive Particle Swarm Optimization) integrated hybrid approach to study the OPF with TCPS for multiple objective minimizations. The objective functions of OPF include minimization of real power generation cost, voltage deviation, voltage stability index and real power loss. The proposed approach is examined with the IEEE 30-bus test system with one TCPS at a time.

II. FACTS DEVICES

FACTS technology is proven to be a promising solution for various power system problems.

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FACTS devices (especially series FACTS devices such as TCPS, TCSC, and SSSC) are considered one such technology that reduces the transmission congestion and allows better utilization of the existing grid infrastructure, along with many other benefits [19].

Several techniques have been proposed in the past for the adjustment of phase angles of phase shifter to alleviate line overloads [20-22]. The optimal power flow (OPF) with phase shifter is a good choice. In order to retain the symmetry of Y bus, the injection model of phase shifter used in [23-24] is adopted in this paper. The proposed approach is tested on an IEEE 30-bus test system with a phase shifters located in a transmission line.

A Phase Shifter Modelling

A flexible power flow model for the phase-shifting transformer is described in this section. It is derived from the two winding, single-phase transformer model, which contains complex taps on both the primary and secondary windings. The Thyristor Controlled Phase shifter circuit diagram can be represented by Figure 1. Due to the installation of phase shifter, the system will have lots of benefits such as overload release, system loss reduction and generation adjustment reduction.

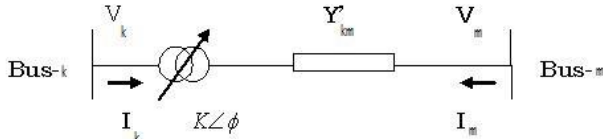


Figure 1 Circuit diagram of phase shifter

It is reasonable to assume that the phase-changing facility is only on the primary side, (i.e. $\phi_\mu = 0$); the primary and secondary windings admittances may be combined together [$Y = Y_{scp} Y_{scs} / (Y_{scp} + Y_{scs})$]; and the impact of magnetizing branch is negligibly small in the power flow solution. ($Y_0 = 0$):

$$\begin{bmatrix} I_k \\ I_m \end{bmatrix} = \begin{bmatrix} Y & -Y(\cos\phi + j\sin\phi) \\ -Y(\cos\phi - j\sin\phi) & Y \end{bmatrix} \begin{bmatrix} V_k \\ V_m \end{bmatrix} = \begin{bmatrix} Y_{kk} & Y_{km} \\ Y_{mk} & Y_{mm} \end{bmatrix} \begin{bmatrix} V_k \\ V_m \end{bmatrix} \quad (1)$$

Similar to the power flow LTC model, it is assumed in this expression that the primary and secondary sides of the transformer are connected to bus k and bus m, respectively. Also, the subscripts k and m are dropped in the admittance term and in the phase angle ϕ , respectively.

Based on equation (1), equations for the nodal power injections of the phase-shifting transformer, where ϕ is allowed to vary within design rating values ($\phi_{min} < \phi < \phi_{max}$), are as follows:

$$P_k = V_k^2 G_{kk} + V_k V_m [G_{km} \cos(\delta_k - \delta_m) + B_{km} \sin(\delta_k - \delta_m)] \quad (2)$$

$$Q_k = -V_k^2 B_{kk} + V_k V_m [G_{km} \sin(\delta_k - \delta_m) - B_{km} \cos(\delta_k - \delta_m)] \quad (3)$$

$$P_m = V_m^2 G_{mm} + V_m V_k [G_{mk} \cos(\delta_m - \delta_k) + B_{mk} \sin(\delta_m - \delta_k)] \quad (4)$$

$$Q_m = -V_m^2 B_{mm} + V_m V_k [G_{mk} \sin(\delta_m - \delta_k) - B_{mk} \cos(\delta_m - \delta_k)] \quad (5)$$

Where

$$\left. \begin{aligned} Y_{kk} &= G_{kk} + jB_{kk} = Y, \\ Y_{mm} &= G_{mm} + jB_{mm} = Y, \\ Y_{km} &= G_{km} + jB_{km} = -Y(\cos\phi + j\sin\phi), \\ Y_{mk} &= G_{mk} + jB_{mk} = -Y(\cos\phi - j\sin\phi). \end{aligned} \right\} \quad (6)$$

Alternatively, substituting equations (6) into equations (2)-(5) leads to the following more explicit expressions:

$$P_k = V_k^2 G - V_k V_m [G \cos(\delta_k - \delta_m - \phi) + B \sin(\delta_k - \delta_m - \phi)], \quad (7)$$

$$Q_k = -V_k^2 B - V_k V_m [G \sin(\delta_k - \delta_m - \phi) - B \cos(\delta_k - \delta_m - \phi)] \quad (8)$$

$$P_m = V_m^2 G - V_m V_k [G \cos(\delta_m - \delta_k + \phi) + B \sin(\delta_m - \delta_k + \phi)] \quad (9)$$

$$Q_m = -V_m^2 B - V_m V_k [G \sin(\delta_m - \delta_k + \phi) - B \cos(\delta_m - \delta_k + \phi)] \quad (10)$$

If the phase-shifting transformer is used to control the active power flowing through it at a specified value then the Jacobian is enlarged to accommodate one additional equation. In this situation ϕ enters as an extra state variable in the Jacobian equation. If the control is extended at the sending end (bus k) of the phase shifter then $P_{km}^{\phi ps}$ is the target power to be regulated.

The set of linearised power flow equations for the phase-shifting transformer is,

$$\begin{bmatrix} \Delta P_k \\ \Delta P_m \\ \Delta Q_k \\ \Delta Q_m \\ \Delta P_{km}^{\phi ps} \end{bmatrix}^{(i)} = \begin{bmatrix} \frac{\partial P_k}{\partial \delta_k} & \frac{\partial P_k}{\partial \delta_m} & \frac{\partial P_k}{\partial V_k} V_k & \frac{\partial P_k}{\partial V_m} V_m & \frac{\partial P_k}{\partial \phi} \\ \frac{\partial P_m}{\partial \delta_k} & \frac{\partial P_m}{\partial \delta_m} & \frac{\partial P_m}{\partial V_k} V_k & \frac{\partial P_m}{\partial V_m} V_m & \frac{\partial P_m}{\partial \phi} \\ \frac{\partial Q_k}{\partial \delta_k} & \frac{\partial Q_k}{\partial \delta_m} & \frac{\partial Q_k}{\partial V_k} V_k & \frac{\partial Q_k}{\partial V_m} V_m & \frac{\partial Q_k}{\partial \phi} \\ \frac{\partial Q_m}{\partial \delta_k} & \frac{\partial Q_m}{\partial \delta_m} & \frac{\partial Q_m}{\partial V_k} V_k & \frac{\partial Q_m}{\partial V_m} V_m & \frac{\partial Q_m}{\partial \phi} \\ \frac{\partial P_{km}^{\phi ps}}{\partial \delta_k} & \frac{\partial P_{km}^{\phi ps}}{\partial \delta_m} & \frac{\partial P_{km}^{\phi ps}}{\partial V_k} V_k & \frac{\partial P_{km}^{\phi ps}}{\partial V_m} V_m & \frac{\partial P_{km}^{\phi ps}}{\partial \phi} \end{bmatrix}^{(i)} \begin{bmatrix} \Delta \delta_k \\ \Delta \delta_m \\ \Delta V_k \\ \Delta V_m \\ \Delta \phi_{ps} \end{bmatrix}^{(i)} \quad \dots \dots \dots (11)$$

where $\Delta P_{km}^{\phi ps}$, given by $\Delta P_{km}^{\phi ps} = P_{km}^{\phi, reg} - P_{km}^{\phi ps}$, is the active power flow mismatch for the phase shifter; $P_{km}^{\phi ps}$ is the calculated power as given by equation (7); $\Delta \phi_{PS}$, given by $\Delta \phi_{PS} = \phi^{(i)} - \phi^{(i-1)}$, is the incremental change in the phase shifter angle at the i^{th} iteration.

III. MATHEMATICAL MODEL OF OPF PROBLEM

The OPF problem is to optimize the steady state performance of a power system in terms of an objective function while satisfying several equality and inequality constraints. Mathematically, the OPF problem can be formulated as given

$$\text{Min } J(x, u) \quad (12)$$

$$\text{Subject to } g(x, u) = 0 \quad (13)$$

$$h(x, u) \leq 0 \quad (14)$$

where x is a vector of dependent variables consisting of slack bus power P_{G_1} , load bus voltages V_L , generator reactive power outputs Q_G , and the transmission line loadings S_l . Hence, x can be expressed as given

$$x^T = [P_{G_1}, V_{L_1} \dots V_{L_{NL}}, Q_{G_1} \dots Q_{G_{NG}}, S_{l_1} \dots S_{l_{nl}}] \quad (15)$$

where NL, NG and nl are number of load buses, number of generators and number of transmission line respectively.

u is the vector of independent variables consisting of generator voltages V_G , generator real power outputs P_G except at the slack bus P_{G_1} , transformer tap settings T , and shunt VAR compensations Q_C . Hence u can be expressed as given

$$u^T = [V_{G_1} \dots V_{G_{NG}}, P_{G_2} \dots P_{G_{NG}}, T_1 \dots T_{NT}, Q_{C_1} \dots Q_{C_{NC}}] \quad (16)$$

Where NT and NC are the number of the regulating transformers and shunt compensators, respectively. F is the objective function to be minimized. g is the equality constraints that represents typical load flow equations and h is the system operating constraints

IV. OBJECTIVE FUNCTIONS

In this paper, the objective(s)(J) is the objective function to be minimized, which is one of the following:

(i) Objective function-1 (Fuel cost minimization)

It seeks to find the optimal active power outputs of the generation plants so as to minimize the total fuel cost. This can be expressed as

$$J = \sum_i^{NG} f_i (\$/h) \quad (17)$$

where f_i is the fuel cost curve of the i th generator and it is assumed here to be represented by the following quadratic function:

$$f_i = a_i P_{G_i}^2 + b_i P_{G_i} + c_i (\$/h) \quad (18)$$

where a_i, b_i , and c_i are the cost coefficients of the i^{th} generator.

(ii) Objective function-2 (Voltage profile improvement)

Voltage profile is one of the quality measures for power system. It can be improved by minimizing the load bus voltage deviations from 1.0 per unit. The objective function can be expressed as

$$J = \sum_{i \in NL} |V_i - 1| \quad (19)$$

(iii) Objective function-3 (Voltage stability enhancement)

Voltage profile improvement does not necessary implies a voltage secure system. Voltage instability problems have been experienced in systems where voltage profile was acceptable [25]. Voltage secure system can be assured by enhancing the voltage stability profile throughout the whole power system.

An indicator L -index is used in this study to evaluate the voltage stability at each bus of the system. The indicator value varies between 0 (no load case) and 1 (voltage collapse) [26-28]. One of the best features of the L -index is that the

computation speed is very fast and so can be used for on-line monitoring of power system. Enhancing the voltage stability and moving the system far from voltage collapse point can be achieved by minimizing the following objective function

$$J = L_{\max} \quad (20)$$

where L_{\max} is the maximum value of L -index as

$$L_{\max} = \max \{L_K, K = 1, \dots, NL\} \quad (21)$$

(iv) Objective function-4 (Real power loss minimization)

The optimal reactive power flow problem to minimize active losses can be formulated as

$$\begin{aligned} \min \quad & J = f(Z) \\ \text{s.t} \quad & g(Z) = 0 \\ & Z_{\min} \leq Z \leq Z_{\max} \end{aligned} \quad (22)$$

Where $f(\cdot)$ Objective function for active losses

$g(\cdot)$ Nonlinear vectors function representing power flow equations

$Z = [x \ u]^T$ Vector of decision variables whose components are the vector of state variables x (voltage phase angles and magnitudes, etc.) and the vector of discrete control variables u (generator terminal voltages, tap position of OLTC transformers, number of connected shunt compensation devices etc.).

Z_{\min} and Z_{\max} vectors modeling operational limits on state and control variables

(v) Constraints

The OPF problem has two categories of constraints:

Equality Constraints: These are the sets of nonlinear power flow equations that govern the power system, i.e.,

$$P_{G_i} - P_{D_i} - \sum_{j=1}^n |V_i| |V_j| |Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) = 0 \quad (23)$$

$$Q_{G_i} - Q_{D_i} + \sum_{j=1}^n |V_i| |V_j| |Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) = 0 \quad (24)$$

where P_{G_i} and Q_{G_i} are the real and reactive power outputs injected at bus i respectively, the load demand at the same bus is represented by P_{D_i} and Q_{D_i} , and elements of the bus admittance matrix are represented by $|Y_{ij}|$ and θ_{ij} .

Inequality Constraints: These are the set of constraints that represent the system operational and security limits like the bounds on the following:

1) generators real and reactive power outputs

$$P_{G_i}^{\min} \leq P_{G_i} \leq P_{G_i}^{\max}, i = 1, \dots, N \quad (25)$$

$$Q_{G_i}^{\min} \leq Q_{G_i} \leq Q_{G_i}^{\max}, i = 1, \dots, N \quad (26)$$

2) voltage magnitudes at each bus in the network

$$V_i^{\min} \leq V_i \leq V_i^{\max}, i = 1, \dots, NL \quad (27)$$

3) transformer tap settings

$$T_i^{\min} \leq T_i \leq T_i^{\max}, i = 1, \dots, NT \quad (28)$$

4) reactive power injections due to capacitor banks

$$Q_{Ci}^{\min} \leq Q_{Ci} \leq Q_{Ci}^{\max}, i = 1, \dots, CS \quad (29)$$

5) transmission lines loading

$$S_i \leq S_i^{\max}, i = 1, \dots, nl \quad (30)$$

6) voltage stability index

$$Lj_i \leq Lj_i^{\max}, i = 1, \dots, NL \quad (31)$$

The equality constraints are satisfied by running the power flow program. The generator bus terminal voltages (V_{gi}), transformer tap settings (t_k) and the reactive power generation of capacitor bank (Q_{Ci}) are the control variables and they are self-restricted by the representation itself. The active power generation at the slack bus (P_{gs}), load bus voltages (V_{Li}) and reactive power generation (Q_{gi}), voltage stability (L_j -index) are state variables which are restricted through penalty function approach.

(vi) FACTS devices constraints:

i) TCPS constraints

$$\alpha_{Pi}^{\min} \leq \alpha_{Pi} \leq \alpha_{Pi}^{\max} \quad \text{Phase angle constraint of TCPS} \quad (32)$$

where α_{Pi} = Phase shift angle of TCPS at line i

$\alpha_{Pi}^{\min}, \alpha_{Pi}^{\max}$ = Lower and upper phase shift angle limits of TCPS at line i

V. OVERVIEW OF PSO

The PSO technique is an evolutionary computation technique, but it differs from other well-known evolutionary computation algorithms such as the genetic algorithms. Although a population is used for searching the space, there are no operators inspired by the human DNA procedures applied on population. Instead, in PSO, the population dynamics simulates a ‘bird flock’s’ behavior, where social sharing of information takes place and individuals can profit from the discoveries and previous experience of all the other companions during the search for food.

Thus, each companion, called *particle*, in the population, which is called *swarm*, is assumed to ‘fly’ over the search space in order to find promising regions of the landscapes. For example, in the minimization case, such regions possess lower function values than other, visited previously. In this context, each particle is treated as a point in a D-dimensional space, which its own ‘flying’ according to its flying experience as well as the flying experience of other particles (companions). In PSO, a particle is defined as moving point in hyperspace. For each particle, at the current time step, a record is kept of the position, velocity, and the best position found in search space so far.

VI. ADAPTIVE PSO (APSO)

The basic system equation of PSO (33, 34 and 35) can be considered as a kind of difference equation.

$$v_i^{k+1} = wv_i^k + c_1 \text{rand}_1 * (pbest_i - s_i^k) + c_2 \text{rand}_2 * (gbest - s_i^k) \quad (33)$$

$$w = w_{\max} - ((w_{\max} - w_{\min}) / (iter_{\max})) * iter \quad (34)$$

$$s_i^{k+1} = s_i^k + v_i^{k+1} \quad (35)$$

Therefore, the system dynamics, that is, the search procedure, can be analyzed using eigen values of the difference equation. Actually, using a simplified state equation of PSO, Clerc and Kennedy developed CFA of PSO by eigen values [29, 30]. The velocity of the constriction factor approach (simplest constriction) can be expressed as follows instead of (33) and (34):

$$v_i^{k+1} = K[v_i^k + c_1 * \text{rand}_1 * (pbest_i - s_i^k) + c_2 * \text{rand}_2 * (gbest - s_i^k)] \quad (36)$$

$$K = \frac{2}{2 - \varphi - \sqrt{\varphi^2 - 4\varphi}},$$

$$\text{Where } \varphi = c_1 + c_2, \varphi > 4 \quad (37)$$

where φ and K are coefficients.

The following points are improved to the original PSO with IWA.

- The search trajectory of PSO can be controlled by introducing the new parameters (P1, P2) based on the probability to move close to the position of (pbest, gbest) at the following iteration.
- The wv_i^k term of (33) is modified as (36). Using the equation, the center of the range of particle movements can be equal to gbest.
- When the agent becomes gbest, it is perturbed. The new parameters (P1, P2) of the agent are adjusted so that the agent may move away from the position of (pbest, gbest).
- When the agent is moved beyond the boundary of feasible regions, pbests and gbest cannot be modified.
- When the agent is moved beyond the boundary of feasible regions, the new parameters (P1, P2) of the agent are adjusted so that the agent may move close to the position of (pbest, gbest).

The new parameters are set to each agent. The weighting coefficients are calculated as follows:

$$c_2 = \frac{2}{P_1}, c_1 = \frac{2}{P_2} - c_2 \quad (38)$$

The search trajectory of PSO can be controlled by the parameters (P1, P2). Concretely, when the value is enlarged more than 0.5, the agent may move close to the position of pbest/gbest.

$$w = gbest - \left(\left\{ c_1 (pbest - x) + c_2 (gbest - x) \right\} / 2 + x \right) \quad (39)$$

Namely, the velocity of the improved PSO can be expressed as follows:

$$v_i^{k+1} = w_i + c_1 \text{rand}_1 * (pbest_i - s_i^k) + c_2 \text{rand}_2 * (gbest - s_i^k) \quad (40)$$

The improved PSO can be expressed as follows (steps 1 and 5 are the same as PSO):

- *Generation of initial searching points:* Basic procedures are the same as PSO. In addition, the parameters (P1, P2) of each agent are set to 0.5 or higher. Then, each agent may move close to the position of (pbest, gbest) at the following iteration.

- *Evaluation of searching points:* The procedure is the same as PSO. In addition, when the agent becomes gbest, it is perturbed. The parameters (P_1, P_2) of the agent are adjusted to 0.5 or lower so that the agent may move away from the position of (pbest, gbest).

Modification of searching points: The current searching points are modified using the state equations (40), (36) of adaptive PSO.

VII. OVERALL COMPUTATIONAL PROCEDURE FOR SOLVING THE PROBLEM

The implementation steps of the proposed IPM-APSO based algorithm can be written as follows;

- Step 1: Input the system data for load flow analysis
- Step 2: Run the power flow
- Step 3a: Select a FACTS device and its location in the system
- Step 3b: At the generation Gen =0; set the simulation parameters of IPM-APSO parameters and randomly initialize k individuals within respective limits and save them in the archive.
- Step 4: For each individual in the archive, run power flow to determine load bus voltages, angles, load bus voltage stability indices, generator reactive power outputs and calculate line power flows.
- Step 5: Evaluate the penalty functions
- Step 6: Evaluate the objective function values and the corresponding fitness values for each individual.
- Step 7: Find the generation local best xlocal and global best xglobal and store them.
- Step 8: Increase the generation counter Gen = Gen+1.
- Step 9: Apply the IPM-APSO operators to generate new k individuals
- Step 10: For each new individual in the archive, run power flow to determine load bus voltages, angles, load bus voltage stability indices, generator reactive power outputs and calculate line power flows.
- Step 11: Evaluate the penalty functions
- Step 12: Evaluate the objective function values and the corresponding fitness values for each new individual.
- Step 13: Apply the selection operator of IPM-APSO and update the individuals.
- Step 14: Update the generation local best xlocal and global best xglobal and store them.
- Step 15: If one of stopping criterion have not been met, repeat steps 4-14. Else go to stop 16
- Step 16: Print the results

VIII. SIMULATION RESULTS

The simulation results of the proposed hybrid OPF method with TCPS for different objective functions (i.e. fuel cost minimization, voltage profile improvement, voltage stability enhancement, and real power loss minimization) have been applied to IEEE-30 bus system with NR-load flow, Newton-OPF Interior Point-OPF and IPM-APSO with TCPS methods. The approach can be generalized and easily extended to large-scale systems.

The IEEE-30 bus system consists of six generators, four transformers, 41 lines, and nine shunt capacitors. In this PSO variant method, the total control variables are 25: six unit active power outputs, six generator bus voltage magnitudes, four transformer tap settings, and nine bus shunt admittances. The proposed algorithms are implemented using MATLAB 7.1 running on Pentium IV, 2.66GHz, and 512MB RAM personal computer. The IPM-APSO parameters used for the simulation are summarized in Table 1

Table 1 Optimal parameter settings for IPM-APSO

Parameter	IPM-APSO
Population size	20
Number of iterations	150
Cognitive constant, c1	2
Social constant, c2	2
Inertia weight, W	0.3-0.95

To test the ability of the proposed hybrid algorithms along with TCPS for solving optimal power flow problem to reduce specified objective function, it was applied on selected bus system. One TCPS is installed. TCPS is installed at line connected between buses 15 and 18 with line real and reactive power settings of TCPS, $P_{mk} = 0.10$, $Q_{mk} = 0.01$ and $-\pi/4 \leq \alpha_{pi} \leq \pi/4$. Four objective functions are considered for the minimization using the proposed hybrid algorithm namely cost of generation, voltage profile improvement, voltage stability enhancement and real power loss minimization.

The best results for APSO method combined with NR-load flow, Newton-OPF, and Interior Point method are compared and results are tabulated in Table 2. In this table, the optimal settings of the control variables and various performance parameters with four objective functions are presented. From Table 2, it was found that all the state variables satisfy lower and upper limits. From the results it is evident that proposed IPM-APSO hybrid method along with TCPS outperforms in achieving minimum of the specified objective when compared with other optimization methods.

Table 2 Optimal settings of control variables of IEEE 30-bus system in APSO based OPF method

IX. CONCLUSION

In this paper, a new IPM-APSO hybrid method has been presented to solve the optimal power flow problem with a FACTS device. The proposed method introduces the voltage source model of FACTS devices into a conventional AC optimal power flow problem to exploit the new characteristic of FACTS devices. Case studies on IEEE-30 bus test system show the potential for application of IPM-APSO to achieve different objectives with FACTS. It has been shown that the FACTS devices can effective in achieving the specified objectives.

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Table 2 Optimal settings of control variables of IEEE 30-bus system in APSO based OPF method

Control Variables	Objective function-1 (cost)			Objective function-2 (V.D)			Objective function-3 (L-index)			Objective function-4 (loss)		
	APSO-Newton	IPM-APSO	IPM-APSO with TCPS	APSO-Newton	IPM-APSO	IPM-APSO with TCPS	APSO-Newton	IPM-APSO	IPM-APSO with TCPS	APSO-Newton	IPM-APSO	IPM-APSO with TCPS
P_1	1.7654	1.7651	1.7815	1.7998	1.7992	1.3860	1.6243	1.7940	1.3038	0.6186	0.3639	0.5140
P_2	0.4935	0.4935	0.4895	0.5107	0.4936	0.5355	0.4886	0.4935	0.4996	0.8000	0.8000	0.8000
P_5	0.2165	0.2165	0.2143	0.2067	0.2167	0.3574	0.2193	0.2165	0.3829	0.5000	0.5000	0.5000
P_8	0.2278	0.2278	0.2284	0.1281	0.1281	0.2468	0.1314	0.2278	0.2067	0.3000	0.3000	0.3000
P_{11}	0.1200	0.1200	0.1203	0.1201	0.1200	0.2444	0.1831	0.1200	0.1608	0.4000	0.3500	0.4000
P_{13}	0.1000	0.1000	0.1000	0.1870	0.1936	0.1445	0.2628	0.1000	0.3500	0.2495	0.3500	0.3500
V_1	1.0863	1.0872	1.0860	0.9945	0.9963	0.9989	1.0467	1.0677	1.0238	1.0592	1.0608	1.0616
V_2	1.0672	1.0683	1.0670	1.0044	1.0032	1.0171	1.0497	1.0138	1.0106	1.0491	1.0565	1.0577
V_5	1.0361	1.0373	1.0362	1.0169	1.0177	1.0194	1.0590	1.0453	0.9830	1.0386	1.0443	1.0377
V_8	1.0406	1.0418	1.0406	1.0082	1.0071	1.0033	1.0504	1.0624	1.0062	1.0109	1.0460	1.0422
V_{11}	1.0450	1.0299	1.0678	0.9916	0.9714	0.9944	1.0282	1.0535	1.1000	1.0308	1.0384	1.0527
V_{13}	1.0300	1.0396	1.0397	1.0176	1.0115	1.0126	1.0280	1.0401	1.0080	1.0443	1.0447	1.0501
T_{11}	0.9821	1.0051	1.0233	1.0019	0.9780	0.9977	1.0477	1.0007	0.9761	0.9543	1.0020	1.0317
T_{12}	1.0063	0.9737	0.9746	0.9542	1.0100	0.9460	1.0458	1.0924	1.1000	1.0272	0.9650	0.9661
T_{15}	0.9623	0.9674	0.9682	1.0152	1.0193	1.0123	0.9919	1.0466	1.1000	1.0198	0.9884	0.9916
T_{36}	0.9766	0.9770	0.9791	0.9690	0.9812	0.9786	0.9825	0.9801	0.9271	0.9820	0.9859	0.9752
Q_{C10}	0.0581	0.0830	0.0346	0.0423	0.0788	0.0249	0.1000	0.1000	0.1000	0.1000	0.0601	0.0815
Q_{C12}	0.1000	0.0484	0.0589	0.0763	0.0344	0.0630	0.1000	0.1000	0.1000	0.1000	0.0653	0.0530
Q_{C15}	0.0437	0.0377	0.0377	0.0568	0.0662	0.0656	0.0915	0.1000	0.1000	0.0778	0.0755	0.0281
Q_{C17}	0.0710	0.0667	0.0632	0.0245	0.0498	0.0328	0.1000	0.1000	0.0938	0.0200	0.0695	0.0601
Q_{C20}	0.0418	0.0433	0.0424	0.0876	0.1000	0.0717	0.0843	0.1000	0.0997	0.1000	0.0000	0.0415
Q_{C21}	0.1000	0.1000	0.1000	0.0686	0.1000	0.0876	0.1000	0.1000	0.1000	0.0140	0.0756	0.0975
Q_{C23}	0.0180	0.0182	0.0239	0.0313	0.0674	0.0395	0.1000	0.1000	0.0711	0.0383	0.0246	0.0319
Q_{C24}	0.0759	0.0786	0.0780	0.0981	0.1000	0.0892	0.1000	0.1000	0.0682	0.1000	0.0720	0.0724
Q_{C29}	0.0247	0.0235	0.0266	0.0215	0.0350	0.0316	0.0306	0.0236	0.0273	0.0375	0.0246	0.0225
P_{kms}	---	---	0.3014	---	---	0.1939	---	---	0.4000	---	---	0.4000
Cost(\$/h)	800.3463	800.2644	800.2275	809.6815	809.4223	830.7991	807.0878	809.8743	846.6384	951.7429	955.5348	971.5899
V.D	0.9580	0.9523	0.9887	0.0752	0.0733	0.0728	0.9840	1.0231	0.4408	0.8532	0.9052	0.9901
L- Index	0.1238	0.1241	0.1263	0.1338	0.1324	0.1315	0.1192	0.1188	0.1138	0.1241	0.1262	0.1226
Ploss(pu)	0.0892	0.0890	0.0901	0.1184	0.1171	0.0805	0.0935	0.1178	0.0699	0.0341	0.0319	0.0299