A Novel Approach for Congestion Management in Transmission System with Advanced Control Using Innovative Algorithm

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Abstract: This paper presents an effective method of congestion management in power systems. In a modern power system, it is sometimes problematic to allocate all the necessary power to a supply due to overloading the power lines. Congestions or overloads in transmission networks are alleviated by generation rescheduling and/or load shedding of participating generators and loads. The main objective is the alleviation of congestion, and the minimization of generation costs is optimised to provide optimal solutions. This work proposes an optimal power flow control for the management of congestion in transmission lines by the advanced interline power flow controller (AIPFC) using the Constriction Factor Based Particle Swarm Optimization (CFBPSO) algorithm. For power flow analysis, an advanced model of interline power flow controller (AIPFC) is embedded in the transmission network and it includes the impedance of the series coupling transformer and the line charging susceptance. An innovative algorithm, i.e., CFBPSO, is proposed to take care of OPF issues in the presence of advanced IPFC. The proposed method is implemented on the IEEE-30 bus test system under different loading and contingency conditions. The results are presented and analysed to establish the effectiveness in the reduction of congestion.

Keywords: Flexible AC Transmission System (FACTS), Congestion management, Advanced Interline Power Flow Controller (AIPFC), Constriction Factor Based Particle Swarm Optimization (CFBPSO) and Optimal Power Flow (OPF).

1. Introduction

With the increasing demand for electric power all around the globe, electric utilities have been forced to meet the same by increasing their generation. The transmission system is the most important intermediate environment between load and generation in power grids. New technologies are being developed to provide such delivery performance. This could happen in the individual planning stage or later in expansion planning, depending on the customer's needs. It could also mean putting in a further device somewhere within the network. The power system's proper operation and performance in dynamic and steady-state conditions play an important role in the adequate and secure operation of the whole power system. Reduction of power loss and voltage drop in the path between generation and load has always been essential for power system efficiency. However, the amount of electrical power that will be transmitted between two locations on a transmission network is restricted by several transfer limits, like thermal limits, voltage limits, and stability limits, with the most restrictive applying at a given time [1]- [6].

Ensuring that the power system operates within its limits is vital to maintaining power system security. Congestion can lead to widespread blackouts with potentially severe social and economic consequences [7]-[8]. The methods generally adopted to manage congestion include rescheduling generator output, supplying reactive power support, or physically curtailing transactions. In this regard, researchers and engineers have come up with a number of approaches to relieve the congestion. The methods for congestion management can be categorised as technical or non-technical. Technical methods include installation of phase-shifting transformers, operation of flexible ac transmission system (FACTS) devices, and outage of overloaded lines [9]–[11]. Non-technical methods can be market-based or non-market-based.

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Market-based methods include counter trading, generation redispatching [12–13], load curtailing, auctioning, market splitting, nodal pricing, and zonal pricing [14] Non-market-based methods include pro-rata and first come, first served approaches.

Several techniques for congestion management have been reported in the literature [15]. The economic efficiency of the energy market is also addressed [16]. Congestion management techniques applied to various kinds of electricity markets are presented [17]. An optimal topological configuration of a power system as a tool of congestion management is presented [18, 19].

Literature on optimal power flow (OPF)-based congestion management schemes for multiple transaction systems is available. In [20], an OPF-based approach that minimises the cost of congestion and service costs has been proposed. A coordination mechanism between generating companies and system operators for congestion management using bender cuts has been discussed in [21]. In [22], a technique has been proposed for alleviating congestion due to voltage instability and thermal overloads. A zonal model based on ac load flow was proposed in [23] and [24]. Zones have been identified based on sensitivity values in these studies also. However, in both [21] and [23], it is necessary to compute the sensitivity values for all the buses in the system, which, given a practical power system, calls for a large amount of computational effort. Sensitivity of line flow to changes in generation has been used in [25] to alleviate congestion, but no effort has been made to reduce the number of participating generators. In [26], a technique has been proposed for the selection of participating generators based on sensitivity to current flow on congested lines as well as the generation bids. A method of overload alleviation by real power generation rescheduling supported by the relative electrical distance (RED) concept has been introduced in [27].

FACTS devices are preferred in modem power systems because of their overall performance [28].Of all the FACTS devices, the combined compensators, such as the unified power flow controller (UPFC) and IPFC, are regarded as the most powerful and versatile ones. Facilitated by its two self-commutated, voltage-sourced switching converters (VSCs) with a common dc voltage link, UPFC is capable of independently controlling both the active and reactive power flows in the line. Unlike UPFC, IPFC can compensate for multiple transmission lines at a given substation because its VSCs are connected in series with, usually, different lines [29]. Proper mathematical modelling of this FACTS device is required for IPFC power flow control and optimal power flow control. Like the UPFC injection models [30] through [31] and the exact pi-model of UPFC-inserted transmission lines [32], the IPFC injection models and transmission lines embedded with IPFC are developed using the mathematical model [33].

This research's goal is to see how well a constraint factor-based particle swarm optimization technique can manage congestion. In traditional OPF solutions, the search direction is the function's derivative. In order for these methods to work, the problem must be expressed as a continuous differentiable function. The paper solves the optimization problem using constriction factor-based particle swarm optimization. Most optimization methods use the fitness function to represent the objective function's value and the penalty function method to represent the constraint values. Constriction factor-based particle swarm optimization was used to manage constraints in this work. With this proposed technique, the original PSO algorithm is constrained. Adding a constriction factor to PSO helps ensure particle swarm algorithm convergence. The constriction factor approach causes individual convergence over time. Unlike other evolutionary computation methods, the constriction factor approach ensures mathematical theory convergence. Thus, the constriction factor approach can generate better solutions than PSO. The constriction factor approach only considers one individual's dynamic behaviour and the effects of inter-individual interactions. This analysis shows the proposed solution's effectiveness in reducing congestion using the IEEE 30-bus system.

2. Advanced Interline Power Flow Controller (AIPFC)

The IPFC has significantly more flexible topologies, at least two converters, and can control power flows over a set of lines. It's possible that the IPFC will be used to address transmission network congestion control issues. This inspires the author to create a novel IPFC model for power flow analysis. Existing steady-state models are decoupled or linked. To change the Jacobian matrix structure, the FACTS devices are frequently replaced by a fictitious PQ or PV bus. VSM [34, 38-39] and PIM [35-37] are the two main models of an interconnected model. Also, dealing with the practical limitations of FACTS devices is important [40]. The IPFC limitations are not addressed in their power flow programmes.

A novel IPFC power injection model is considered in this study. This model includes the series converter transformer's impedance and line charging susceptance. The sparsity technique can be used to preserve the admittance matrix's original structure and symmetry, and thus the Jacobian matrix's block-diagonal properties. The IPFC state variables are modified simultaneously with the network state variables to achieve the control targets. The model can also account for IPFC's practical constraints, as shown in Newton power flow [41, 42].

Operating Principle of Advanced Interline Power Flow Controller (AIPFC)

It is composed of several DC-to-AC converters, each of which provides series compensation for a separate line. They are linked to the AC systems via series coupling transformers and their DC terminals. In this design, any converter can provide active power to the common DC link as well as series reactive compensation. All *m-1* series converters in an IPFC have two control degrees of freedom, except one, which has one because the active power exchange among the m series converters must always be balanced. The IPFC with two series converters shown in Figure 1 is used to illustrate the basic operation principles. The mathematical derivation works for any IPFC with series converters.

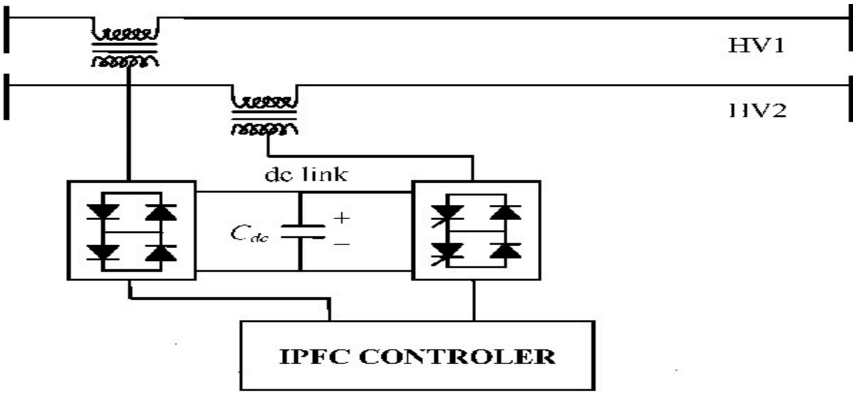


Figure1. Arrangement of two-converter AIPFC

Equivalent Circuit and Mathematical Model of AIPFC

The mathematical derivation applies to an AIPFC with any number of series converters.

$V_{i_n} = V_{i_n} \angle \theta_{i_n}$ and

$V_{j_n} = V_{j_n} \angle \theta_{j_n}$:The complex bus voltages at buses i_n and j_n

I_{i_n} and I_{j_n} :The complex currents injection at buses i_n and j_n

$V_{se_n} = V_{se_n} \angle \theta_{se_n}$: The complex controllable series injected voltage

$Z_{se_n} = R_{se_n} + jX_{se_n}$: The series transformer impedance

$Z_{l_n} = X_{l_n} + jX_{l_n}$: The line series impedance

B_{10} : The line charging susceptance

From Figure 2:

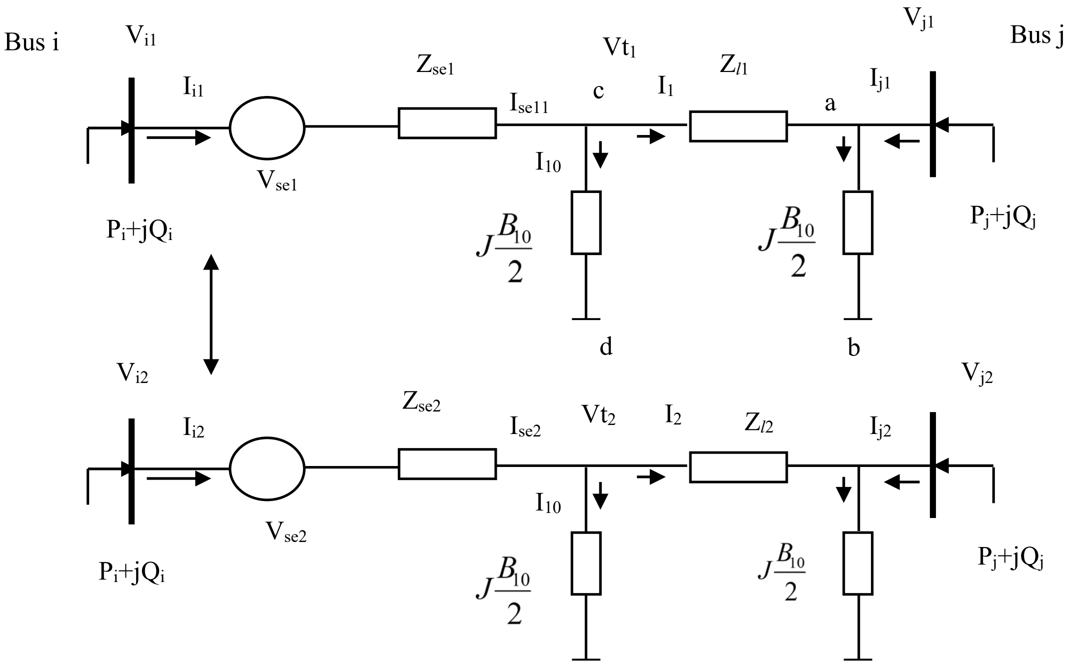


Figure 2. Equivalent Circuit diagram of AIPFC

$$V_{i_n} = V_{se_n} + I_{i_n} Z_{se_n} + V_{t_n} \tag{1}$$

$$I_{i_n} = I_1 + I_{10} = \frac{\left(V_{t_n} - V_{r_n}\right)}{Z_{l_n}} + V_{t_n}\left(j\frac{B_{10}}{2}\right) \tag{2}$$

We can express V_{t_n} and I_{i_n} according to V_{j_n} and I_{j_n} as

$$V_{t_n} = I_1 Z_{l_n} + V_{j_n} \tag{3}$$

$$I_1 = -I_{j_n} + I_{ab} \tag{4}$$

Where $I_{ab} = \frac{V_{ab}}{Z_{ab}} = \frac{V_{j_n}}{\left(\frac{2}{jB_{10}}\right)} = V_{j_n}\left(j\frac{B_{10}}{2}\right)$ (5)

$$I_1 = -I_{j_n} + V_{j_n}\left(j\frac{B_{10}}{2}\right) \tag{6}$$

$$V_{t_n} = V_{j_n}\left[1 + \left(j\frac{B_{10}}{2}\right)Z_{l_n}\right] - I_{j_n}\left[Z_{l_n}\right] \tag{7}$$

$$I_{10} = I_{cd} = \frac{V_{cd}}{Z_{cd}} = \frac{V_{t_n}}{\left(\frac{2}{jB_{10}}\right)} = V_{t_n}\left(\frac{jB_{10}}{2}\right) \tag{8}$$

$$I_{10} = V_{j_n}\left(\frac{jB_{10}}{2}\right) + V_{j_n} Z_{l_n}\left(\frac{B_{10}^2}{4}\right) - I_{jn} Z_{l_n}\left(j\frac{B_{10}}{2}\right) \tag{9}$$

Substitute equation (6) and (9) in equation (2)

$$I_{i_n} = V_{j_n}\left[\left(jB_{10}\right) + Z_{l_n}\left(\frac{B_{10}^2}{4}\right)\right] - I_{jn}\left[1 + Z_{l_n}\left(j\frac{B_{10}}{2}\right)\right] \tag{10}$$

For reducing the complexity of equations (7) and (10) take

$$D = \left[\left(jB_{10}\right) + Z_{l_n}\left(\frac{B_{10}^2}{4}\right)\right]$$ and

$$E = \left[1 + Z_{l_n}\left(j\frac{B_{10}}{2}\right)\right]$$

From equations (1), (2), (7) and (10): I_{i_n} & I_{j_n} in terms of V_{i_n} , V_{j_n} & V_{se_n} as

From (7) & (10) rewrite

$$V_{t_n} = V_{j_n} E - I_{j_n} Z_{l_n} \tag{11}$$

$$I_{i_n} = V_{j_n} D - I_{jn} E \tag{12}$$

Substitute equation (11) and (12) in equation (1)

$$I_{jn} = \frac{V_{se_n}}{Z_{se_n} E + Z_{l_n}} - \frac{V_{i_n}}{Z_{se_n} E + Z_{l_n}} + \frac{V_{j_n}\left\lfloor Z_{se_n} D + E \right\rfloor}{Z_{se_n} E + Z_{l_n}} \tag{13}$$

For reducing the complexities of equation (13) take

$$N = Z_{se_n} E + Z_{l_n}$$ and

$$M = Z_{se_n} D + E$$

$$I_{jn} = V_{j_n}\frac{M}{N} - \frac{V_{i_n}}{N} + \frac{V_{se_n}}{N} \tag{14}$$

$$I_{i_n} = V_{j_n}\left(D - \frac{EM}{N}\right) + V_{i_n}\frac{E}{N} - V_{se_n}\frac{E}{N} \tag{15}$$

Equation (14) and (15) can also be written in matrix form as

$$\begin{bmatrix} I_{i_n} \\ I_{j_n} \end{bmatrix} = \begin{bmatrix} A_{ii_n} & A_{ij_n} \\ A_{ji_n} & A_{jj_n} \end{bmatrix}\begin{bmatrix} V_{i_n} \\ V_{j_n} \end{bmatrix} + \begin{bmatrix} W_{ii_n} \\ W_{ji_n} \end{bmatrix} V_{se_n} \tag{16}$$

Where

$$A_{ii_n} = \frac{E}{N},\ A_{jj_n} = \frac{M}{N},\ A_{ij_n} = D - \frac{ME}{N},\ A_{ji_n} = -\frac{1}{N}$$

$$W_{ii_n} = -\frac{E}{N},\ W_{ji_n} = \frac{1}{N}$$

$$A_{ij_n} = A_{ji_n} \tag{17}$$

$$A_{ii_n} = -A_{ij_n} + A_{i_n}^{0},$$

$$A_{i_n}^{0} = D + \frac{E(1-M)}{N}$$

$$A_{jj_n} = -A_{ji_n} + A_{j_n}^{0},$$

$$A_{j_n}^{0} = D + \frac{M-N}{N} \tag{18}$$

From the equation (16) the equivalent circuit shown in Figure 3:

$$P_{i_n}^{se} = \frac{\left(1 - \frac{B_{10}}{2} X_{l_n}\right)}{H} V_{i_n} V_{se_n} \sin\left(\theta_{i_n} - \theta_{se_n}\right) \tag{19}$$

$$Q_{i_n}^{se} = \frac{-\left(1 - \frac{B_{10}}{2} X_{l_n}\right)}{H} V_{i_n} V_{se_n} \cos\left(\theta_{i_n} - \theta_{se_n}\right) \tag{20}$$

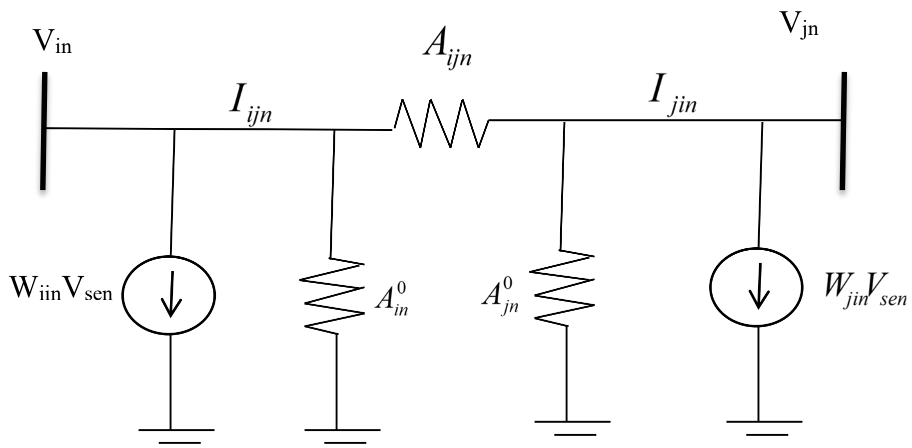


Figure 3. Representation of AIPFC using current source

$$P_{j_n}^{se} = \frac{-V_{j_n} V_{se_n}}{H} \sin\left(\theta_{j_n} - \theta_{se_n}\right) \tag{21}$$

$$P_{j_n}^{se} = \frac{V_{j_n} V_{se_n}}{H} \cos\left(\theta_{j_n} - \theta_{se_n}\right) \tag{22}$$

Where $H = X_{se_n}\left[1 - \left(\frac{B_{10}}{2}\right) X_{l_n}\right] + X_{l_n}$

Power Injection Model of AIPFC

It can be concluded that the admittance matrix still keeps the same structure and symmetry as that of the case without IPFC.

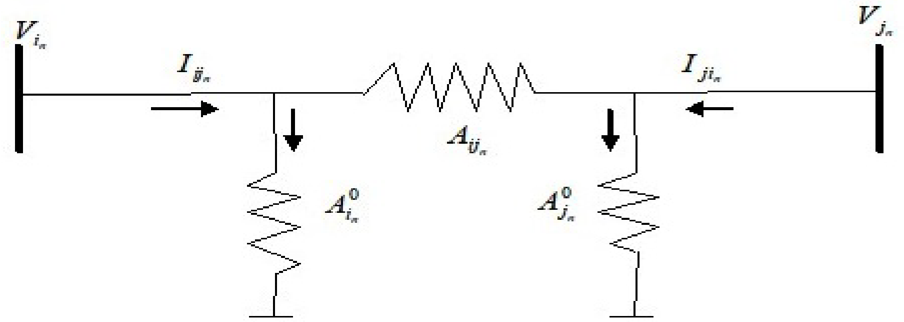


Figure 4. Power injections π-model of AIPFC

$$I_{ij_n} = \left(V_{i_n} - V_{r_n}\right) A_{ij_n} + V_{i_n} A_{i_n}^0 \tag{23}$$

$$I_{ji_n} = \left(V_{j_n} - V_{i_n}\right) A_{ij_n} + V_{j_n} A_{j_n}^0 \tag{24}$$

$$P_{ij_n} = \mathrm{Re}\left(V_{i_n} I_{ij_n}^*\right) = \frac{-1}{H} V_{i_n} V_{j_n} \sin\theta_{ij_n} \tag{25}$$

$$Q_{ij_n} = \mathrm{Im}\left(V_{i_n} I_{ij_n}^*\right) = \frac{-\left(1 + \frac{B_{10}}{2} X_{l_n}\right) V_{i_n}^2 + V_{i_n} V_{j_n} \cos\theta_{ij_n}}{H} \tag{26}$$

$$P_{ji_n} = \mathrm{Re}\left(V_{j_n} I_{ji_n}^*\right) = \frac{-1}{H} V_{i_n} V_{j_n} \sin\theta_{ji_n} \tag{27}$$

$$Q_{ji_n} = \mathrm{Im}\left(V_{j_n} I_{ji_n}^*\right)$$

$$Q_{ji_n} = \frac{V_{j_n}}{H}\left(-V_{j_n} + V_{i_n} \cos\theta_{ji_n}\right) - V_{j_n}\left[X_{se_n}\left(B_{10} - \frac{B_{10}^2 X_{l_n}}{4}\right) + \frac{B_{10} X_{l_n}}{2}\right] \tag{28}$$

$$P_{dc} = \sum_n P_{ex_n} = 0 \tag{29}$$

Where

$$P_{ex_n} = \mathrm{Re}\left(V_{se_n} I_{i_n}^*\right)$$

$$P_{ex_n} = \left(B_{10} - \frac{B_{10}^2 X_{l_n}}{4} + \frac{G}{H}\right) V_{se_n} V_{j_n} \sin\left(\theta_{se_n} - \theta_{j_n}\right) - \frac{\left(1 - \frac{B_{10} X_{l_n}}{2}\right) V_{i_n} V_{se_n} \sin\left(\theta_{se_n} - \theta_{i_n}\right)}{H} = 0 \qquad (30)$$

Where $G = \left[-X_{se_n}\left(B_{10} - X_{l_n}\left(\frac{B_{10}^2}{4}\right)\right) + 1 - X_{l_n}\left(\frac{B_{10}}{2}\right)\right]\left[1 - X_{l_n}\left(\frac{B_{10}}{2}\right)\right]$

3. Particle Swarm Optimization

Particle swarm optimization was created by Kennedy and Eberhart in 1995 [43]. Example of social behaviour in creatures: schools of fish or birds. A flock of birds found food in an area at random. While not all birds in a flock know exactly where food is, they know the position closest to it (the food). The easiest and most effective way to find food is to search the area around your current best position. Unlike other optimization algorithms, PSO does not require derivative information. The procedure can continue until the optimization model's fitness values are computed. The PSO algorithm is also easy to understand while having a solid intellectual foundation.

PSO has already been used to optimise power systems. In [44], a PSO was used to solve the problem of economic generator dispatch. [45] It proposes a method for controlling reactive power and voltage to ensure system voltage stability. [46] Describes using PSO for sensitivity-based congestion management. It does not provide a method for dealing with constraints.

Constriction Factor Based PSO (CFBPSO)

Velocity of each agent can be modified by the following equation:

$$v_i^{k+1} = wv_i^k + c_1 rand_1 * (pbest_i - s_i^k) \quad + c_2 rand_2 * (gbest - s_i^k) \qquad (31)$$

where v_i^k is velocity of agent i at iteration k, w is weighting function, c_1 and c_2 are weighting factors, $rand_1$ and $rand_2$ are random numbers between 0 and 1, s_i^k is current position of agent i at iteration k, $pbest_i$ is the pbest of agent i, and gbest is gbest of the group. Namely, velocity of an agent can be changed using three vectors such like boid. The velocity is usually limited to a certain maximum value. PSO using (31) is called the Gbest model.

$$w = w_{\max} - ((w_{\max} - w_{\min})/(iter_{\max})) * iter \qquad (32)$$

Where $w_{\max}$ is the initial weight, $w_{\min}$ is the final weight, $iter_{max}$ is maximum iteration number and iter is current iteration number.

The meanings of the right-hand side (RHS) of (31) can be explained as follows. The RHS of (31) consists of three terms (vectors). The first term is the previous velocity of the agent. The second and third terms are utilized to change the velocity of the agent. Without the second and third terms, the agent will keep on "flying" in the same direction until it hits the boundary. Namely, it tries to explore new areas and, therefore, the first term corresponds with diversification in the search procedure. On the other hand, without the first term, the velocity of the "flying" agent is only determined by using its current position and its best positions in history. Namely, the agents will try to converge to their pbests and/or gbest and, therefore, the terms correspond with intensification in the search procedure. As shown below, for example, $w_{\max}$ and $w_{\min}$ are set to 0.9 and 0.4. Therefore, at the beginning of the search procedure, diversification is heavily weighted, while intensification is heavily weighted at the end of the search procedure such like simulated annealing (SA). Namely, a certain velocity, which gradually gets close to pbests and gbest, can be calculated. PSO using (31), (32) is called inertia weights approach (IWA). The current position (searching point in the solution space) can be modified by the following equation:

$$s_i^{k+1} = s_i^k + v_i^{k+1} \tag{33}$$

PSO's basic system equation [(31), (32), and (33)] can be seen of as a difference equation. As a result, the eigen values of the difference equation can be used to study the system dynamics, or the search operation. Clerc and Kennedy constructed CFB of PSO by eigen values using a simplified state equation of PSO. Instead of (31) and (32), the velocity of the constriction factor approach (simplest constriction) might be represented as follows:

$$v_i^{k+1} = K[v_i^k + c_1 * rand_1 * (pbest_i - s_i^k) + c_2 * rand_2(gbest - s_i^k)] \tag{34}$$

$$K = \frac{2}{2 - \varphi - \sqrt{\varphi^2 - 4\varphi}}, \text{ where } \varphi = c_1 + c_2, \varphi > 4 \tag{35}$$

where φ and K are coefficients.

For example, if φ =4.1, then K = 0.73. As w increases above 4.0, K gets smaller.For example, if φ =5.0, then K =0.38, and the damping effect is even more pronounced.

However, CFB uses a different equation for calculating velocity than IWA [(34)]. Unlike other EC approaches, the PSO with CFB ensures mathematical theory-based search algorithm convergence. PSO with CFB can produce better solutions than PSO with IWA in some cases. However, CFB only considers one agent's dynamic behaviour and studies the effects of agent interaction.

These people tend to converge over time. Unlike other evolutionary computation approaches, the constriction factor approach guarantees mathematical theory convergence. As a result, the restriction factor strategy outperforms the PSO strategy. However, the restriction factor method only addresses one individual's dynamic behaviour and the effects of inter-individual interactions. However, Pbest and Gbest change during the search procedure in the basic PSO equation. As a result, CFBPSO can produce better solutions than PSO [47-49].

4. Problem Formulation for Congestion Management

The optimal power flow (OPF) problem is a static non-linear constrained optimization problem, the solution of which determines the optimal setting for control variables in a power network.

Minimize f(x)
Subject to h(x)=0 (36)
g(x)≤0

The objective of congestion management problem is to alleviate the congestion and minimize the cost of generation. Mathematically, this can be represented as in the following.

$$\min c(x) = \min \sum_{i=1}^{Ng} \left(c_i + b_i P_{Gi} + a_i P_{Gi}^2\right) \tag{37}$$

P_{Gi} : Generation of active power of i^{th} bus
N_G is the number of generators in the test system
a_i, b_i and c_i are the cost coefficients of 'i^{th}' generating unit

Equality constraints

These constraints are typically power flow equations satisfied in Newton–Raphson load flow solution:

$$P_{Gi} - P_{Di} - \sum_{j=1}^{nb} |V_i||V_j||Y_{ij}| \cos(\theta_{ij} + \delta_j - \delta_i -) = 0 \tag{38}$$

$$Q_{Gi} - Q_{Di} - \sum_{j=1}^{nb} |V_i||V_j||Y_{ij}| \sin(\theta_{ij} + \delta_j - \delta_i) = 0 \quad (39)$$

b. Inequality Constraints

Active Power Generation limits

$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max}$ i=1,…,NG (40)

Reactive Power Generation limits

$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max}$ i=1,…,NG (41)

Active Power demand

$P_{Di}^{\min} \le P_{Di} \le P_{Di}^{\max}$ i=1,…,NG (42)

Reactive Power demand

$Q_{Di}^{\min} \le Q_{Di} \le Q_{Di}^{\max}$ i=1,…,NG (43)

Load bus voltage magnitude limits

$V_i^{\min} \le V_i \le V_i^{\max}$

i=1,…,NL (44)

Tap settings for transformer

$T_i^{\min} \le T_i \le T_i^{\max}$

i=1,…,NT (45)

Transmission lines loading

$S_i \le S_i^{\max}$

i=1,…,nl (46)

A. Procedure for Congestion Management by AIPFC Using CFBPSO Algorithm

The step by step procedure to solve the optimization problem by proposing CFBPSO method is given below.

Set the initial variables of the PSO and the power system variables along with the parameters of AIPFC.

Initialize the i^{th} particle with random solution along with its initial position, maximum velocity and inertia weight.

Check the AIPFC for proper arrangement and compute bus voltage for each particle, update line data and bus data.

Calculate the objective function for all particles.

Calculate the personal best position of the i^{th} particle, then set Pbest and keep track of the overall best value (Gbest), and its location.

Calculate the global best position Gbest, such that the best of Pbests as Gbest

Update the inertia weight as in equation (32)

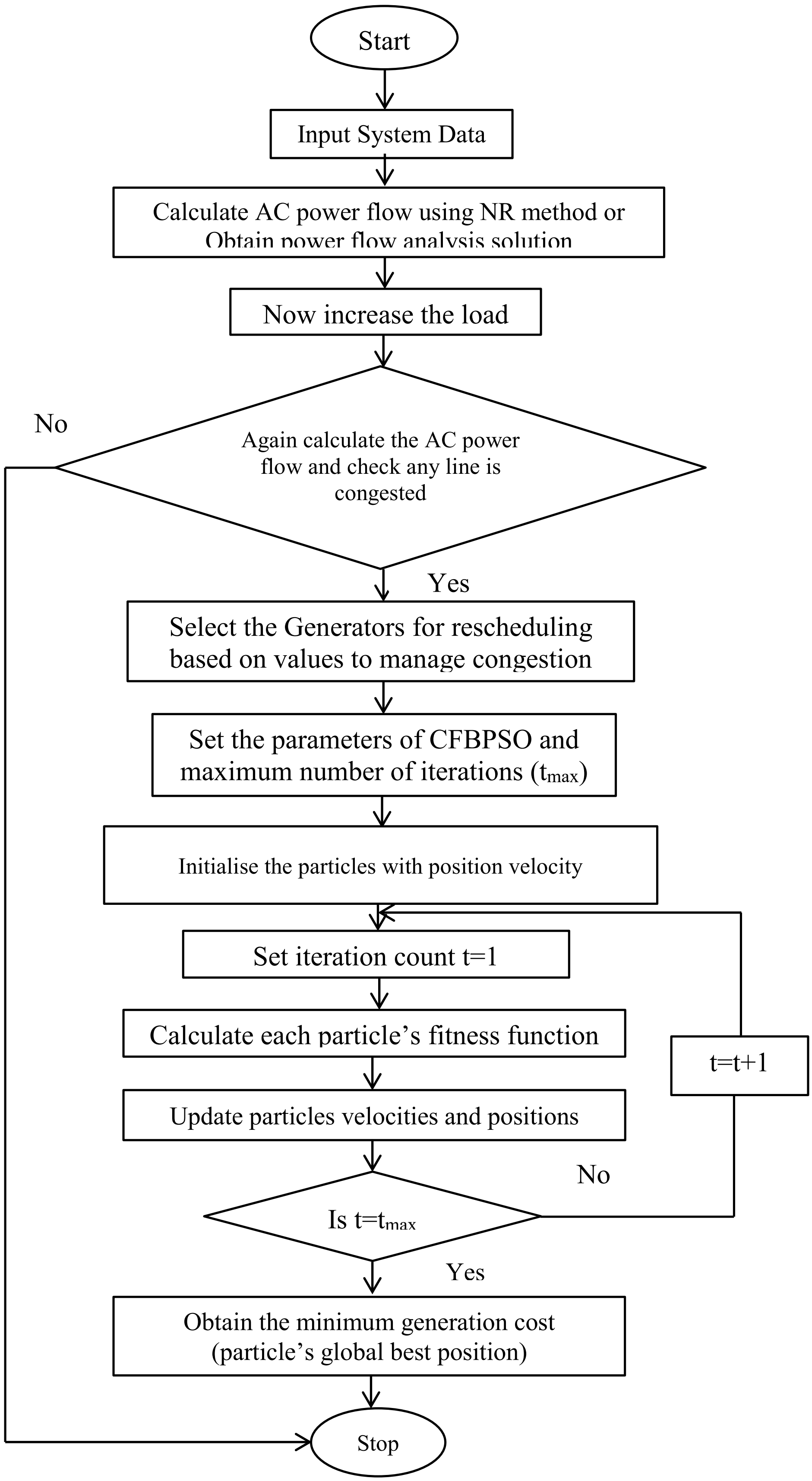
Estimate the new particle velocity and positions as in (33) and (34)

Checking the limit violation for security constraints. If iterations reach its max value, then go to step-10 or else go to step 2.

Stop.

5. Case Studies and Results

Congestion is a major issue in power systems. This section presents the optimal placement of an advanced IPFC model while minimising expected cost using CFBPSO. The proposed method has been tested on an IEEE 30 bus system. In an IEEE 30 bus test system, bus 1 is a slack bus, buses 2, 5, 8, 11, and 13 are PV buses, and bus 3 is a load bus. With 41 interconnected


Start
Input System Data
Calculate AC power flow using NR method or Obtain power flow analysis solution
Now increase the load
Again calculate the AC power flow and check any line is congested
No
Yes
Select the Generators for rescheduling based on values to manage congestion
Set the parameters of CFBPSO and maximum number of iterations (t_{max})
Initialise the particles with position velocity
Set iteration count t=1
Calculate each particle's fitness function
Update particles velocities and positions
Is $t=t_{max}$
No
t=t+1
Yes
Obtain the minimum generation cost (particle's global best position)
Stop

lines and a total demand of 283.40 MW, control variables include active power outputs, generator terminal voltages, transformer tap settings, and shunt compensations. The IEEE 30 bus test system load flow was obtained using MATLAB software. Only load buses are considered for advanced IPFC placement. The results show transmission congestion due to overload. Where increased demand for load buses has caused system congestion. Three cases are considered for simulation studies: base case, overload, and contingency analysis. Table 1 lists the CFBPSO parameters used in the simulation.

Figure 5. Flowchart of CFBPSO algorithm for transmission congestion management

Parameter	Value
Population size	20
Number of iterations	100
Cognitive constant,c1	2
Social constant,c2	2
Inertia weight ,w	0.3-0.95

Table 1. Optimal Parameter Settings for CFBPSO

Parameter	Value
Population size	20
Number of iterations	100
Cognitive constant,c1	2
Social constant,c2	2
Inertia weight ,w	0.3-0.95

Table 2. Comparison of Fuel Costs

Method	Fuel Cost ($/hr)
EP[29]	802.907
TS[29]	802.502
TS/SA[29]	802.788
ITS[29]	804.556
IEP[29]	802.465
MDE-OPF[30]	802.376
PSO[30]	800.966
CFBPSO (Proposed)	800.235

The number of iterations needed to find a good solution varies by problem. A lack of iteration may prematurely end the search. An excessive number of iterations add unnecessary computational complexity. The acceleration coefficients c1 and c2 control the stochastic influence of the cognitive and social components on the overall particle velocity. The constants c1 and c2 are also known as trust parameters, expressing a particle's confidence in itself and its neighbours.

To validate the proposed method's OPF results, they are compared to several current methods in the literature, as shown in Table 2 and Figure 6. As shown in the table and picture, the suggested CFBPSO approach outperforms other methods.

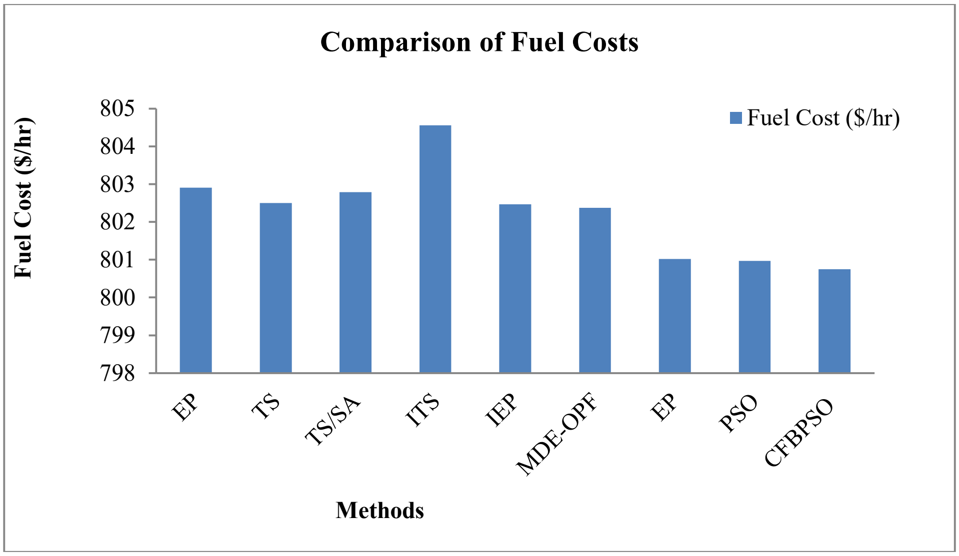


Figure 6. Comparison of Fuel Costs

Case a: Base case condition

Table 3. Optimal control variables settings for base case condition using CFBPSO with AIPFC

Control variables		Base Case condition	
		NR	CFBPSO with AIPFC
Real Power Generation (p.u)	P_{G1}	1.5929	1.7695
	P_{G2}	0.5812	0.4887
	P_{G3}	0.1287	0.2111
	P_{G4}	0.1871	0.1182
	P_{G5}	0.2242	0.2159
	P_{G6}	0.211	0.12
Generator Voltages (p.u)	V_{G1}	1.05	1.1
	V_{G2}	1.045	1.0878
	V_{G3}	1.01	1.0698
	V_{G4}	1.05	1.1
	V_{G5}	1.01	1.0619
	V_{G6}	1.05	1.1
Loss (p.u)		0.0911	0.0894
Cost ($/hr)		810.911	800.235

The proposed CFBPSO with AIPFC is used to determine the optimal power system scheduling for the base case condition. The objective function is to minimise the cost of generator fuel. Table 2 and Table 3 present the optimal control variable settings for the base case condition when CFBPSO is used in conjunction with AIPFC. The AIPFC method yields a minimum generator fuel cost of 800.235 \$/hr, which is less than the Newton Raphson (NR) method. Additionally, it is established that all solutions obtained satisfy the constraints on control variable and transmission line flow limits.

Case b: Congestion due Overloading

This section deals with transmission congestion is due to overload, where the This section deals with transmission congestion due to overload, where the congestion has been created in the system by increasing the demand. The proposed methodology has been tested for 10% load, 15% load, and 20% loading conditions. Table 4 indicates the overloaded lines for different cases and the amount of power violated in each case. It shows 311.74 MW in the first case when 10% of the load is increased on the base load. In the second case, load shows 325.91MW, i.e., 15% of the increase in base load. In the last case, 340.08 MW of load was obtained, i.e., 20% of the increase in base load. Under base case conditions, i.e., with a load of 283.4 MW, the line flow limit of 130 MW is not violated for lines 1-2. As shown in the simulation results, line 1-2 is violated in the tested cases.

In the 30 bus system, two lines are connected to lines 3 and 4. So, two test cases for AIPFC placement are considered. For each test case, congestion between buses is calculated, and it is observed that it is maximum between lines connected to buses 3–4 and 4–12. Hence, lines between buses 3–4 and buses 4–12 are selected for optimal placement of AIPFC. The placement of AIPFC in an optimal location will alleviate congestion.

Table 4. Line flows under different overloading conditions of IEEE-30 bus system

Over loaded line		Increment in load (%)	Line flow Limit (MVA)	Line flow (MVA)	Congestion
From bus	To bus				
1	2	10	130	131.062	Congested
1	2	15	130	131.305	Congested
1	2	20	130	133.423	Congested

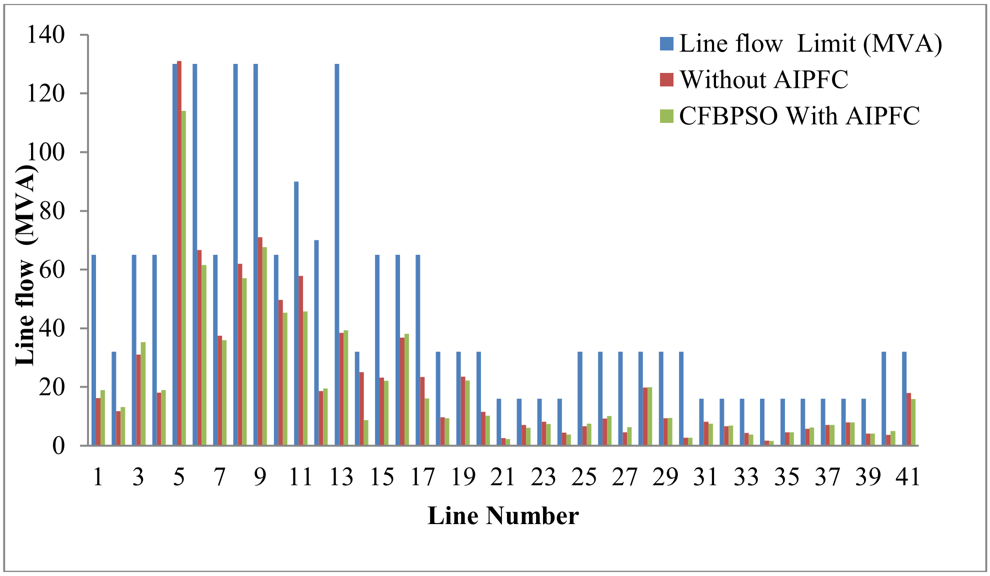


Figure 7. Line loadings under 10% loading condition

Table 5. Control variables for 10%t loading conditions of IEEE-30 bus system

Control variables		NR	CFBPSO with AIPFC
Real Power Generation (p.u)	P_{G1}	1.9473	1.6948
	P_{G2}	0.5412	0.6048
	P_{G3}	0.1287	0.35
	P_{G4}	0.1871	0.1734
	P_{G5}	0.2242	0.2474
	P_{G6}	0.211	0.12
Generator Voltages (p.u)	V_{G1}	1.05	1.05
	V_{G2}	1.045	0.9501
	V_{G3}	1.01	0.95
	V_{G4}	1.05	1.1
	V_{G5}	1.01	0.95
	V_{G6}	1.05	1.1
Loss (p.u)		0.1221	0.073
Cost ($/hr)		913.983	902.6309

Table 6. Control variables for 15%t loading conditions of IEEE-30 bus system

Control variables		NR	CFBPSO with AIPFC
Real Power Generation (p.u)	P_{G1}	1.9902	1.787
	P_{G2}	0.66315	0.6255
	P_{G3}	0.189	0.35
	P_{G4}	0.1137	0.1909
	P_{G5}	0.2597	0.2509
	P_{G6}	0.1753	0.1201
Generator Voltages (p.u)	V_{G1}	1.05	1.05
	V_{G2}	1.045	0.95
	V_{G3}	1.01	0.95
	V_{G4}	1.05	1.1
	V_{G5}	1.01	0.95
	V_{G6}	1.05	1.1
Loss (p.u)		0.132	0.0652
Cost ($/hr)		969.725	949.477

Power flows of all the lines, without and with optimal placement of AIPFC using CFBPSO, are presented in figure 7. Due to 10% overload, the transmission line between buses 1-2 was congested. The actual power rating of the line was 130 MVA but the MVA flow due to over load was 130.764 MVA, which caused congestion. It is established that lines 1-2 are the most congested lines. Hence, lines between buses 3–4 and buses 4–12 are selected for optimal placement of AIPFC. It is observed that the placement of AIPFC at the location reduces the congestion in lines 1-2.

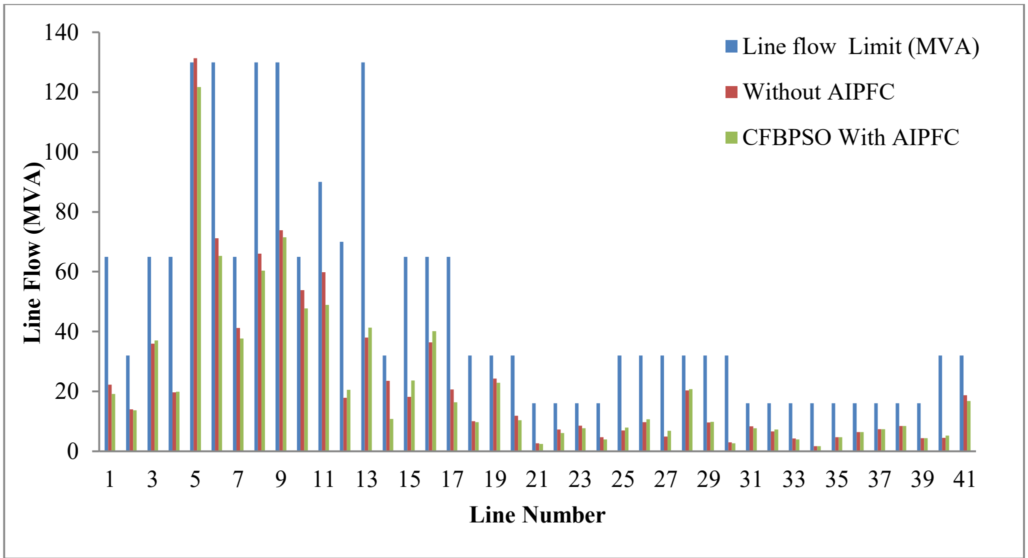


Figure 8. Line loadings under 15% loading condition

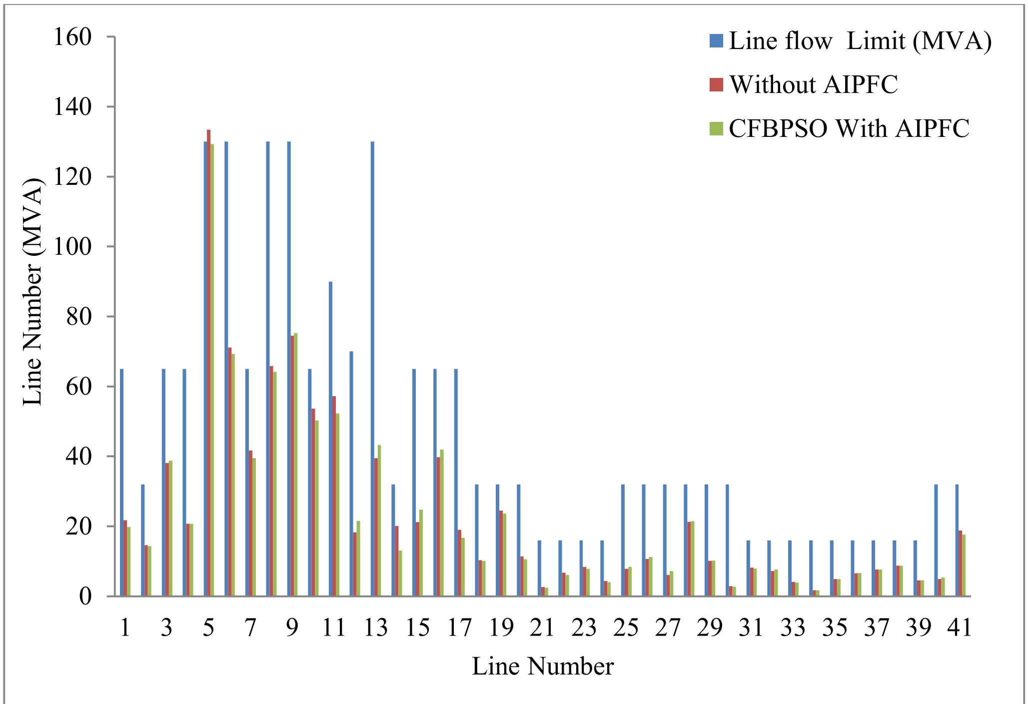


Figure 9. Line loadings under 20% loading condition

Due to 15% overload, the transmission line between buses 1-2 was congested. The actual power rating of the line was 130 MVA but the MVA flow due to over load was 131.305 MVA, which caused congestion. AIPFC was connected between the congested lines using CFBPSO to relieve the congestion. After connecting to the AIPFC, the congestion was relieved.

Table 7. Control variables for 20%t loading conditions of IEEE-30 bus system

Control variables		NR	CFBPSO with AIPFC
Real Power Generation (p.u)	P_{G1}	1.9385	1.8949
	P_{G2}	0.58675	0.6376
	P_{G3}	0.35	0.35
	P_{G4}	0.1569	0.202
	P_{G5}	0.2303	0.2561
	P_{G6}	0.12	0.12
Generator Voltages (p.u)	V_{G1}	1.05	1.05
	V_{G2}	1.045	0.9501
	V_{G3}	1.01	0.95
	V_{G4}	1.05	1.1
	V_{G5}	1.01	0.95
	V_{G6}	1.05	1.1
Loss (p.u)		0.1346	0.0599
Cost ($/hr)		1026.882	997.375

Due to 20% overloads, the transmission line between buses 1-2 was congested. The actual power rating of the line was 130 MVA but the MVA flow due to over load was 131.411 MVA, which caused congestion. AIPFC was connected between the congested lines to relieve the congestion. After connecting to the AIPFC, the congestion was relieved.

Table 8. Summary of line flow of overloaded lines under overloading using CFBPSO with AIPFC

Sending bus	Receiving bus	Increment in load (%)	Line flow Limit (MVA)	Without AIPFC	CFBPSO With AIPFC	Congestion
1	2	110	130	130.764	114.021	Relieved
1	2	115	130	131.305	121.742	Relieved
1	2	120	130	131.011	129.318	Relieved

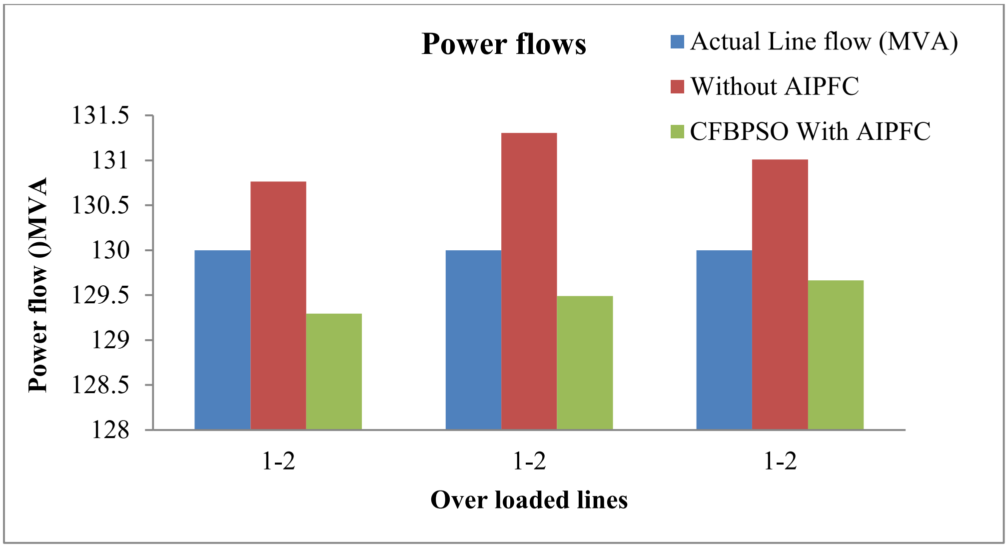


Figure 10. Summary of line flow of overloaded lines under overloading using CFBPSO with AIPFC

Thus, this shows the CFBPSO with the AIPFC method to solve the OPF problem in attaining the specified objective by satisfying constraints on control variables and transmission line flow limit. Based on the observed results, it can be mentioned that the CFBPSO with AIPFC method relieves congestion under overloading conditions in all cases, as shown in Table 8 and Figure 10.

Case c: Contingency Analysis

This section deals with transmission congestion due to line outages. In Table 9, a contingency analysis is proposed for the IEEE 30 bus system. For the simulation of congestion cases, it is assumed that four lines 1-2, 1-3, 3-4, and 2-5 are congested simultaneously. From the contingency analysis, it is found that line outages 1-2, 1-3, 3-4, and 2-5 have resulted in heavy overload on other lines.

Table 9. Contingency Analysis for IEEE 30-Bus System

Line outage buses	Over Loaded lines	Line flow limit (MVA)	Line flow (MVA)	Congestion
1-2	1-3	130	171.733	Congested
	3-4	130	161.812	Congested
	4-6	90	104.112	Congested
1-3	1-2	130	167.330	Congested
3-4	1-2	130	164.542	Congested
2-5	2-6	65	74.082	Congested
	5-7	70	83.094	Congested

Table 10 shows the control variable settings for the IEEE 30-bus system, CFBPSO with AIPFC at various line outages. It is clear from Table 10 that all control variables are within their limits and the lines are operating within the specified limits under different contingency cases.

Table 10. Optimal control variables settings under the selected network contingencies using CFBPSO with AIPFC

Control Variables		1-2 Line outage	1-8 Line outage	8-11 Line outage	2-5 Line outage
Real Power Generation (p.u)	P_{G1}	1.5597	1.7042	1.7148	1.7465
	P_{G2}	0.5845	0.4929	0.494	0.4773
	P_{G3}	0.3	0.264	0.2674	0.2521
	P_{G4}	0.1595	0.138	0.12	0.1325
	P_{G5}	0.2365	0.217	0.2175	0.247
	P_{G6}	0.1474	0.1328	0.1339	0.1206
Generator Voltages (p.u)	V_{G1}	1.1	1.1	1.1	1.1
	V_{G2}	1.0804	1.0847	1.0849	1.1
	V_{G3}	1.0781	1.0585	1.0589	1.0795
	V_{G4}	1.1	1.1	1.1	1.1
	V_{G5}	1.0592	1.0568	1.0568	1.0329
	V_{G6}	1.1	1.1	1.1	1.1
Transformer Tap Setting (p.u)	Tap-1	1.1	0.9242	0.9297	1.0613
	Tap-2	1.0726	0.9395	0.9394	0.9971
	Tap-3	0.9952	0.9373	0.9308	0.9759
	Tap-4	0.9935	0.9935	0.9376	0.9
Loss (p.u)		0.1537	0.1148	0.1136	0.1419
Cost ($/hr)		832.758	811.634	810.815	821.07

Table 11. Line flow under the selected four network contingencies

S. No.	From Bus	To Bus	Line Limit (MVA)	Power flow (MVA)			
				1-2 Line outage	1-8 Line outage	8-11 Line outage	2-5 Line outage
1	1	2	130	0	167.330	164.542	95.4973
2	1	3	130	171.733	0	2.6188	74.2383
3	2	4	65	34.762	59.926	58.726	54.799
4	3	4	130	161.812	2.525	0	69.3582
5	2	5	130	47.139	71.969	71.5525	0
6	2	6	65	22.536	64.103	63.1952	74.0818
7	4	6	90	104.117	25.806	26.6306	86.3644
8	5	7	70	33.243	10.921	11.0494	83.0935
9	6	7	130	51.183	25.353	25.7554	102.185
10	6	8	32	24.931	26.254	25.8779	24.0598
11	9	11	65	23.636	23.575	23.5338	23.4111
12	9	10	65	32.853	35.070	35.0258	33.1501
13	12	13	65	23.990	24.316	24.2401	23.4113
14	12	14	32	9.261	8.820	8.82701	9.19174
15	12	15	32	23.120	21.282	21.309	22.8107
16	12	16	32	12.141	10.287	10.3139	11.8284
17	14	15	16	2.721	2.362	2.36739	2.66655
18	16	17	16	7.961	6.289	6.31224	7.66939
19	15	18	16	8.376	7.308	7.32373	8.19141
20	18	19	16	4.941	3.976	3.98968	4.77237
21	19	20	32	5.191	6.349	6.33135	5.38504
22	10	20	32	7.588	8.752	8.73404	7.78277
23	10	17	32	2.892	4.876	4.84277	3.13201
24	10	21	32	18.297	18.538	18.5331	18.3273
25	10	22	32	8.641	8.802	8.7982	8.66193
26	21	22	32	2.752	2.581	2.5849	2.73815
27	15	23	16	8.427	7.510	7.52332	8.28954
28	22	24	16	5.882	6.327	6.31837	5.94816
29	23	24	16	4.725	3.952	3.96174	4.6038
30	24	25	16	2.160	1.659	1.66323	1.97658
31	25	26	16	4.267	4.267	4.26652	4.26649
32	25	27	16	5.353	5.573	5.56894	5.33215
33	27	29	16	6.420	6.419	6.41931	6.41932
34	27	30	16	7.295	7.295	7.29446	7.29448
35	29	30	16	3.755	3.755	3.75523	3.75523
36	8	28	32	4.318	4.553	4.46981	4.0831
37	6	28	32	15.487	16.128	16.1301	15.6469
38	6	9	65	12.723	15.143	15.0882	13.2111
39	6	10	32	9.173	10.729	10.7071	9.49283
40	4	12	65	31.102	26.524	26.5303	29.6023
41	28	27	65	15.690	16.544	16.5332	15.8535

Table 12. Line flow with AIPFC & CFBPSO

S.No	From Bus	To Bus	Line Limit (MVA)	Power flow (MVA)			
				1-2 Line outage	1-8 Line outage	8-11 Line outage	2-5 Line outage
1	1	2	130	0	99.78	93.59	34.19
2	1	3	130	102.56	0	2.84	45.29
3	2	4	65	20.92	47.88	45.80	40.62
4	3	4	130	83.40	2.78	0	41.70
5	2	5	130	42.46	56.76	55.36	0
6	2	6	65	22.57	50.01	48.17	52.03
7	4	6	90	62.98	16.65	17.16	52.14
8	5	7	70	20.68	9.76	9.60	55.68
9	6	7	130	41.36	25.26	25.47	75.57
10	6	8	32	6.24	12.58	11.61	3.73
11	9	11	65	30.71	31.05	30.98	30.52
12	9	10	65	38.23	39.48	39.15	36.16
13	12	13	65	33.77	34.44	34.36	33.56
14	12	14	32	10.13	9.77	9.71	9.50
15	12	15	32	24.99	23.67	23.54	23.55
16	12	16	32	12.61	11.36	11.34	12.03
17	14	15	16	2.84	2.59	2.59	2.73
18	16	17	16	8.05	6.93	6.94	7.74
19	15	18	16	8.85	8.12	8.09	8.36
20	18	19	16	5.04	4.40	4.40	4.82
21	19	20	32	6.19	6.84	6.74	5.71
22	10	20	32	8.87	9.50	9.38	8.20
23	10	17	32	3.68	4.91	4.81	3.37
24	10	21	32	20.17	20.20	20.05	19.05
25	10	22	32	9.58	9.62	9.55	9.04
26	21	22	32	2.76	2.63	2.63	2.68
27	15	23	16	8.94	8.29	8.27	8.56
28	22	24	16	6.89	7.13	7.07	6.48
29	23	24	16	4.89	4.34	4.34	4.75
30	24	25	16	2.32	1.95	1.97	2.36
31	25	26	16	4.64	4.60	4.57	4.39
32	25	27	16	5.57	5.65	5.62	5.34
33	27	29	16	7.17	7.11	7.05	6.67
34	27	30	16	8.16	8.09	8.02	7.58
35	29	30	16	4.20	4.17	4.13	3.90
36	8	28	32	4.53	5.25	5.14	4.35
37	6	28	32	15.00	14.87	14.69	13.58
38	6	9	65	10.47	99.78	11.63	9.30
39	6	10	32	9.49	11.89	10.07	8.35
40	4	12	65	24.84	10.26	22.22	21.48
41	28	27	65	17.50	22.55	17.60	16.05

Congested transmission lines are identified and listed as 1-3, 3-4, 4-6, 2-6, and 5-7 with an overloading of 171.733 MVA, 161.812 MVA, 74.082 MVA, and 83.094 MVA, respectively, for the most dangerous case, i.e., the outage of lines 1-2, 1-3, 3-4, and 2-5 shown in Table 11. After placing the IPFC device in selected locations, the contingency assessment is performed again and the results are listed in Table 12. It is apparent that the congestion in all lines due to various contingencies is completely alleviated.

Table 13. Summary of line flow of overloaded lines under the selected four network contingencies using CFBPSO with AIPFC method

Line outage between buses	Over Loaded lines	Line flow limit (MVA)	Line flow (MVA)	CFBPSO with AIPFC	Congestion
1-2	1-3	130	171.733	102.563	Relieved
	3-4	130	161.812	83.401	Relieved
	4-6	90	104.112	62.983	Relieved
1-3	1-2	130	167.330	99.776	Relieved
3-4	1-2	130	164.542	93.594	Relieved
2-5	2-6	65	74.082	52.030	Relieved
	5-7	70	83.094	55.677	Relieved

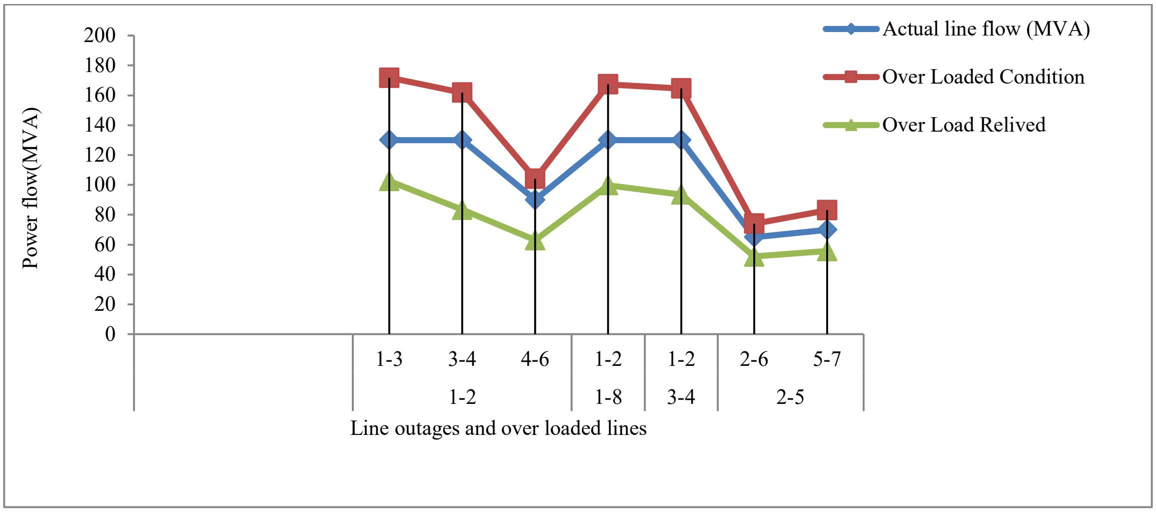


Figure 11. Summary of line flow of overloaded lines under the selected four network contingencies using CFBPSO with AIPFC method

Thus, this shows the CFBPSO with the AIPFC method to solve congestion problems in attaining the specified objective by satisfying constraints on control variables and transmission line flow limit. Based on the observed results, it can be said that the CFBPSO with AIPFC method relieves the congestion under contingency conditions.

6. Conclusion

The problem of congestion is modelled as an optimization problem and solved by the CFBPSO technique with AIPFC. Thus, the congestion due to sudden increases in loads and various line outages is relieved using real power rescheduling of generators. The rescheduling process is effectively performed using CFBPSO with the help of AIPFC. The proposed method is implemented on the IEEE 30 bus test system. The results are presented and analysed under normal loading, overloading, and contingency conditions to ascertain the effectiveness of the proposed method on the power system performance. It is observed that the placement of AIPFC by the proposed methodology causes an effective reduction in congestion in the lines. Simulated results show that the CFBPSO algorithm technique is very good at getting the job done and finding the best AIPFC parameters for different loads.

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