Advanced Control with an Innovative Optimization Algorithm for Congestion Management in Power Transmission Networks

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***Abstract*—In a modern power system, it may be difficult to assign all of the necessary power to a source due to overloaded transmission lines. The conventional power system within Flexible AC Transmission System (FACTS) controllers is a solution to these problems and can enhance the electricity supply system's capacity to respond to sudden changes in operating conditions. In this research, the advanced model of an interline power flow controller (AIPFC) with constriction factor-based particle swarm optimization (CFBPSO) analysis is considered to continue providing optimal power flow regulation in the scenario of transmission line congestion. Multi-line FACTS controllers exceed single-line FACTS controllers. This research examines the impact of an ideal area as well as the entire precise presentation of a sophisticated interline power flow controller (AIPFC). A novel algorithm, such as CFBPSO, is proposed to deal with OPF issues within the scope of the advanced model IPFC. Using the IEEE-30 bus test system, the presented method is evaluated over different loading and contingency situations. The results are presented and evaluated to illustrate their validity in relieving congestion.**

***Index Terms*— Congestion management, Constriction Factor Based Particle Swarm Optimization (CFBPSO), Advanced Interline Power Flow Controller (AIPFC) and Flexible AC Transmission System (FACTS).**

I. INTRODUCTION

THE demand for electricity around the world is growing. Electric utilities have had to make more electricity. In a power system, the transmission system is the most important link between the load and the generator. The development of transmission systems for electricity is now more crucial than ever due to the evolution of power delivery methods. Therefore, more careful planning of power systems is necessary. There is a search for new technologies that can give such provision presentation. However, the installation of a new device within the network will be evaluated. This may occur initially during the state of an individual's development or later on during the process of designing for advancement.

The whole power system can only work well and safely if this system works and performs as it should in both dynamic and steady-state conditions. Reducing voltage drops and line losses between the generator and the load has generally been seen as fundamental to the efficiency of the power network in steady-state conditions. In the alternative, the electricity system's transient stability is the result. Another quality of a reliable power system is its resistance to disturbances. There are a number of transmission limitations, such as temperature limits, voltage limits, and safety limits, which limit the quantity of electricity that can be transmitted between two locations on a transmission line. At any given time, the most stringent transfer restrictions are in effect. When this limit is reached, it is said that the system is crowded. If the congestion persists, the facility grid is at risk of experiencing a blackout. Also, if there isn't enough reactive power, the voltage may go up and down, which can cause the voltage to drop. In fact, the network's reactive power restriction is one of the main reasons why the voltage drops. [1]- [6].

In order to prevent severe outages that could have serious social and economic effects, it is essential that the power system operate within its set limits. Congestion control, or the process of regulating transmission to maintain transfer limits, is likely the most fundamental challenge in transmission management [7]-[8]. Congestion can be fixed in a number of ways: by changing the timing of generator outputs, providing reactive power support, or putting physical limits on transactions.

Researchers and engineers have proposed and implemented a number of solutions to lessen congestion and enrich the quality of the electricity system. There are both technological and non-technological approaches to managing congestion problems. Technical options include phase-shifting transformers, flexible alternating current transmission system (FACTS) devices, and turning off power to overloaded lines [9]-[11]. Market-based and non-market-based approaches both exist within the realm of non-

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technical methods. A few examples of market-based approaches are load restriction, auctioning, arcade splitting, nodal rating, and territorial estimating [12]–[14].

Numerous methods for dealing with congestion have been described in existing literature [15]. Various models for accounting for the variety of market transactions, the interplay between transmission system attributes and constraints, and the importance of economic efficiency in the energy market are discussed in [16]. In [17], designers see how congestion management strategies can be adapted for use in numerous electrical markets. Management of congestion and maintaining voltage stability are discussed in [18]. In [19], the authors detail the optimal configuration of a power system for managing congestion problems.

Congestion controlling strategies based on optimal power flow (OPF) have been written about in the works. An OPF-based solution that reduces congestion and operating prices is proposed in [20]. In [21], the use of breaker cuts for congestion control in coordination between generators and system operators is considered. The technique provided in [22] alleviates congestion brought on by voltage instabilities and thermal overloads. These also make use of OPF, which can be solved using common applications. In [23], [24], zonal modeling with air conditioning load flow was proposed. Additionally, zones have been delineated in this research by using sensitivity levels. Given a real-world power system, however, the computation required by [21] and [23] to determine all of the system's bus sensitivities is too enormous. Congestion has been alleviated using line flow sensitivities to change generation [25], but there has been no attempt to limit the number of participating generators. In [26], an approach is presented for selecting active generators that takes into account both the generation prices and the sensitivity of the current flow on overloaded lines. In [27], the author proposes the idea of "relative electrical distance" (RED) to minimize overloads through the rescheduling of actual power generation. In that concept, this method would reduce system losses and provide a more stable voltage profile and power supply. However, this study does not account for the bids of individual power units or the expenses associated with rescheduling. If two generators submit identical REDs but different price offers, each must reschedule their outputs so that the total cost of rescheduling is minimized.

With their high efficiency and reliability, FACTS devices [28] are preferred in modern power systems. The unified power flow controller (UPFC) and the interline power flow controller (IPFC) are two examples of coupled compensators that are among the most potent and flexible FACTS resources available. Because it uses two voltage-sourced switching converters (VSCs) connected via a shared dc voltage connection, UPFC has the ability to regulate active and reactive power flows separately. Similar to UPFC, IPFC uses at least two VSCs to regulate the power flow of several lines from a single substation [29]. However, unlike UPFC, IPFC's VSCs are typically coupled in series with separate lines, allowing it to compensate for many transmission lines at once. Correct mathematical modelling of this FACTS device is necessary for the implementation of IPFC for power flow control and optimal power flow control. The mathematical model described in [33] is used to build injection models of IPFC and the transmission lines that are embedded with IPFC. This is similar to how injection models of UPFC are often used [30], [31], and the exact pi-model of UPFC-inserted transmission lines can be found [32].

In this paper, researchers want to examine whether or not the constriction factor-based particle swarm optimization method can be used to effectively address the congestion management issue. The overloaded network is represented as an optimization problem model. The derivative of the function is traditionally used to identify the search direction for OPF solutions. All these methods work best when the problem is represented as a function that can be differentiated indefinitely. In this paper, the optimization problem is solved using a method called "constriction factor-based particle swarm optimization." The objective function's value is typically treated as the fitness function in optimization methods, and the penalty function approach is typically used to deal with binding restrictions. Since the penalty parameters are assigned empirically and are severely affected by the matter model, this approach has significant drawbacks. Particle swarm optimization with a constriction factor is one such unique method used in this research to deal with limitations. Using the IEEE 30 bus system, this research demonstrates the usefulness of the proposed approach to congestion avoidance problems.

II. ADVANCED INTERLINE POWER FLOW CONTROLLER (AIPFC)

The STATCOM, SSSC, UPFC and IPFC are all examples of FACTS controllers that were developed in the last generation and made use of a self-commutated voltage sourced converter (VSC). The power flow on only one transmission line can be managed by the UPFC and SSSC. The IPFC is able to regulate power flows between many lines, unlike the UPFC and SSSC, and it has a more versatile topology. It is made up of at least two converters. Congestion control in power transmission is a challenging issue that may be amenable to IPFC solutions. As a result, the author is inspired to develop a novel model for IPFC in power flow analysis.

One type of existing steady-state model is a decoupled model, whereas the other type is a coupled model. In a decoupled model, the Jacobian matrix structure is altered by substituting a fictitious PQ or PV bus for the FACTS devices. The VSM [34], [38]-[39] and the power injection model (PIM) [35]-[37] are the two main components of a coupled model. Managing the limitations of FACTS devices in practise is another critical issue [40]. The authors did not discuss how the IPFC limitations were integrated into the power flow models.

Well within the scope of this research, researchers introduce a unique power injection model of IPFC for power flow analysis. It is a complete model that takes into account both the susceptance of the line charging and the impedance of the series converter transformer. Keeping the admittance matrix's original structure and symmetry is demonstrated; this allows the Jacobian matrix to retain its block-diagonal features and permits the sparsity technique to be used. Control objectives are accomplished by coordinating changes to IPFC state variables and network state variables. Additionally, the model can account for IPFC's real-world restrictions, which are proven to be incorporated in Newton power flow. [41]- [42].

In its most basic form, the IPFC uses a group of dc-to-ac converters, each of which supplies series compensation for a distinct line. Series coupling transformers connect the converters' dc terminals to the AC networks. Any converter in the system can be directed to provide active power to the shared DC connection over its own transmission line, in addition to providing series reactive compensation. As the active power exchange among the *m* series converters must be balanced at all times, the degree of freedom of control for an IPFC with *m-1* series converters is two, except for the single series converter, which has just one degree of freedom of control. To better illustrate the fundamentals of IPFC operation, Figure 1 uses the IPFC with two series converters. This mathematical formula can be used for any number of series converters in an IPFC.

A. *Mathematical Model of AIPFC*

The numerical induction applies to an AIPFC with quite a several series converters.

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

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

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

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

B_{10} : The line charging susceptance

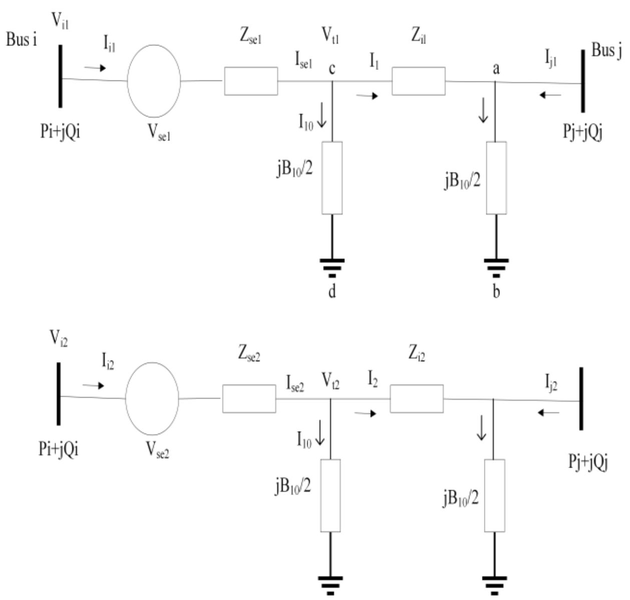

Fig. 1. Equivalent Circuit diagram of AIPFC

From Figure 1:

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

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

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

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

Where

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

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

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

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

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

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

$$D = \left[(jB_{10}) + Z_{l_n}\left(\frac{B_{10}^2}{4}\right)\right] \quad E = \left[1 + Z_{l_n}\left(j\frac{B_{10}}{2}\right)\right]$$

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

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

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

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

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

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

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 $A_{ii_n} = \frac{E}{N} \quad A_{jj_n} = \frac{M}{N}$

$$A_{ij_n} = D - \frac{ME}{N} \quad A_{ji_n} = -\frac{1}{N}$$

$$W_{ii_n} = -\frac{E}{N} \quad W_{ji_n} = \frac{1}{N} \quad A_{ij_n} = A_{ji_n} \quad (17)$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$P_{dc} = \sum\nolimits_n P_{ex_n} = 0 \tag{29}$$

Where $P_{ex_n} = Re\left(V_{se_n} I^*_{i_n}\right)$

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

Where

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

III. PARTICLE SWARM OPTIMIZATION

In 1995, Kennedy and Eberhart [43] devised the evolutionary algorithm known as "particle swarm optimization." Fish schooling and bird flocking are two examples of social behavior that served as inspiration. A flock of birds has been seen randomly discovering food sources. Some members of a flock may not know exactly where the food is, but they all recognize the general area. The quickest and most direct route to finding food is to look around the animal's current best location.

The derivative of functions is not necessary in the PSO process model, unlike in conventional optimization techniques. As long as optimum values for the optimization method can be derived, the algorithm will function. In addition, PSO's algorithm is intuitive enough for laypeople to grasp but grounded in sophisticated theory.

Several power system optimization issues have already benefited from PSO's application. The economic load dispatch of power plant generators is a problem addressed by PSO in [44]. Reactive power and voltage control are proposed in [45] to maintain reliable power and prevent power grid disruptions. The use of PSO for sensitivity analysis in congestion control is mentioned in [46]. On the other hand, it does not give away any information on how limits are dealt with.

A. *Constriction Factor Based PSO (CFBPSO)*

The following equation can be used to change each agent's speed:

$$v_i^{k+1} = wv_i^k + c_1 rand_1 * \left(pbest_i - s_i^k\right) + c_2 rand_2 * \left(gbest_i - s_i^k\right) \tag{31}$$

$$w = w_{max} - \left(\frac{\left(w_{max} - w_{min}\right)}{\left(iter_{max}\right)}\right) * iter \tag{32}$$

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

Each of the three equations (31), (32) and (33) in the PSO's foundational system can be interpreted as a difference equation. Therefore, the eigenvalues of the difference equation can be used to probe the system's or the search's behavior.

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

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

Where φ and K are coefficients.

For example, if we enter the values and discover that K = 0.73 when φ = 4.1, When w is greater than 4, K decreases. The damping effect is amplified, for example, if φ = 5.0, because K = 0.38. Users of the restriction factor technique tend to converge as time progresses. Unlike other evolutionary computation systems, the constriction factor methodology mathematically assures the search operation will converge. Therefore, the limiting factor approach can yield superior results compared to the standard PSO method. On the other hand, the dynamic behavior of a single individual and the impacts of inter-individual interactions are not taken into account by the restriction factor method. Because of this, the CFBPSO is able to produce higher-quality solutions than the standard PSO method. [47]- [49].

IV. PROBLEM FORMULATION FOR CONGESTION MANAGEMENT

The solution to the non-linear, static advancement problem known as the "optimal power flow" (OPF) problem reveals the most effective configuration for a power firm's control variables.

$$\begin{aligned} &Minimize\ f(x) \\ &Subject\ to\ h(x) = 0 \\ &g(x) = 0 \end{aligned} \tag{36}$$

Mathematically, this can be represented as in the following.

$$\min c(x) = min \sum\nolimits_{i=1}^{N_g}\left(c_i + b_i P_{gi} + a_i P^2_{gi}\right) \tag{37}$$

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

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

$$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max} \; i = 1, \dots, NG \quad (40)$$

$$Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max} \; i = 1, \dots, NG \quad (41)$$

$$P_{Di}^{min} \leq P_{Di} \leq P_{Di}^{max} \; i = 1, \dots, NG \quad (42)$$

$$Q_{Di}^{min} \leq Q_{Di} \leq Q_{Di}^{max} \; i = 1, \dots, NG \quad (43)$$

$$V_i^{min} \leq V_i \leq V_i^{max} \; i = 1, \dots, NL \quad (44)$$

$$T_i^{min} \leq T_i \leq T_i^{max} \; i = 1, \dots, NT \quad (45)$$

$$S_i \leq S_i^{max} \; i = 1, \dots, n1 \quad (46)$$

V. CASE STUDIES AND RESULTS

Congestion in the power system's networks is a common consequence of overuse. In this section, we show you the outcome of minimizing projected costs using CFBPSO to find the best possible location for an advanced IPFC model. An IEEE 30 bus system has been used to successfully implement the proposed method. There are six generators in total in an IEEE 30 bus test system; bus number 1 is the slack bus, buses 2, 5, 8, 11, and 13 are the PV buses, and buses 3, 4, 6, and 7 are the load buses. There are 41 lines in all, and the system requires a total of 283.40 MW to operate. Shunt compensations, tap settings on the transformer, and active power outputs from the generators are all used as control variables. In this presentation, we show how to use MATLAB to calculate the load flow of the IEEE 30 bus test system. When deciding where to put an advanced IPFC model, only load buses are taken into account. According to an overload analysis, transmission capacity has been reduced as a result of increased demand for fully loaded buses. In the simulation tests that show how well the proposed CFBPSO algorithm works with AIPFC, the base case, overload, and contingency analysis are all looked at.

A. Flowchart for Congestion Management by AIPFC Using CFBPSO Algorithm

The CFBPSO approach that will be proposed to solve the optimization problem could well be found in flow chart, along with the step-by-step procedure for doing so. Detailed analysis of transmission congestion management in power transmission lines using CFBPSO algorithm is presented in Figure 2.

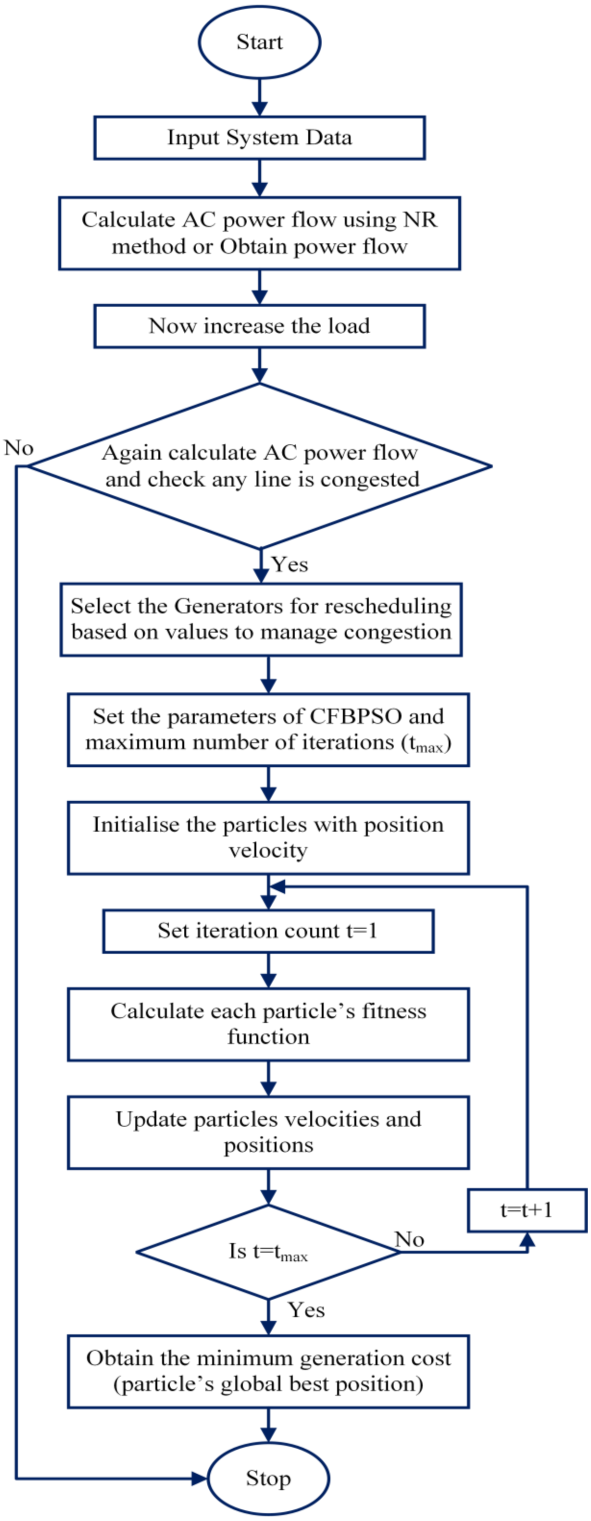

Fig. 2. A flowchart representation of the CFBPSO algorithm for the management of transmission congestion

Figure 3 shows how the OPF's findings with the proposed strategy compare to a small part of the writing processes that are used now to approve them. When compared to other tactics, the suggested CFBPSO strategy produces better results, as shown in this figure.

In Figure 3, researchers compared the OPF results generated using the proposed method to those acquired using other techniques found in the literature. The presented CFBPSO approach is superior to the alternatives as seen in the figure.

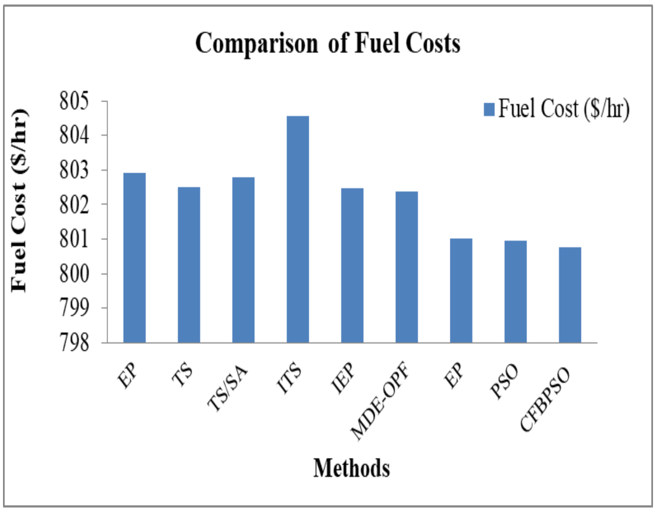

Fig. 3. Comparison of Fuel Costs

B. Base case condition

Initially, the Newton-Raphson load flow method is used to observe violations of temperature limitations in transmission lines. When the stated limit is exceeded, congestion occurs on the related transmission line. According to the results of the load flow analysis for the basic case, the thermal characteristics of all transmission networks are within the allowable range. Thus, it is observed that none of the 41 power lines are congested.

TABLE I
OPTIMAL CONTROL FACTORS SETTINGS FOR BASE CASE CONDITION USE OF CFBPSO WITH AIPFC

Control variables		NR method	CFBPSO with AIPFC
Active Power Generation (p.u)	P_{G1}	1.592	1.776
	P_{G2}	0.582	0.482
	P_{G3}	0.127	0.214
	P_{G4}	0.181	0.12
	P_{G5}	0.222	0.213
	P_{G6}	0.211	0.115
Generator Voltages (p.u)	V_{G1}	1.05	1.1
	V_{G2}	1.045	1.088
	V_{G3}	1.01	1.069
	V_{G4}	1.05	1.1
	V_{G5}	1.01	1.069
	V_{G6}	1.05	1.1
Loss (p.u)		0.0911	0.08
Cost ($/hr)		810.91	799.92

In determining the most effective schedule for the power system's operations under the base case scenario, the proposed CFBPSO is incorporated with the AIPFC. Minimizing fuel expenses for the generator is the optimal solution under consideration. Table I displays the results of applying CFBPSO with AIPFC to determine the optimal values for the control variables in the base-case scenario. Compared to the Newton-Raphson (NR) method, the AIPFC approach to CFBPSO yields a lower minimum generator fuel cost of $799.92/hr. All of the solutions are also shown to be in line with the control variables and the flow limit of the transmission line.

C. Congestion due to Overloading

In This section discuss the issue of transmission congestion brought on by system overload, when a rise in demand has led to an overload. All three loads (10%, 15%, and 20%) were used to test the proposed technique. Excessive line loads and the associated power levels are shown in Table II. In the first case, when 10% of the base load is raised, it shows 311.74 MW. In the second scenario, an increase in load of 325.91 MW (15 percent of the base load) is seen. In the prior scenario, 340.08 MW of load was obtained, which is equivalent to 20% more base load. At a load of 283.4 MW, the line flow limit of 130 MW for lines 1-2 is not achieved under base case conditions. The results of the simulations show that lines 1–2 are violated in all cases.

Two lines of the 30 bus system are connected to buses 3-4. Consequently, two test cases for AIPFC placement are evaluated. For each test instance, the congestion between buses is computed, and it is determined that it is greatest between the lines serving buses 3-4 and 4-12. For best placement of the AIPFC, thus, the lines between buses 3–4 and buses 4–12 are chosen. The appropriate placement of AIPFC will reduce line congestion.

On an IEEE 30-bus system, the load is increased to 10%, 15%, and 20% and a simulation is performed. It is observed that the actual and reactive power losses rise as the load increases. From Tables III, V, and VII, it is evident that efficient placement of AIPFC using the CFBPSO algorithm minimizes the installed AIPFC's loss and capacity. The power flow performance of the IEEE 30-bus system without AIPFC and with AIPFC optimized with CFBPSO is illustrated in Tables IV, VI, and VIII and Figures 4, 5, and 6. It is observed that optimally tuned AIPFC performs better than without AIPFC.

TABLE II
POWER FLOWS IN THE IEEE-30 BUS SYSTEM AT DIFFERENT LEVELS OF OVERLOADING

Over loaded line From bus	To bus	Load increment in (%)	Power flow Limit (MVA)	Power flow (MVA)
1	2	10	130	131.062
1	2	15	130	131.305
1	2	20	130	132.512

TABLE III
IEEE-30 BUS SYSTEM CONTROL VARIABLES FOR 10% LOADING CONDITIONS

Control variables		NR method	CFBPSO with AIPFC
Real Power Generation (p.u)	P_{G1}	1.943	1.694
	P_{G2}	0.541	0.604
	P_{G3}	0.128	0.35
	P_{G4}	0.187	0.174
	P_{G5}	0.222	0.274
	P_{G6}	0.211	0.12
Generator Voltages (p.u)	V_{G1}	1.05	1.05
	V_{G2}	1.04	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)		0.122	0.073
Cost ($/hr)		913.98	902.63

TABLE IV
POWER FLOWS UNDER 10% LOADING CONDITION

Line Number	Limit	NR method	CFBPSO with AIPFC
1	130	131.062	114.021
2	130	66.702	61.599
3	65	37.458	35.949
4	130	61.960	57.051
5	130	71.000	67.698
6	65	49.668	45.356
7	90	57.808	45.807
8	70	18.625	19.509
9	130	38.415	39.307
10	32	25.039	8.776
11	65	23.248	22.082
12	65	36.819	38.167
13	65	23.403	16.114
14	32	9.720	9.379
15	32	23.591	22.185
16	32	11.520	10.218
17	16	2.605	2.354
18	16	7.113	6.060
19	16	8.215	7.452
20	16	4.516	3.874
21	32	6.619	7.507
22	32	9.252	10.141
23	32	4.628	6.349
24	32	19.834	19.945
25	32	9.406	9.480
26	32	2.772	2.685
27	16	8.230	7.539
28	16	6.668	6.864
29	16	4.317	3.852
30	16	1.724	1.699
31	16	4.573	4.573
32	16	5.824	6.272
33	16	7.045	7.045
34	16	8.018	8.017
35	16	4.129	4.128
36	32	3.765	5.027
37	32	18.035	15.902
38	65	16.262	18.912
39	32	11.754	13.139
40	65	31.004	35.324
41	65	18.131	19.014

TABLE V
IEEE-30 BUS SYSTEM PARAMETER FOR 15% LOAD CASE

Control variables		NR method	CFBPSO with AIPFC
Real Power Generation (p.u)	P_{G1}	1.992	1.787
	P_{G2}	0.6635	0.625
	P_{G3}	0.189	0.35
	P_{G4}	0.117	0.199
	P_{G5}	0.257	0.25
	P_{G6}	0.173	0.12
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	0.065
Cost ($/hr)		969.72	949.47

TABLE VI
POWER FLOWS UNDER 15% LOADING CONDITION

LINE NUMBER	LINE LIMIT	NR METHOD	CFBPSO WITH AIPFC
1	130	131.305	121.742
2	130	71.1701	65.2603
3	65	41.1433	37.6571
4	130	66.0487	60.4096
5	130	73.8364	71.4737
6	65	53.8203	47.7337
7	90	59.8251	48.8764
8	70	17.8148	20.5622
9	130	38.0308	41.3164
10	32	23.5007	10.773
11	65	18.1516	23.6817
12	65	36.4046	40.1576
13	65	20.6398	16.3988
14	32	10.0646	9.72475
15	32	24.3092	22.9099
16	32	11.8213	10.371
17	16	2.64254	2.39072
18	16	7.24986	6.07827
19	16	8.51086	7.63265
20	16	4.64727	3.90363
21	32	6.93808	7.94687
22	32	9.68712	10.6998
23	32	4.90005	6.79276
24	32	20.3436	20.7263
25	32	9.61412	9.8679
26	32	2.98555	2.69428
27	16	8.29148	7.6987
28	16	6.56373	7.25363
29	16	4.26402	3.88279
30	16	1.6841	1.69999
31	16	4.72989	4.72973
32	16	6.35647	6.42445
33	16	7.36124	7.36082
34	16	8.38204	8.38153
35	16	4.316	4.31588
36	32	4.43916	5.18293
37	32	18.6655	16.7614
38	65	22.1977	19.1881
39	32	14.0372	13.661
40	65	35.8994	36.9794
41	65	19.7183	19.8568

TABLE VII
IEEE-30 BUS SYSTEM PARAMETER FOR 20% LOAD CASE

Control variables		NR method	CFBPSO with AIPFC
Real Power Generation (p.u)	P_{G1}	1.985	1.849
	P_{G2}	0.5675	0.676
	P_{G3}	0.35	0.35
	P_{G4}	0.169	0.202
	P_{G5}	0.233	0.251
	P_{G6}	0.12	0.12
Generator Voltages (p.u)	V_{G1}	1.05	1.05
	V_{G2}	1.045	0.901
	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)		0.134	0.059
Cost ($/hr)		1026.82	997.35

TABLE VIII
POWER FLOWS UNDER 20% LOADING CONDITION

Line Number	Line Limit	NR method	CFBPSO with AIPFC
1	130	133.423	129.32
2	130	71.1161	69.302
3	65	41.6401	39.456
4	130	65.8529	64.126
5	130	74.4905	75.24
6	65	53.6762	50.266
7	90	57.1957	52.237
8	70	18.2543	21.506
9	130	39.4404	43.187
10	32	20.1205	12.995
11	65	21.2168	24.79
12	65	39.7362	41.94
13	65	18.9658	16.702
14	32	10.2709	10.082
15	32	24.4562	23.679
16	32	11.3625	10.569
17	16	2.57	2.4346
18	16	6.73434	6.1285
19	16	8.33032	7.8435
20	16	4.35598	3.9567
21	32	7.78333	8.3524
22	32	10.6539	11.226
23	32	6.09842	7.1744
24	32	21.2675	21.492
25	32	10.0953	10.244
26	32	2.88098	2.7184
27	16	8.19399	7.8724
28	16	7.19604	7.6021
29	16	4.10646	3.9201
30	16	1.70193	1.7104
31	16	4.88836	4.8883
32	16	6.56901	6.5971
33	16	7.67838	7.6782
34	16	8.74802	8.7477
35	16	4.50381	4.5037
36	32	4.85955	5.3778
37	32	18.79	17.647
38	65	21.6682	21.6958
39	32	14.5301	14.5488
40	65	38.1747	38.0988
41	65	20.6553	20.6794

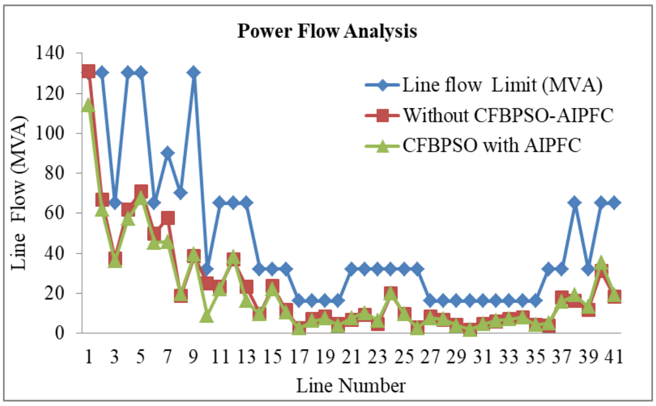

Fig. 4. In a 10% loading situation line flows

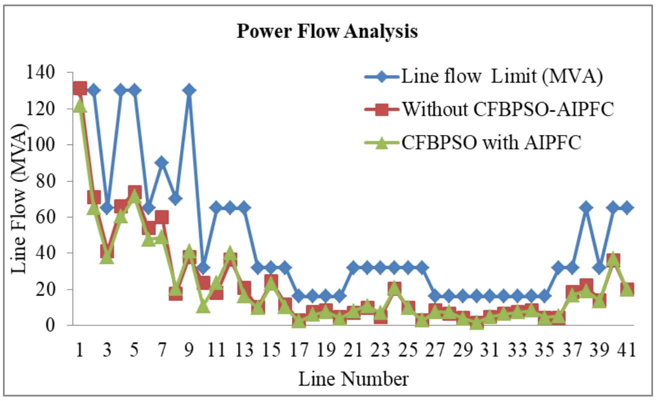

Fig. 5. In a 15% loading situation line flows

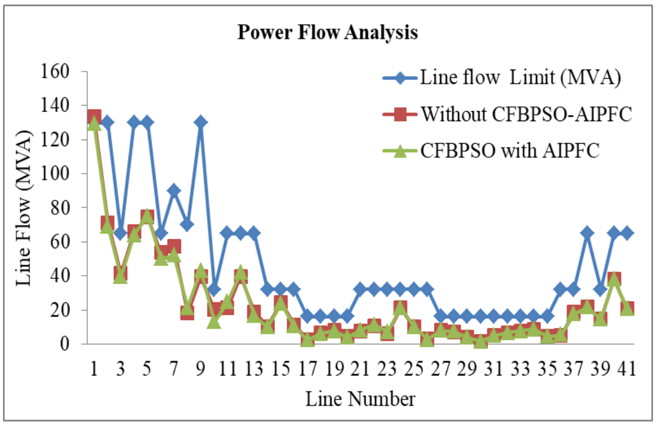

Fig. 6. In a 20% loading situation line flows

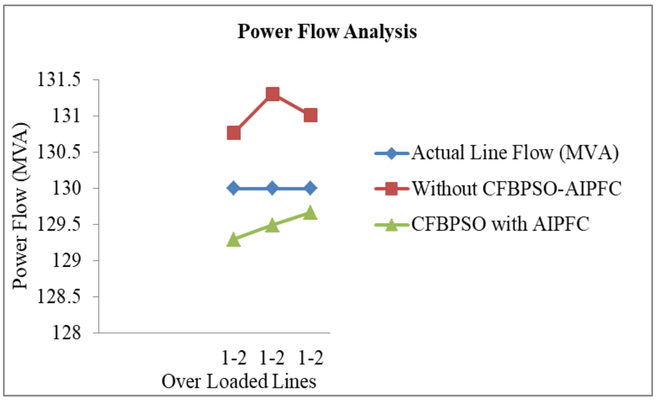

Fig. 7. Overview of overloading line flow under overloaded conditions using CFBPSO with AIPFC

TABLE IX
CFBPSO AND AIPFC POWER FLOWS OF OVERLOADED LINES UNDER OVERLOADING

Bus	Load increment in (%)	Limit of line flow (MVA)	Line flow under over loading	AIPFC with CFBPSO line flow
2	110	130	130.764	114.021
2	115	130	131.305	121.742
2	120	130	131.011	129.318

This demonstrates that the OPF problem can be solved with the CFBPSO with AIPFC approach, and that the desired outcome may be attained subject to limits placed on the control variables and the capacity of the transmission line. Based on the results given in Table IX and Figure 7, it can be concluded that the CFBPSO with AIPFC technique reduces congestion during overloading conditions.

D. Contingency Analysis

A line outage is a regular issue for electric power providers. Since the line of power flow has been disrupted, the power must choose an alternate route to reach the load requirement. Due to the line disruption, this detour generates congestion. AIPFC can be utilized to alleviate this type of congestion and improve control and operation. In this scenario, the congestion-related outages of 41 lines were studied individually. In Table X are depicted the four line outages that contribute to system congestion. Using Newton-Raphson power flow data, the optimal location for AIPFC with CFBPSO was determined. This was accomplished by computing alternative lines for the overloaded line.

TABLE X
POWER FLOW ANALYSIS UNDER CONTINGENCY FOR THE IEEE 30-BUS SYSTEM

Outage of lines	Effected lines	Power flow limit (MVA)	Power flow (MVA)
1-2	1-3	130	171.733
	3-4	130	161.812
	4-6	90	104.112
1-3	1-2	130	167.330
3-4	1-2	130	164.542
2-5	2-6	65	74.082
	5-7	70	83.094

Interruptions to transmission lines as a result of outages are discussed here. Table X displays a sample sensitivity analysis for the IEEE 30 bus system, where it is assumed that lines 1-2, 1-3, 3-4, and 2-5 are all congested at the same time in order to model potential situations of congestion. What-if analysis shows that line 2 has been underutilized whereas lines 1-2, 1-3, and 3-4 have been severely overloaded.

TABLE XI
LINE FLOW UNDER THE SELECTED FOUR NETWORK CONTINGENCIES

Line Number	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	167.33	164.542	95.4973
2	130	171.733	0	2.6188	74.2383
3	65	34.762	59.926	58.726	54.799
4	130	161.812	2.525	0	69.3582
5	130	47.139	71.969	71.5525	0
6	65	22.536	64.103	63.1952	74.0818
7	90	104.117	25.806	26.6306	86.3644
8	70	33.243	10.921	11.0494	83.0935
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 XI reveals based on contingency concerns, as follows: Seven lines are subject to the severe contingency scenario, and the CFBPSO method is used to identify the voltage violation and overload lines. On the lines where the overload occurred, the AIPFC with CFBPSO approach is implemented.

TABLE XII
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
10	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 XII presents the power flow distribution for the IEEE 30-bus system with and without AIPFC placed at the optimal point using CFBPSO. After implementing AIPFC with optimization approaches, a power flow violation existing in all buses has been eliminated.

TABLE XIII
OVERLOADED TRANSMISSION LINE FLOW DESCRIPTION UTILIZING CFBPSO WITH AIPFC FOR FOUR SIMULATED NETWORK SCENARIOS

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

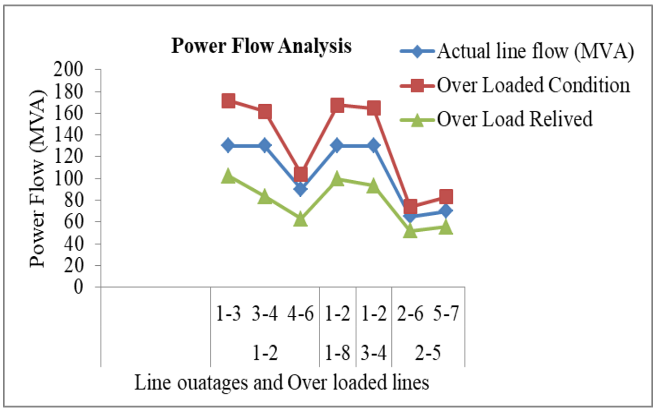

Fig. 8. Overloaded Transmission Line Flow Description Utilizing CFBPSO with AIPFC for Four Simulated Network Scenarios

As a result, this demonstrates the CFBPSO with AIPFC method for solving congestion problems while meeting control variable and transmission line flow limit constraints. Based on what has been seen, we can say that the CFBPSO with AIPFC method relieves congestion in case of an emergency.

VI. CONCLUSION

The application of the CFBPSO method with FACTS devices such as AIPFC for solving congestion-constrained optimal power flow problems under overloading conditions and the most severe network contingencies has been presented. To alleviate traffic jams, the CFBPSO method is used with the AIPFC to model the issue as an optimization problem. The method has been tried and proven effective on IEEE 30-bus systems, and the cost results achieved on the systems have been compared to the results reported using other methodologies. It was found that the proposed method, when used in conjunction with the AIPFC device, successfully converged to the optimal solution for achieving the designated goal while satisfying limits on control variables and the transmission line flow limit. The advantages of the CFBPSO algorithm include its straightforward design and explanation. The algorithm's strength is shown by its ability to withstand being overwhelmed and by solving for unforeseen circumstances. The test results, however, demonstrate that the proposed solution is effective at managing congestion and outperforms in overloaded and contingency condition.

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