Congestion Management in Power Transmission Lines with Advanced Control Using Innovative Algorithm

BALA SAIBABU BOMMIDI[1], BADDU NAIK BHUKYA[2]
SWARUPA RANI BONDALAPATI[3], HEMANTH SAI MADUPU[4]
[1,2&4]Department of Electrical and Electronics Engineering,
Prasad V. Potluri Siddhartha Institute of Technology, Vijayawada, Andhra Pradesh, INDIA
[3]Department of Electrical and Electronics Engineering,
Velagapudi Ramakrishna Siddhartha Engineering College, Vijayawada, Andhra Pradesh, INDIA

Abstract: It can be challenging to allocate all the necessary power to a supply in a modern power system if the power lines are overloaded. The conventional power system, monitored by flexible AC transmission system (FACTS) controllers, is one answer to this issue because it can increase the electrical power system's ability to deal with rapid variations in working circumstances. The advanced interline power flow controller using a constriction factor-based particle swarm optimization (CFBPSO) algorithm (AIPFC) was proposed in this paper as an optimal power flow control for controlling congestion in transmission lines. When comparing the performance of single-line and multi-line FACTS controllers, the latter is shown to be more effective overall. This paper presents a comprehensive model of an advanced interline power flow controller (AIPFC) and explores the effect of situating the controller in the most advantageous physical location. To address OPF concerns when using state-of-the-art IPFC, a novel algorithm, CFBPSO, is proposed. A traditional IEEE 30 bus test system is used to verify the proposed method. A standard IEEE 30 bus test system is used to verify the accuracy of the proposed method. In their paper, the researchers show that their proposed algorithm works by showing that the value of the objective function goes down.

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

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1. Introduction

Power companies have to increase their production in response to rising global demand for electricity. The amount of electrical power that can be transmitted between any two nodes in a transmission network is, however, constrained by a number of transfer limits, including thermal limits, voltage limits, and stability limits. Once that threshold is hit, we say that the system is congested. Maintaining power system security requires constant vigilance to prevent outages that could have far-reaching social and economic effects if not kept within acceptable parameters. Perhaps the most basic challenge of transmission management is congestion management or regulating the system so that transfer limits are respected [1]–[3]. Normal methods for dealing with congestion include rescheduling generator outputs, providing reactive power support, and imposing physical limits on transactions. System operators typically prefer the former and only resort to the latter.

Several methods for dealing with traffic jams have been detailed in published works [4]. Multiple models are discussed in [5] for dealing with the economic viability of the energy market and the transmission system's myriad dealings, interactions, and constraints. Methods for reducing traffic congestion in a range of electricity markets are detailed in [6]. The issue of voltage stability is addressed by congestion management in [7]. In [8], the authors show the best way to set up a power system's topology so that it can be used to manage congestion.

There is existing research on multiple transaction systems that explores congestion management schemes based on optimal power flow (OPF). Congestion and service costs can be reduced using the method proposed in [9], which is based on optimal path finding (OPF). In [10], the possibility of power generators and system operators coordinating via load flow analysis via Benders cuts is discussed. Congestion caused by voltage instability and thermal loads is reduced by the method proposed in [11]. Standard solvers can also solve this because it employs OPF. In [12]-

[13], a zonal model is proposed that is based on the circulation of air conditioning loads. In [14], the authors use the sensitivity of line flow to modifications in generation to alleviate congestion, but they make no attempt to decrease the number of generators implicated. In [15], a method is proposed for selecting the participating generators that takes into account both their bids and their sensitivity to the current flow on a crowded line. The concept of relative electrical distance (RED) is introduced as a means of rescheduling actual power generation to reduce overload. This method is supposed to increase stability margin by reducing system losses and keeping a more constant voltage across the board. While rescheduling costs and individual generation unit bids are considered elsewhere, they are not included here The output values of generators that have the same RED but separate price bids must be rescheduled to reduce the overall rescheduling cost. [16] Does not attempt to solve this issue.

Because of their superior performance and reliability, FACTS devices [17] are favored in modern power systems. The unified power flow controller (UPFC) and the intelligent power factor corrector (IPFC) are two examples of combined compensators that are among the most powerful and flexible FACTS devices. The two voltage-sourced switching converters (VSCs) in a UPFC share a common DC voltage link, allowing for separate active and reactive power flow regulation. IPFC, on the other hand, can compensate for multiple transmission lines at a given substation because its VSCs are connected in series with different lines, whereas UPFC is limited to controlling the power flow of a single line. Optimal power flow control and power flow control utilizing IPFC necessitate accurate mathematical modeling of this FACTS device. IPFC injection models and transmission lines with IPFC built in are created using the mathematical model shown in [22], just as UPFC injection models are frequently used [18]-[20] and the exact pi-model of UPFC-inserted transmission lines can be found [21].

This paper's goal is to investigate whether or not the particle swarm optimization method, which is based on the concept of a "congestion factor," can be used to effectively address the issue of congestion management. A mathematical optimization problem is used to represent the clogged system. Methods for solving OPFS that have been around for a while typically use search directions calculated from the derivative of the function. As a result, it is crucial to formulate the problem as a continuously differentiable function; otherwise, the effectiveness of these techniques will be diminished. In this paper, we use a particle swarm optimization strategy based on the constriction factor to solve this problem. Optimization algorithms typically refer to the value of the objective function as the fitness function and the binding constraints as the penalty functions. In particular, it has many drawbacks because the penalty variables are assigned empirically and are heavily dependent on the test, as is typical. In this paper, however, we take a fresh approach to addressing these constraints by employing restriction factor-based particle swarm optimization. This paper uses the IEEE 30 bus system to prove that the envisaged technique for congestion management works.

2. Advanced Interline Power Flow Controller (AIPFC)

The IPFC is a flexible replacement for the UPFC and the SSSC because it employs at least two converters and controls power flows over several lines. Transmission network congestion management is a challenging problem that may be tackled with the help of the IPFC. So, the author is inspired to come up with a new model for IPFC that can be used in power flow analysis.

In general, the current steady-state models can be split up into two categories: decoupled and coupled. As part of a decoupled model, the FACTS devices are replaced by a made-up PQ or PV bus, resulting in a different Jacobian matrix structure. Power injection models (PIM) [24]–[26] and voltage source models (VSM) [23] and [27]–[29] are the two main components of a coupled model. Furthermore, dealing with the practical limitations imposed by FACTS devices is significant issue [30] .The power flow software in the papers didn't say anything about how IPFC's limitations are dealt with.

This paper introduces a new IPFC Power Injection Model to analyze power flow. This model takes into account both the line charging susceptance and the impedance of the series converter transformer. It is demonstrated that the admittance matrix's original structure and symmetry can be maintained, thus allowing the Jacobian matrix to keep its block-diagonal properties and facilitating the application of a sparsity technique. When making changes to the network state variables, it's also necessary to make corresponding changes to the IPFC's state variables. In addition, the model can account for IPFC's real-world limitations, and we show how to do so in detail using Newton power flow. [31]-[32].

2.1 Intuitive Model of the AIPFC

An AIPFC with many series converters can use the numerical induction method.

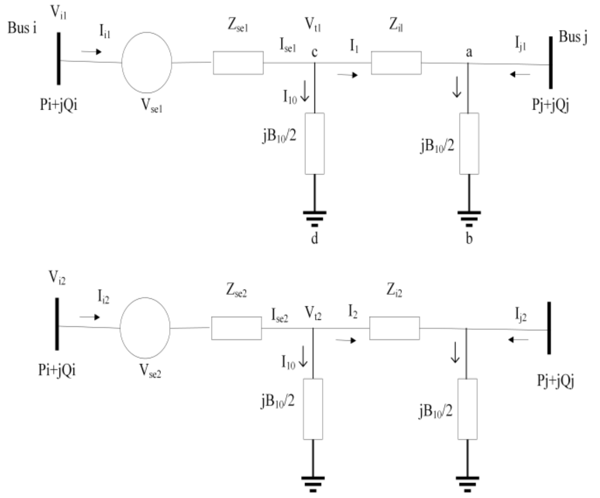

Fig. 1: The AIPFC equivalent circuit

$V_{i_n} = V_{i_n}\angle\theta_{i_n}$ 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 1:

$$V_{i_n} = V_{se_n} + I_{i_n} Z_{se_n} + V_{t_n} \quad (1)$$

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

$$V_{t_n} = I_1 Z_{l_n} + V_{j_n} \quad (3)$$

$$I_1 = -I_{j_n} + I_{ab} \quad (4)$$

Where

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

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

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

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

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

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

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

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

$$V_{t_n} = V_{j_n} E - I_{j_n} Z_{l_n} \quad (11)$$

$$I_{i_n} = V_{j_n} D - I_{jn} E \quad (12)$$

$$I_{jn} = \frac{V_{se_n}}{Z_{se_n} E + Z_{l_n}} - \frac{V_{i_n}}{Z_{se_n} E + Z_{l_n}} + \frac{V_{j_n}\left[Z_{se_n} D + E\right]}{Z_{se_n} E + Z_{l_n}} \quad (13)$$

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

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

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

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

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

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

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

$$A_{ij_n} = A_{ji_n} \quad (17)$$

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

$$A_{jj_n} = -A_{ji_n} + A_{j_n}^0, \qquad A_{j_n}^0 = D + \frac{M-N}{N} \quad (18)$$

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

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

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

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

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

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

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

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

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

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

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

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

$$P_{dc} = \sum_n P_{ex_n} = 0 \quad (29)$$

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

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

3. Particle Swarm Optimization

In 1995, Kennedy and Eberhart [33] introduced the evolutionary algorithm known as particle swarm optimization. Fish schooling and bird flocking are two examples of social behaviour in nature that serve as inspiration. A flock of birds has been seen to discover food sources in an area through a random process. In a flock, some members may know the general area around the food source, but everyone knows the general area around the food source (the food). In order to find food quickly and easily, it is best to start your search near your current best position.

PSO is an alternative to more common optimization algorithms because it does not require knowing the derivative of functions used in the model. If fitness values for the optimization model can be calculated, then the algorithm will work. Also, the PSO algorithm is based on a lot of deep thinking, but it is still easy enough for non-experts to understand.

Several power system optimization issues have already benefited from PSO's application. The economic dispatch of power plant generators is a problem addressed by PSO in [34]. In [35], a method for regulating voltage and reactive power was proposed for ensuring the reliability of power grids. It has been discussed in [36] how PSO can be used for congestion management with a focus on sensitivity. But it does not explain how constraints are dealt with in any detail.

3.1 Constriction Factor Based PSO (CFBPSO)

The following equation can be used to adjust the speed of each actor:

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

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

$$s_i^{k+1} = s_i^k + v_i^{k+1} \quad (33)$$

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The equations [(31), [(32), and [(33)] that make up the PSO system can be interpreted as a difference equation. It is possible to investigate the dynamics of the system or the search procedure by examining the eigen values of the difference equation.

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

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

$$\varphi = c_1 + c_2, \varphi > 4 \quad (35)$$

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.

Users of the restriction factor method tend to converge in the long run. Contrary to other evolutionary computation approaches, the constriction factor approach theoretically guarantees the search procedure's convergence. Since this is the case, the restriction factor approach can yield superior results compared to the standard PSO method. Contrarily, the dynamic behaviour of a single individual and the impact of inter-individual interactions are not taken into account by the restriction factor approach. That's why CFBPSO is able to produce higher-quality results than the standard PSO method.

4. Formulation of the Congestion Management Problem

Optimal control settings in a power network are found by solving the optimal power flow (OPF) problem, a static non-linear constrained optimization problem. To do this, it simultaneously optimises for a set of objective functions while trying to minimise the network's equality and inequality constraints.

The optimal power flow problem is an example of a nonlinear optimization issue that can be written as:

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

The corresponding mathematical expression is as follows.

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

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

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

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

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

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

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

$$V_i^{\min} \le V_i \le V_i^{\max} \quad \text{i=1,…,NL} \quad (44)$$

$$T_i^{\min} \le T_i \le T_i^{\max} \quad \text{i=1,…,NT} \quad (45)$$

$$S_i \le S_i^{\max} \quad \text{i=1,…,nl} \quad (46)$$

5. Results and Discussion

Power systems face serious challenges due to network congestion. This problem is due to system overload. This section describes the end result of applying CFBPSO to locate a state-of-the-art IPFC model in an optimal spot to simultaneously reduce expected costs. The proposed technique was successfully implemented on the IEEE 30 bus test system. A slack bus (Bus 2), PV buses (Bus 5, 8, 11, and 13), and load buses (Bus 3-6) make up an IEEE 30 bus test system with six generators. A total of 41 lines and 283.40 MW are needed to power the system. The generator can be adjusted in a number of ways, including its active power outputs, terminal voltages, tap settings on the transformer, and shunt compensations. The results of a MATLAB calculation of the load flow for the IEEE 30 bus test system are presented. The only thing you need to worry about with a sophisticated IPFC model is where to put the load buses. We present the results of an analysis of peak demand that reveals the presence of transmission bottlenecks. Where traffic jams have formed due to an increase in the use of load buses. Simulation studies are conducted in three distinct scenarios (base case, overload, and contingency) to demonstrate the efficacy of the proposed CFBPSO algorithm with AIPFC.

The OPF results obtained using the proposed strategies are presented in comparison to some of the most popular current writing methods in

Figure 2. When compared to other strategies, it is clear that the proposed CFBPSO strategy provides superior results.

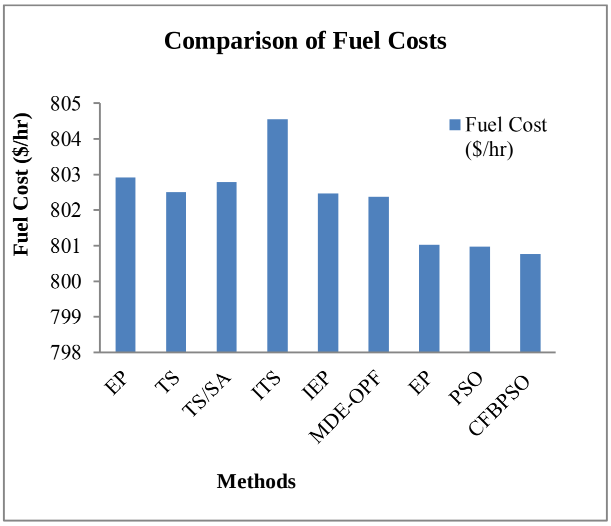

Fig. 2: Comparison of Fuel Costs

Case a: Base case condition

For the baseline scenario, the optimal power system scheduling is determined by employing the proposed CFBPSO with AIPFC. Reduced fuel costs for the generator are the objective function under consideration. Table 1 shows the optimum values for the control variables in the base case scenario when using CFBPSO with AIPFC. Through CFBPSO, the AIPFC method yields a lower generator fuel cost than the Newton Raphson (NR) method, at **799.904$/hr.** All of the solutions found also meet the limits for the control variables and the flow through the transmission lines.

Table 1. Using the CFBPSO with the AIPFC with the optimal settings for the base case scenario.

Variables		NR	CFBPSO with AIPFC
Real Power Generation	P_{G1}	159.29	177.66
	P_{G2}	58.12	48.82
	P_{G3}	12.87	21.34
	P_{G4}	18.71	12
	P_{G5}	22.42	21.33
	P_{G6}	21.1	11.15
Generator Voltages	V_{G1}	105	105
	V_{G2}	104.5	95.05
	V_{G3}	101	95
	V_{G4}	105	110
	V_{G5}	101	95
	V_{G6}	105	110
Loss (MW)		9.11	8.9
Cost ($/hr)		**809.211**	**799.904**

Case b: Congestion due Overloading

Overloading the system causes congestion, and that's what this section is about. The proposed approach has been tried and true under 10% load, 15% load, and 20% load.

A breakdown of the overloaded lines and the associated power violations can be seen in Table 2. Assuming a 10% increase in the base load, the first case displays 311.74 MW. Load readings in the second scenario show 325.91 MW, which is equivalent to an increase in base load of 15%. A load of 340.08 MW was achieved in the latter case; this represents an increase in base load of 20%. The line flow limit of 130 MW is not exceeded by Lines 1-2 under the base case conditions, i.e. with a load of 283.4 MW. The simulation results demonstrate that conditions 1-2 are always not met.

Two of the 30 bus lines are linked to the other two lines, 3 and 4. For this reason, we use two scenarios to evaluate AIPFC placement. Congestion between buses is measured and found to be worst between lines serving buses 3-4 and 4-12 across all test cases. Thus, AIPFC is best installed along routes 3–4 and 4–12, which correspond to certain bus lines. Congestion can be reduced if AIPFC is located strategically.

Table 2. Power flows under various over-burdening states of IEEE-30 bus system

Over loaded line		Load increment in (%)	Power flow Limit (MVA)	Power flow (MVA)
From bus	To bus			
1	2	10	130	**141.052**
1	2	15	130	**142.206**
1	2	20	130	**148.421**

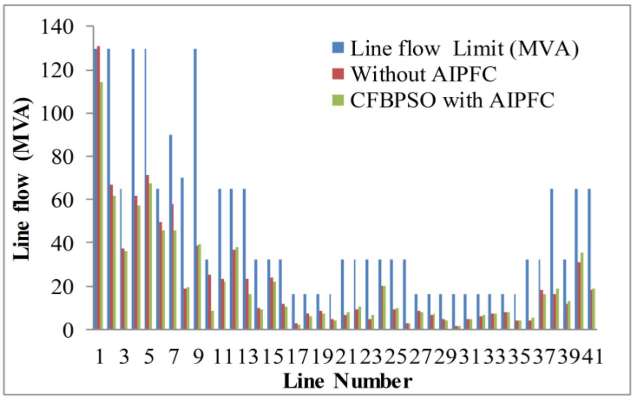

Fig. 3: Power flows in 10% loading situation

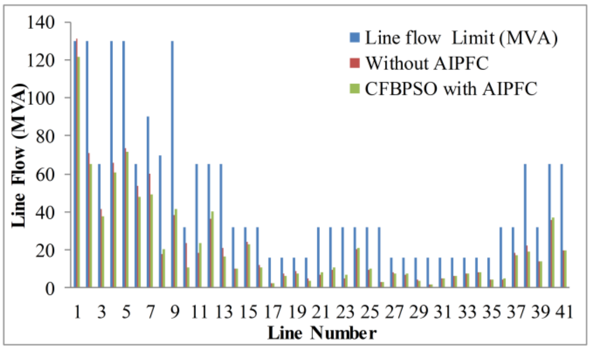

Fig. 4: Power flows in 15% loading situation

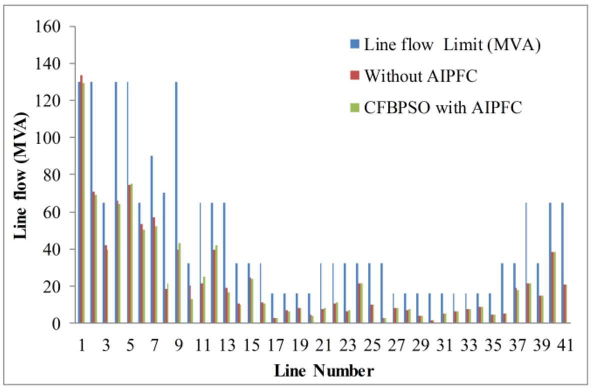

Fig. 5: Power flows in 20% loading situation

Table 3. Rundown of power flows of over-burden lines under over-burdening utilizing CFBPSO with AIPFC

Lines	Load increment in (%)	Power flow Limit (MVA)	Power flow with AIPFC using CFBPSO
1-2	110	130	**114.021**
1-2	115	130	**121.742**
1-2	120	130	**129.318**

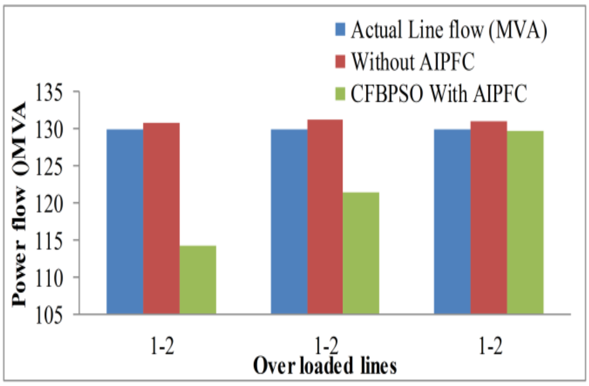

Fig. 6: Rundown of power flows of over-burden lines under over-burdening utilizing CFBPSO with AIPFC

This proves that the OPF problem can be solved by the CFBPSO using the AIPFC method while fulfil constraints on dependent variables and the flow limit in the transmission line. As can be seen in Table 3 and Figure 6, the CFBPSO with AIPFC method effectively reduces congestion under overloading conditions.

Case c: Contingency Analysis

Congestion in transmission due to line failures is discussed here. A potential risk assessment for the IEEE 30 bus system is presented in Table 4. It is assumed in the simulated world of congestion scenarios that lines 1-2, 1-3, 3-4, and 2-5 are all clogged at the same time. The contingency analysis shows that lines 2-5 are severely overloaded due to the outages of lines 1-2, 1-3, 3-4, and 2-5.

Table 4. Analysis of Power flows under contingency for IEEE 30-Bus System

Outage of lines	Effected lines	Power flow limit (MVA)	Power flow (MVA)
1-2	1-3	130	**195.872**
	3-4	130	**183.793**
	4-6	90	**112.914**
1-3	1-2	130	**188.395**
3-4	1-2	130	**185.580**
2-5	2-6	65	**76.123**
	5-7	70	**85.611**

Table 5. Power flow under the particular four network contingencies

S. No.	Line Limit (MVA)	Power flow (MVA)			
		1-2 Line outage	1-3 Line outage	3-4 Line outage	2-5 Line outage
1	130	0	**188.395**	**185.580**	95.4973
2	130	**195.872**	0	2.6188	74.2383
3	65	34.762	59.926	58.726	54.799
4	130	**183.793**	2.525	0	69.3582
5	130	47.139	71.969	71.5525	0
6	65	22.536	64.103	63.1952	**76.123**
7	90	**112.914**	25.806	26.6306	86.3644
8	70	33.243	10.921	11.0494	**85.611**
9	130	51.183	25.353	25.7554	102.185
10	32	24.931	26.254	25.8779	24.0598
11	65	23.636	23.575	23.5338	23.4111
12	65	32.853	35.070	35.0258	33.1501
13	65	23.990	24.316	24.2401	23.4113
14	32	9.261	8.820	8.82701	9.19174

15	32	23.120	21.282	21.309	22.8107
16	32	12.141	10.287	10.3139	11.8284
17	16	2.721	2.362	2.36739	2.66655
18	16	7.961	6.289	6.31224	7.66939
19	16	8.376	7.308	7.32373	8.19141
20	16	4.941	3.976	3.98968	4.77237
21	32	5.191	6.349	6.33135	5.38504
22	32	7.588	8.752	8.73404	7.78277
23	32	2.892	4.876	4.84277	3.13201
24	32	18.297	18.538	18.5331	18.3273
25	32	8.641	8.802	8.7982	8.66193
26	32	2.752	2.581	2.5849	2.73815
27	16	8.427	7.510	7.52332	8.28954
28	16	5.882	6.327	6.31837	5.94816
29	16	4.725	3.952	3.96174	4.6038
30	16	2.160	1.659	1.66323	1.97658
31	16	4.267	4.267	4.26652	4.26649
32	16	5.353	5.573	5.56894	5.33215
33	16	6.420	6.419	6.41931	6.41932
34	16	7.295	7.295	7.29446	7.29448
35	16	3.755	3.755	3.75523	3.75523
36	32	4.318	4.553	4.46981	4.0831
37	32	15.487	16.128	16.1301	15.6469
38	65	12.723	15.143	15.0882	13.2111
39	32	9.173	10.729	10.7071	9.49283
40	65	31.102	26.524	26.5303	29.6023
41	65	15.690	16.544	16.5332	15.8535

Table 6. Line flow with AIPFC & CFBPSO

S.No	Line Limit (MVA)	Power flow (MVA)			
		1-2 Line outage	1-8 Line outage	8-11 Line outage	2-5 Line outage
1	130	0	**99.78**	**93.59**	34.19
2	130	**102.56**	0	2.84	45.29
3	65	20.92	47.88	45.80	40.62
4	130	**83.40**	2.78	0	41.70
5	130	42.46	56.76	55.36	0
6	65	22.57	50.01	48.17	**52.03**
7	90	**62.98**	16.65	17.16	52.14
8	70	20.68	9.76	9.60	**55.68**
9	130	41.36	25.26	25.47	75.57
P10	32	6.24	12.58	11.61	3.73
11	65	30.71	31.05	30.98	30.52
12	65	38.23	39.48	39.15	36.16
13	65	33.77	34.44	34.36	33.56
14	32	10.13	9.77	9.71	9.50
15	32	24.99	23.67	23.54	23.55
16	32	12.61	11.36	11.34	12.03
17	16	2.84	2.59	2.59	2.73
18	16	8.05	6.93	6.94	7.74
19	16	8.85	8.12	8.09	8.36
20	16	5.04	4.40	4.40	4.82
21	32	6.19	6.84	6.74	5.71
22	32	8.87	9.50	9.38	8.20
23	32	3.68	4.91	4.81	3.37
24	32	20.17	20.20	20.05	19.05
25	32	9.58	9.62	9.55	9.04
26	32	2.76	2.63	2.63	2.68
27	16	8.94	8.29	8.27	8.56
28	16	6.89	7.13	7.07	6.48
29	16	4.89	4.34	4.34	4.75
30	16	2.32	1.95	1.97	2.36
31	16	4.64	4.60	4.57	4.39
32	16	5.57	5.65	5.62	5.34
33	16	7.17	7.11	7.05	6.67
34	16	8.16	8.09	8.02	7.58
35	16	4.20	4.17	4.13	3.90
36	32	4.53	5.25	5.14	4.35
37	32	15.00	14.87	14.69	13.58
38	65	10.47	99.78	11.63	9.30
39	32	9.49	11.89	10.07	8.35
40	65	24.84	10.26	22.22	21.48
41	65	17.50	22.55	17.60	16.05

Table 7. An overview of CFBPSO with AIPFC-calculated power flow for four network-loading scenarios

Outage Lines	Over Loaded lines	Line flow limit (MVA)	CFBPSO with AIPFC
1-2	1-3	130	**102.563**
	3-4	130	**83.401**
	4-6	90	**62.983**
1-3	1-2	130	**99.776**
3-4	1-2	130	**93.594**
2-5	2-6	65	**52.030**
	5-7	70	**55.677**

This proves that congestion problems can be solved and the goal can be reached using the CFBPSO and the AIPFC technique by satisfying constraints on control variables and transmission line flow limits. According to the data, the CFBPSO with AIPFC technique reduces critical congestion.

6. Conclusion

In the face of network overloading and the worst-case scenarios, it has been shown that the CFBPSO method, in conjunction with FACTS devices like AIPFC, can solve congestion-constrained optimal power flow issues. The CFBPSO technique, in conjunction with AIPFC, is applied to the analysis of congestion as an optimization problem. The method has been successfully tested on IEEE 30-bus systems, and the cost results obtained on the systems have been compared with the results reported using other techniques. The proposed method with the AIPFC device reliably converged to the optimal solution in reaching the specified goal, provided that constraints on control variables and the transmission line flow limit were met. Along with its many advantages, the CFBPSO algorithm is also conceptually simple and straightforward. We demonstrate the algorithm's robustness by solving some overloaded and emergency situations. Poor results can be achieved with the CFBPSO algorithm if the particle size, inertia weight, and maximum velocity are all chosen incorrectly. However, results from the tests show that the proposed implementation performs better under heavily loaded and emergency conditions, and that congestion is better managed.

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