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Rescheduling of Generators with Pumped Hydro Storage Units to Relieve Congestion Incorporating Flower Pollination Optimization

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Abstract: In this paper, a Flower Pollination Algorithm (FPA) has been proposed for relieving congestion in the deregulated power electricity industry. Congestion in the power market is one the contemplative challenges to be overcome in the era of deregulation. The primary cause of congestion is due to the loss of the transmission line, an increase in load, or loss of generator(s). Hence, managing congestion is one of the issues which have to be tackled in the present scenario. There are several techniques to relieve congestion. It is quite well-known that the thermal limits of transmission lines in a power system are fixed. One of the methods to abate congestion is to reschedule the real power of the generators. The purpose of the present work is to benefit the Independent System Operator (ISO) in reliving congestion. (1) In order to meet this objective effectively, a FPA algorithm has been proposed for relieving congestion and is simulated on a modified IEEE 30-bus system initially. (2) Congestion cost, compared with and without the application of FPA, is computed. (3) To validate its effectiveness, the obtained results are compared with recent power system optimization algorithms present in the literature. (4) Further, the work has been extended with the incorporation of a Pumped Hydro Storage Unit (PHSU). Here an economic analysis of congestion cost reduction employing FPA before and after the incorporation of PHSU is investigated applying FPA. In comparison with other evolutionary algorithms, the uniqueness of generating a new population is attained in FPA by the levy flight procedure. It is one of the latest evolved algorithms and is suited for different power system problem due to fewer clear-cut tuning parameters in contrast with other algorithms. (5) Furthermore, the effects of other network parameters, including system losses and voltage, has been computed. The result obtained is tested in terms of congestion mitigation with and without the incorporation of PHSU, in terms of novel objective improvement, and with and without applying recently evolving FPA for the above application. Thus the objective-wise and algorithmic-wise innovative concept has been presented. This proves effectiveness of the algorithm in terms of minimized cost convergence and other parameter including system losses and voltage before and after the incorporation of PHSU as compared with other recent trendsetting reported optimization techniques.

Keywords: congestion management; power flow; generator rescheduling; Flower Pollination Algorithm (FPA); Pumped Hydro Storage Unit (PHSU)

1. Introduction

The integration of utilities being vertical, the task of separating the cost incurred in generation, transmission and distribution is quite difficult. Thus, the utilities put an average tariff on to their customer which relies on the aggregated fixed price for a specific period. Some of the external agencies fix the price which focuses more on consideration rather than economics. Occurrence of Congestion at a location in power transmission system will not be able to suit all the proposed bi/multilateral exchanges. It is due to the inability to incorporate the Existing Transmission Commitments (ETC), due to the infringement of operating constraints. A glimpse of a detailed survey related to managing the congestion issues occurring worldwide has been schemed in [1]. The authors have explained the techniques for consolidating deregulated market arrangements for the better utilizations of the power resources thereby providing solution to the issues [2]. A model with the inclusion of system stability criterion has been accounted for so as to relieve congestion [3]. A methodology for the embodiment of the reactive power services and real power loss while overseeing congestion has been considered [4]. The authors have examined the effects of FACTS arrangement for pacifying this problem [5]. The impact of congestion on the power system, and the financial signs of dispensing the associated cost venture have been discussed in [6]. The authors have proposed congestion management based zones/cluster; wherein the zones are being decided by the congestion distribution factors [7,8]. A combination of pool and bilateral trading has been considered for managing the congestion in a market based environment [9]. The author has assessed a detailed review on managing the congestion in different scenario of the market under privatization structure [10,11]. This paper ranks the management of congestion activities and its trappings on socio-economic impacts has been addressed in a divergent private mob. An analytical model based optimal technology comprising elements such as transformer taps and optimal switching has been incorporated for eliminating congestion [12]. A secure path of managing congestion with the due consideration of stability has been urged in [13,14]. Here the optimization problem has been effectively handled incorporated with penalty constraints [15,16].

Managing the congestion can be eased with different algorithm such as Simulated Annealing (SA), Random Search Method (RSM) and Particle Swarm Optimization (PSO) and tested on modified IEEE 30 bus system and IEEE 57 bus system. Further this issue has been dealt with the embodiment of nonconventional wind energy system [17]. This paper addresses the combined operation of energy utilization from hydro and wind is utilized for devising the mathematical model for bidding in a day-ahead energy market [18]. Adjusting the real power output of generators in order to meet the power demand is a real time challenge in the present scenario in the power grid. PHSU has commercially proven to meet the changes in power demand owing to its capability to start/stop quickly in accordance to change in load. The authors have presented the erection and devising of PHSU to serve peak demand. Further an insight analysis has been carried out on electricity pricing and its associated guidelines adopted [19]. This paper renders a wide vision into the recent development of PHSU in relation to its participation in deregulated energy market [20]. Further it addresses the flexibility of PHSU aiding in shift of generation thereby avoiding congestion and manages reliable supply of power in the grid. A formative structure has been incorporated with combined operation of hydro and PHSU for apprehending the volatility in pricing for in order to improvise the payoff from the generators [21]. Implementation of PSHU along with thermal plants enabled a steady decrease in emission [22,23]. This paper interprets the saving in cost yielded by optimal use of PHSU when operated during peak demand and thermal usage during off-peak demand [24]. The superiority of PHSU elevated the efficiency in energy transaction [25–27]. FPA and its variants have been developed in recent years which are found to yield better efficient outputs in applications for optimization designing due to its single probability switching parameter [28]. It associates the non-linearity Levy flight mechanism which proves to be effectively suited for multi-objective for enhancing the algorithmic performance of exploring the distant pollinator thereby globally exploring and locally exploiting by the consistency of flowers chosen [29,30]. FPA has been tested on IEEE 30 bus system with three different objective functions incorporating economic load dispatch and result obtained is compared with other optimization techniques proving for its robustness over other existing algorithms [31]. Symbiotic Organisms Search algorithm [32], Ant lion algorithm [33], Gravitational Search Algorithm [34], Teaching Learning Based Optimization (TLBO) [35] are few of the latest algorithms have been found proposed for extenuating congestion. Switching the transmission lines in optimal sequence is one of the novel technologies to subdue congestion [36]. A novel distribution Algorithm has been proposed using nash equilibrium for effective cost reduction due to wheeling [37]. The technological advancements employing Power Electronic circuitry for Hydro Energy Electric Systems contributes widely in terms of economical payment and space reduction [38]. The reliability of the PHSU is effectively eased with the incorporation of Doubly-Fed Induction Motor [39]. The future prospects of adventing compressed air storage embedded with PHSU has been discussed. This could increase the performance utilization of energy. This proves to be a viable solution for the power industry in the future [40].

The major contributions of the paper are as follows. The main idea is to propose a methodology for managing the problem of congestion with cost reduction by rescheduling the generators active power. To achieve this task, FPA Algorithm is presented here. The stimulus of the present effort is to benefit the ISO in reliving the congestion. Here, modified IEEE 30 bus system is used as the test case. Initially an outage is created to cause the Congestion which results in power flow violation in certain transmission lines and the Congestion cost has been computed. Then the novel FPA is schemed as an efficient optimizing tool for rescheduling cost minimization as well as reduces the system losses. Further the rescheduling Congestion cost is compared with and without the application of FPA is computed. The effectiveness of the proposed Algorithm is proven in terms of minimized Congestion cost. To validate its effectiveness, the obtained results are compared with other optimization algorithms already reported in literature. Thereafter to replenish the varying load demand nature, a PHSU unit has been incorporated in it. The efficacy of FPA algorithm incorporating with PHSU is then investigated in terms of congestion cost minimization.

The paper is methodized as follows: Section 2 deals with the frame work criterion of managing congestion by rescheduling of generator's active power with the inclusion of PHSU in terms of congestion cost and loss minimization. Section 3 accomplishesFPA as an efficient optimizing tool for congestion cost minimization as well as reduces the system losses. Section 4 discusses the power flow violation due to congestion and the application of suitable methodology namely FPA. The efficacy of FPA in benefitting the Independent System Operator (ISO) in reliving the congestion is presented here. Here, modified IEEE 30 bus system is used as the test case. There after it is validated with other optimization techniques. Section 5 presents the significance of PHSU incorporated in the test system in aiding further reduction in congestion cost, losses and voltage profile improvement embodying BSF and GSF. Furthermore an economic analysis of congestion cost reduction using FPA before and after the incorporation of PHSU is investigated.

2. Problem Formulation

The main objective that is been focused is to reduce the congestion cost of the system taken into consideration.

$$\text{Minimize} \sum_{k=1}^{N_k} C_k^n \left(\Delta P_k^n\right) \Delta P_k^n \tag{1}$$

where,

C_k^n : Rescheduling cost of power by generators as per increase and decrease price bids at interval n.
ΔP_k^n: Incremental change in active power adjustment of the generator at interval n.
P_k^{min} & P_k^{max}: Minimum and maximum limits of generation.

Subject to constraints mentioned below.

$$P_{gj} - P_{dj} = \sum_{k=1}^{n} \left| V_j \| V_k \| Y_{jk} \right| \cos\left(\delta_i - \delta_k - \theta_{jk}\right) \tag{2}$$

$$Q_{gj} - Q_{dj} = \sum_{k=1}^{n} \left| V_j \| V_k \| Y_{jk} \right| \cos\left(\delta_j - \delta_k - \theta_{jk}\right) \ j = 1,\ 2,\ \ldots,\ n \tag{3}$$

$$P_{gk}^{min} \leq P_{gk} \leq P_{gk}^{max} \tag{4}$$

$$Q_{gk}^{min} \leq Q_{gk} \leq Q_{gk}^{max} \ k = 1,\ 2,\ \ldots,\ N_g \tag{5}$$

As the pumped storage units are connected on to the bus to reduce the congestion cost of the system, the additional constraints considered are as follows

$$e^n = e^{initial} \ n = 0, e^n = e^{final} \ n = 24 \tag{6}$$

$$e^{n+1} = e^n + t \left(\eta_{Ps} \ P^n{}_{ps} - \frac{P_{Hs}^n}{\eta_{Hs}}\right) \tag{7}$$

$$P_{Ps}^{min} \leq P_{Ps}^n \leq P_{Ps}^{max} \tag{8}$$

$$P_{Hs}^{min} \leq P_{Hs}^n \leq P_{Hs}^{max} \tag{9}$$

$$e^l \leq e^n \leq e^u \tag{10}$$

2.1. Bus Sensitivity Factor

The bus sensitivity factor (BSF) is expressed as the ratio of incremental real power change flowing in bus '*i*' connected between buses '*j*' and '*k*' to the incremental change in *m*th power of the bus as given below. BSF provides the optimal location for the placement of PHSU based on highest negative sensitive indexes.

$$BSF_m^i = \frac{\Delta P_{jk}}{\Delta P_m} \tag{11}$$

where, BSF_m^i indicates the quantum of real power change in real power flows in a transmission line in accordance to real power injection at bus *m*.

BSF can be derived from Equation (2) as illustrated below.

$$\Delta P_{jk} = \frac{\partial P_{jk}}{\partial \delta_j} \Delta \delta_j + \frac{\partial P_{jk}}{\partial \delta_k} \Delta \delta_k + \frac{\partial P_{jk}}{\partial V_j} \Delta V_j + \frac{\partial P_{jk}}{\partial V_k} \Delta V_K \tag{12}$$

$$\Delta P_{jk} = a_{jk} \Delta \delta_j + b_{jk} \Delta \delta_k + c_{jk} \Delta V_j + d_{jk} \Delta V_k \tag{13}$$

$$\Delta P_{jk} = a_{jk} \Delta \delta_j + b_{jk} \Delta \delta_k + c_{jk} \Delta V_j + d_{jk} \Delta V_k \tag{14}$$

where,

$$a_{jk} = V_j V_k Y_{jk} \sin\left(\theta_{jk} + \delta_k - \delta_j\right) \tag{15}$$

$$b_{jk} = -V_j V_k Y_{jk} \sin\left(\theta_{jk} + \delta_k - \delta_j\right) \tag{16}$$

$$c_{jk} = -V_k Y_{jk} \cos\left(\theta_{jk} + \delta_k - \delta_j\right) - 2V_k Y_{jk} \cos \theta_{jk} \tag{17}$$

$$d_{jk} = V_j Y_{jk} \cos\left(\theta_{jk} + \delta_k - \delta_j\right) \tag{18}$$

The Jacobian Matrix using Newton–Raphson (NR) method is given in Equation (19).

$$\begin{pmatrix} \Delta P \\ \Delta Q \end{pmatrix} = [J]\begin{pmatrix} \Delta\delta \\ \Delta V \end{pmatrix} = \begin{pmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{pmatrix}\begin{pmatrix} \Delta\delta \\ \Delta V \end{pmatrix} \tag{19}$$

where,

$$\Delta\delta = [J_{11}]^{-1}[\Delta P] = [M][\Delta P] \tag{20}$$

$$\Delta\delta_j = \sum_{l=1}^{n} m_{jl}\Delta P_l j = 1, 2, \ldots\ldots\ldots, n, j \neq s \tag{21}$$

Thus

$$BSF_m^i = a_{jk}m_{jl} + b_{jk}m_{jl} \tag{22}$$

2.2. Generator Sensitivity Factor

The generator sensitivity factor (GSF) is expressed as the ratio of incremental change in real power flowing in bus 'i' connected between buses 'j' and 'k' to the incremental change in the active power supply of the generator as shown below. Generators are rescheduled based on highest negative indexes.

$$GSF_{gn} = \frac{\Delta P_{jk}}{\Delta P_{gn}} \tag{23}$$

Congestion management is formulated using the Newton–Raphson power flow method. Congestion results in the power flow violation in certain transmission lines and the congestion cost have been computed. Then the novel FPA is schemed as an efficient optimizing tool for rescheduling cost minimization as well as reducing the system losses. Further the rescheduling congestion cost is compared with and without the application of FPA is computed. The effectiveness of the proposed Algorithm is proven in terms of minimized congestion cost and its validation is presented in Figure 1. The efficacy of FPA algorithm incorporating with PHSU is then investigated in terms of congestion cost minimization, as shown in Figure 2. The impetus to carry out this work relies on a novel methodology for figuring out complexity that arises in managing the congestion. Despite the fact the problem of managing congestion has been endorsed in the literature for decades, at most gets committed on meta-heuristic and artificial intelligence approaches. Iteration number and population size are the typical monitoring criterion shared among these different methodologies. Distinct from these general monitoring criterions, some techniques incorporates algorithmic based specific tuning criterion like mutation rate and cross-over rate in the Genetic Algorithm (GA). Lack of proper tuning of algorithmic parameters can lead to local minima and increases time of computation for convergence. Particle Swarm Optimization (PSO) handles inertial weight adjustments. Although Simulated Annealing (SA) can solve optimization problems of complicated nature, the drawback is the inability to obtain the best solution without integrating another technique in it. Further, Harmony Search Algorithm (HSA) embodies the heed on memory rate and adjustments in pitch weight. Thus the fulfillment of the final solution is attained by the legitimate control of this algorithmic based specific tuning criterion. Commemorating these concepts, the proposed paper employs the implementation of FPA Algorithm. This relies on the mechanism of levy flight using a common probability switching parameter thus eliminating the need of algorithmic based specific tuning criterion and makes it effective for optimization problems.

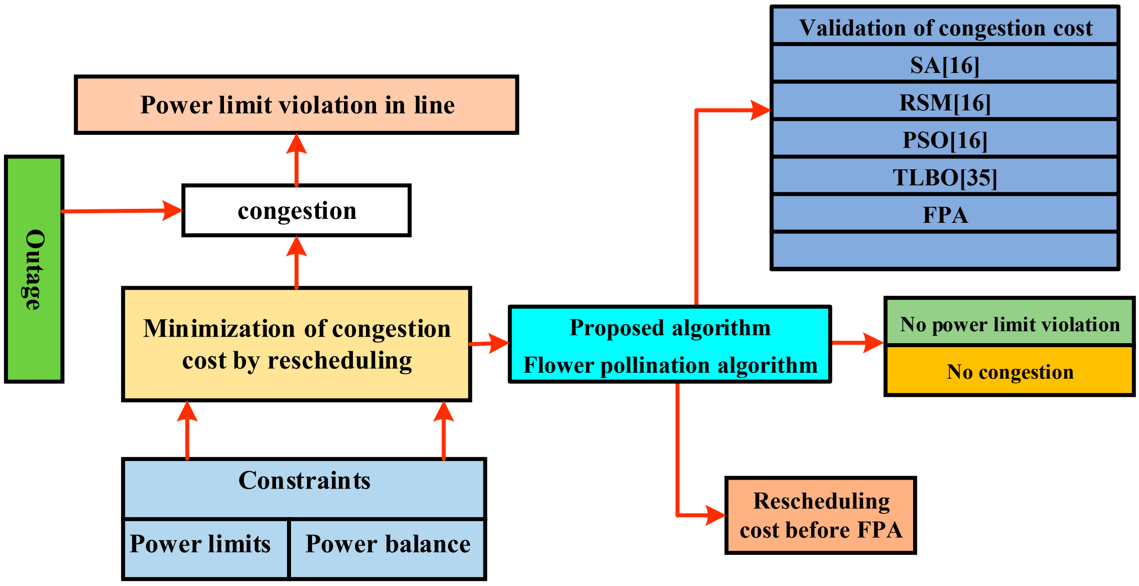

Figure 1. Congestion cost minimization using Flower Pollination Algorithm (FPA) and its validation with other optimization techniques (Part I).

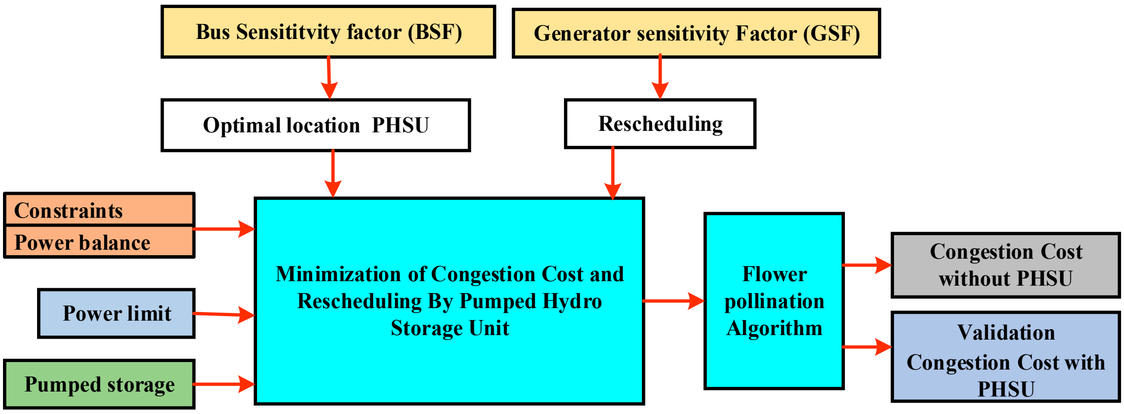

Figure 2. Congestion cost minimization using FPA incorporating Pumped Hydro Storage Unit (PHSU) and its validation (Part II).

3. Flower Pollination Technique

Flower pollination is a process adopted by flowers and plants to reproduce. It is classified into biotic and abiotic. Biotic pollination is done by living organisms whereas nonliving accounts for abiotic pollination. The other way of classifying pollination is self and cross. Self-pollination means fertilization of the same plant and cross-fertilization happens for different plants. The long distance process is called global pollination, and implantation, happening over short distance, is called local pollination. Flower constancy also provides an assurance of nectar for the pollinators with minimum effort of learning, exploration and exploitation. The global pollination is carried out by the equation

$$a_i^{m+1} = a_i^m + L\left(a_i^m - c_*\right) \tag{24}$$

where,

$$L \simeq \lambda\Gamma(\lambda)\frac{\sin\left(\frac{\pi\lambda}{2}\right)}{\pi} * \frac{1}{s^{1+\lambda}} \tag{25}$$

a_i^m *i*th pollen at *m*th iteration

L—Levy weight-based size of each step ($s; s > 0$).

c_*—Best current solution at current iteration.
$\Gamma(\lambda)$Gamma distribution function

The pollination occurring locally is carried out by the following equation

$$a_i^{m+1} = a_i^m + \in (a_o^m - a_q^m) \tag{26}$$

a_i^m ith pollen at mth iterations
$\in$—takes a value of [0,1]
a_o^m and a_q^m—pollen from different flowers from same plant.

Biotic, also called cross-pollinators, follows movement of step flight, which aids in attaining. A set of N flower population is generated with random solutions. Global pollination follows the rule of biotic and cross-pollination; the reproduction probability depends on flower constancy.

The two indispensable concepts of FPA are local and global pollination steps. Pollinators carry the pollens of the flower to far reaching places due to its custom manner. This helps in the exploration of the larger search space. Here the general tuning parameter of levy flight mechanism, which essentially incorporates the various distant step sizes carried out by the pollinator. Usually the nearby flower is pollinated by the pollens of the local adjacent flowers rather than the far-off flowers. Thus, the general probability tuning parameter using levy fight mechanism switches effectively between global pollination and local pollination ensures the effective exploration and exploitation of the learning with minimum learning effect.

A simple numerical example is illustrated here for the implementation of FPA, as given below.

Consider a simple objective function $f(z) = z_1^2 + z_2^2$ subject to $z_{g,i}$ = (0.3,0.3). The fitness value obtained is $f(z_{g,i}) = 0.18$. Equation (26) is then applied and $z_{g+1,i} = (0.3, 0.3)$ and then updated to (0.1,1) for illustration. Then the newly updated. $z_{g+1,i} = (0.1, 0.3)$. As a result, the new fitness value solution $f(z_{g+1,i}) = 0.04$. Here $f(z_{g+1,i}) < f(z_{g,i})$. This infers that the old fitness value solution can be replaced by the currently obtained fitness value. For example, if the newly updated. $z_{g+1,i} = (0.9, 0.3)$, this results in the new fitness solution $f(z_{g+1,i}) = 0.9$. Here $f(z_{g+1,i}) > f(z_{g,i})$. This clearly indicates there is no progress to advance $z_{g,i}$. Thus, this value should be discarded and proceeded for the updating the next fitness value as indicated in pseudocode.

4. Algorithmic Steps in FPA

The sequential steps carried out in pseudocode of the flower pollination algorithm are presented as follows. The minimization objective function:

$$min\, f(x),\, x = (x_1, x_2, \ldots .., x_l) \tag{27}$$

- Initially generate t population of flowers randomly
- Fitness solution c_* is then obtained from t population generated.
- While (m < maxgen)
  for i = 1:*t*
  if r and < *p*,
    - A step vector has been drawn with levy's distribution
    - And carry out Global population given by Equation (24)
- else
  Uniform distribution in between the range 0 to 1 is then drawn for $\in$.
- Pollination is then carried out with local population with the random r and s variables by
- Equation (26).
  end if

- New solutions are then calculated

- If current solution obtained is better, replace the old solution by the current solution.
  end for
- Best current solution c_* is then updated
- end while

Managing the congestion is coded using the Flower Pollination Algorithm. The process of carrying the pollens of the flower to far reaching places assures the fittest population for survival in the search space. The efficacy of FPA is implemented in terms of congestion cost minimization as shown in Figure 3. The parameters of FPA are λ, s, and size of population and iteration number. The criteria for optimal tuning obtained using FPA are λ = 1.6, s = 1, and size of population is 6 has been carried out for 25 iterations. Here the expedition between the global and local search using levy flight mechanism ensures the optimal output. Further FPA relieves congestion by suitable rescheduling of the real power of the generators. To validate its effectiveness, the obtained results are compared with other optimization algorithms already reported in literature.

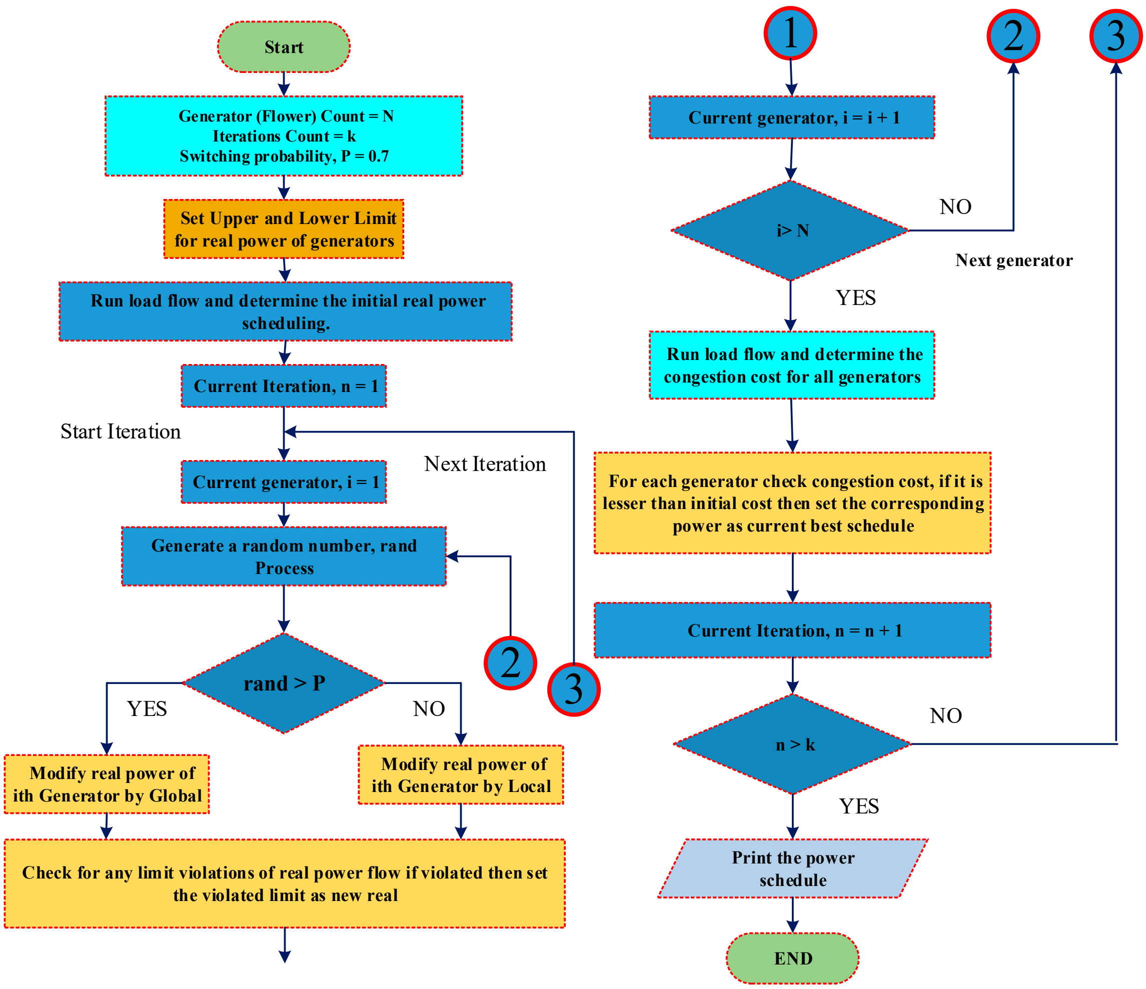

Figure 3. Implementation of FPA for congestion management.

5. Results and Discussions

The proposed method is schemed considering IEEE modified 30-bus system, which consists of six generator buses and 24 load buses. The slack node has been assigned as bus number 1. The numbering of buses has been done in a way that the generator buses are numbered first followed by load bus. Figure 4 depicts the single line diagram of the modified IEEE 30-bus system considered here.

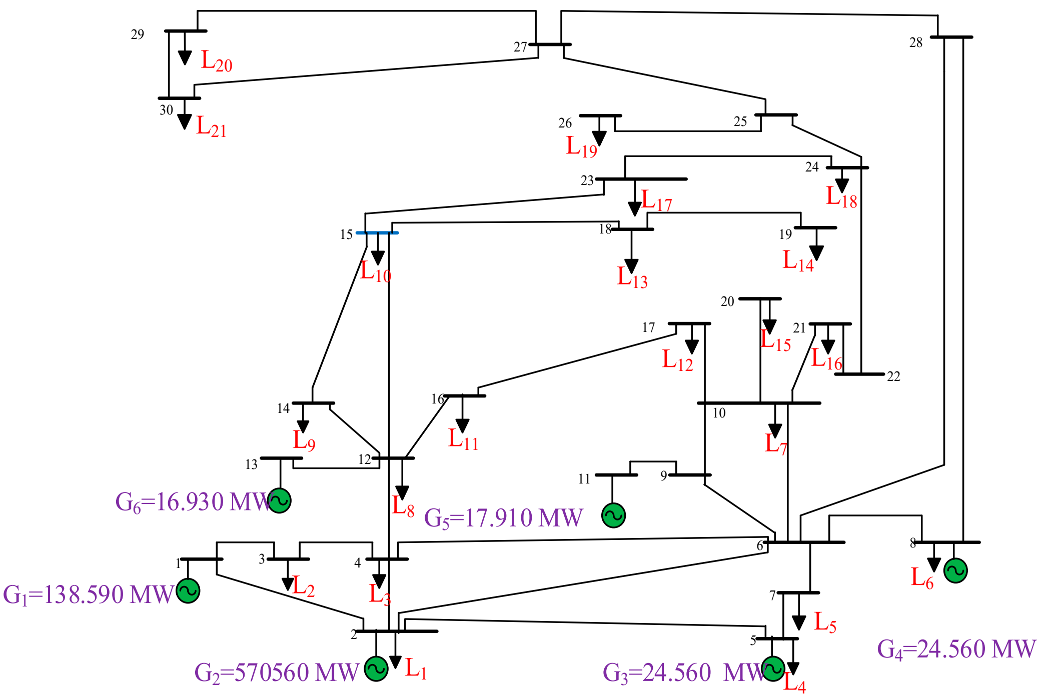

Figure 4. Single line diagram of modified IEEE 30-bus system.

Contingency analysis was conducted under the base load condition to identify the harmful contingencies. Here the outage of line 1–2 with normal loading is considered and has been illustrated out in Figure 5. It is ascertained from Figure 5. The actual power flow violation rises to 1.14%, 2.13%, and 1% in the lines connected between 1 and 3, 2 and 6, and 4 and 6, respectively. The system has been simulated with a line outage so as to create the contingency and results of line flow and its violations are reported in Table 1. Here, from Table 1 we can observe that there are three lines those are violating their limit that is line number 1, 5, and 6 which have 130 MW, 65 MW, and 90 MW of line flow limit, respectively. The power flows on the three violated lines are nearly 148 MW, 138 MW, and 90 MW. Even though the line 6 is violating by a small amount that is nearly equal to 0.59 MW, it has also been taken into consideration in the calculation. Congestion due to outage of line 1–2 and its effect on network framework parameters has been tabulated in Table 2. Here, due to congestion the percentage of overload on the congested line is reflected. The most overloaded line among the three lines that has to get congestion due to the line outage of lines 1–2 is the line connecting between buses 2 and 6.

The amount of power violated by each of the congested line is also shown in Figure 6. The line 2–6 has violated the limits the most that is nearly 73 MVA of power. The total amount of power violated due to the outage is 92.292 MVA. This power violation has to be now rescheduled through other lines so as to get rid of the congestion that has appeared. It is highlighted from Figure 7 the increase in overload amounts to 13.89%, 113.29%, and 0.65% in the lines connected between 1–3, 2–6, and 4–6, respectively. This violation is one of the issues critically faced by ISO. To achieve this task, the novel FPA is schemed as an efficient optimizing tool for congestion cost minimization as well as reduces the system losses. The stimulus of the present effort is to benefit the ISO in reliving the congestion. The rescheduling line flow is compared with and without the application of FPA is computed. The Flower Pollination Algorithm is used here as an optimization tool and it can be seen that the result obtained in Table 3 reflects its validity. The line which were violating the their line flow limits are now under the limits of their flow after the rescheduling of the generators is done by utilizing the FPA as shown in Figure 8.

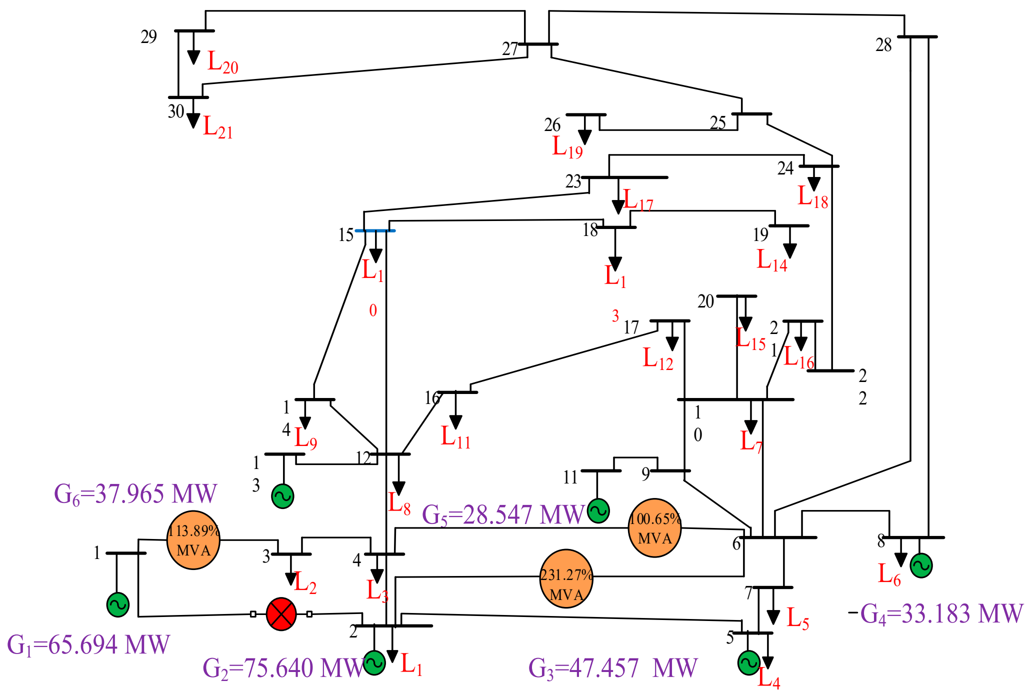

Figure 5. Effect of MVA violations due to an outage.

Table 1. Line flows in test case.

Line No.	MVA	Flow Rating (MVA)	Violation (MVA)	Line No.	MVA	Flow Rating (MVA)	Violation (MVA)
1	148	130	**−18.0636**	21	17.3	65	47.718
2	19	65	46.0397	22	8.34	16	7.66181
3	45.9	130	84.1025	23	19.9	32	12.0516
4	5.51	130	124.486	24	8.84	32	23.1584
5	139	65	**−73.6385**	25	1.85	32	30.1469
6	90.6	90	**−0.590291**	26	6.77	32	25.2275
7	37.7	70	32.2841	27	6.12	32	25.8765
8	34.1	130	95.9333	28	5.18	32	26.8177
9	51.3	65	13.7257	29	3.49	16	12.5059
10	24.5	65	40.5254	30	7.06	16	8.9363
11	13.8	65	51.1833	31	2.85	16	13.1489
12	12	65	53.0422	32	6.05	32	25.9523
13	16.5	65	48.482	33	2.86	16	13.1409
14	4.45	65	60.5462	34	1.35	16	14.6473
15	17.9	65	47.0647	35	4.27	65	60.7337
16	30.8	35	4.1557	36	5.26	16	10.7365
17	9.52	32	22.4836	37	6.42	16	9.58086
18	7.51	32	24.4883	38	7.29	16	8.70574
19	18.3	32	13.6829	39	19	32	28.2448
20	8.66	32	23.3388	40	3.76	32	12.9574

Table 2. Impact on network framework parameters due to outage of lines 1–2.

Type of Contingencies	Congested Lines	Line Limits MVA	Actual Power Flow (MVA)	Amount Power Violation (MVA)	Total Power Violation (MVA)	Overload %
Outage of line 1–2	1–3	130	148.06	**18.06**	92.29	**13.89**
	2–6	65	138.63	**73.63**		**113.29**
	4–6	90	90.590	**0.59**		**0.65**

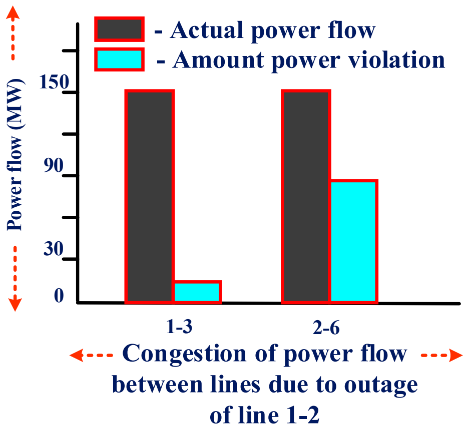

Figure 6. Power violation between lines due to line outage between lines 1–2.

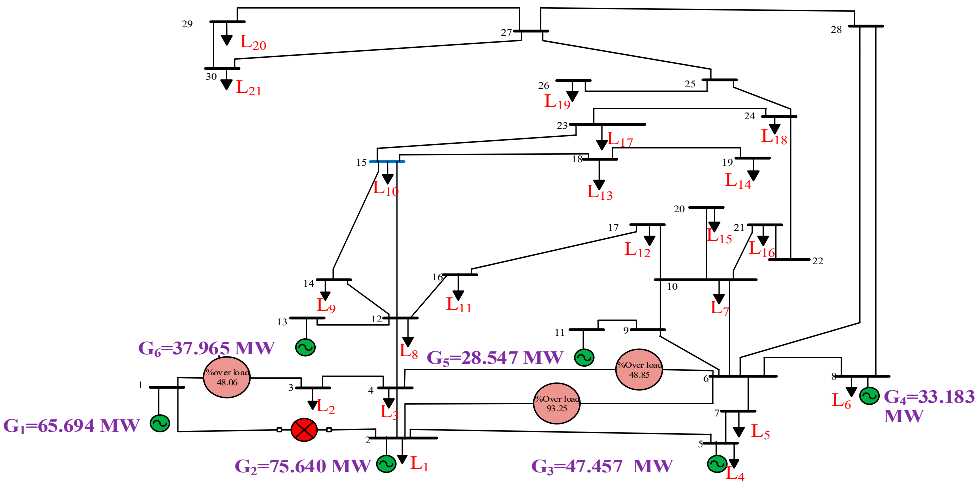

Figure 7. Effect of overload due to an outage.

Table 3. Comparison of congested line flow.

Congested Line	Limit (MVA)	Before Applying FPA (MVA)	After Applying FPA (MVA)
1–3	130	148.0636	63.5146
2–6	65	138.6385	60.6178
4–6	90	90.5903	43.2578

Table 4 indicates the economic cost analysis of cost before rescheduling is 941.208 $/hr, while after rescheduling it reduces to 460.616 $/hr. Here the expedition between the global and local search using levy flight mechanism ensures the optimal output. This validates the effectiveness of the algorithm. Further the changes in active power rescheduling have been graphically depicted in Figure 9.

Table 4. Rescheduling of generators in the modified IEEE 30-bus system.

Generator No.	Before Rescheduling (MW)	After Rescheduling (MW)	Increment in Generation (ΔPgi)
1	138.590	65.694	−72.896
2	57.560	75.640	18.080
3	24.560	47.457	22.897
4	35.000	33.183	−1.817
5	17.910	28.547	10.637
6	16.930	37.965	21.035
Total cost ($/hr)	**941.208**	**460.616**	

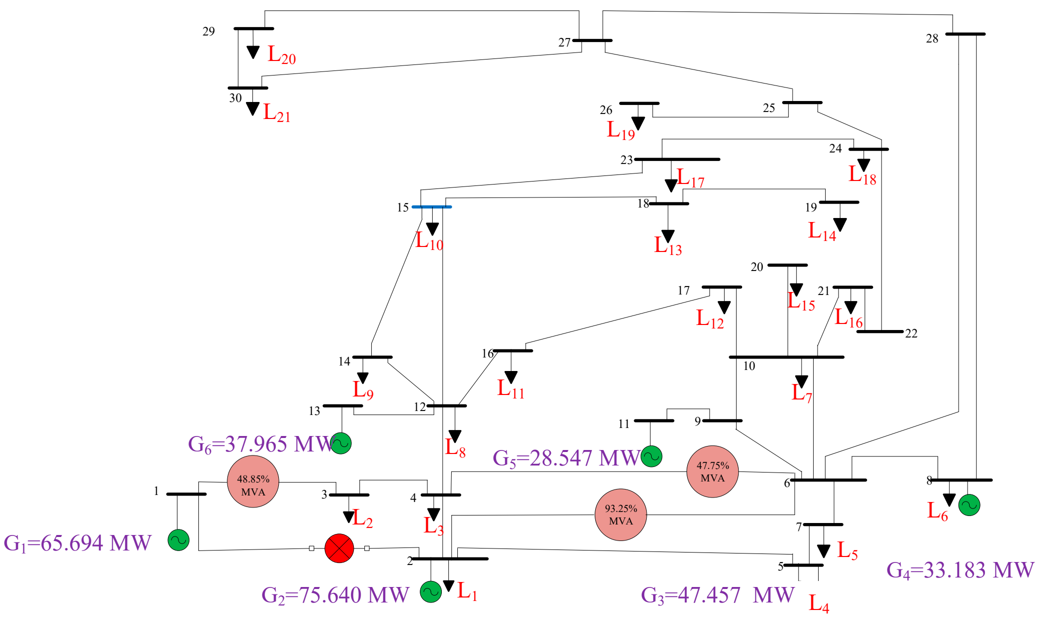

Figure 8. Mitigation of congestion employing Flower Pollination Algorithm.

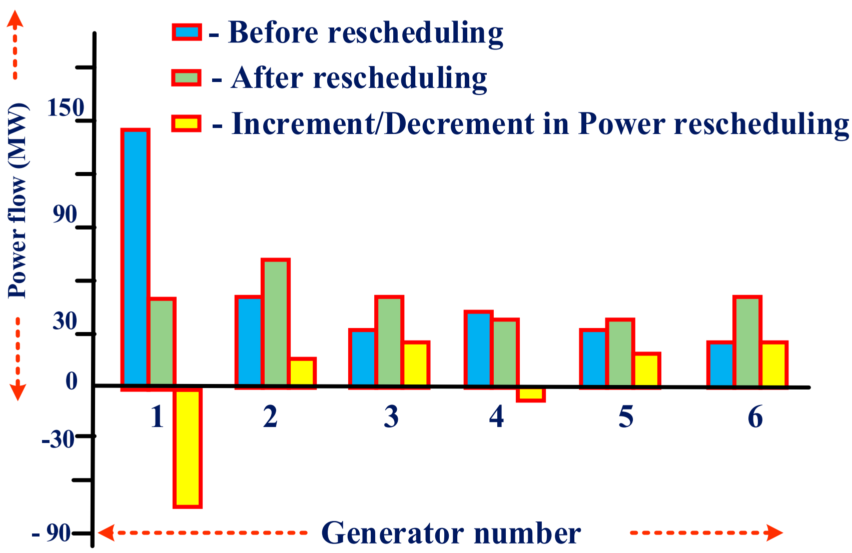

Figure 9. Comparison of power rescheduling in the modified IEEE 30-bus system employing FPA.

The results gained from the implementation of FPA for alleviation of congestion are tabulated in Table 5. With the results obtained in [16], the effectiveness of the proposed algorithm is illustrated with the reduction in congestion cost of 1.60%, 1.55%, 1.17%, and 1.07% as compared with other optimization algorithms like Simulated Annealing (SA), Random Search Method (RSM), Particle Swarm Optimization (PSO), and Teaching Learning-Based Optimization (TLBO). The best effective final solution is attained due to the legitimate control of the algorithmic based specific tuning criterion. Figure 10 infers that Flower Pollination Algorithm (FPA) yields the minimum congestion of 460.616 $/hr as compared with the results obtained with other optimization techniques. Figure 11 validates the effectiveness of the algorithm in terms of its convergence in seven iterations as compared with 25 iterations in SA and RM, while 50 iterations are required in PSO to obtain solution consistency. Table 6 provides the parametric settings of the proposed FPA with other optimization techniques.

Table 5. Validation of proposed FPA with other optimization techniques.

Parameters	SA [16]	RSM [16]	PSO [16]	TLBO [26]	Proposed FPA
Total congestion cost ($/hr)	719.86	716.25	538.95	494.66	**460.62**

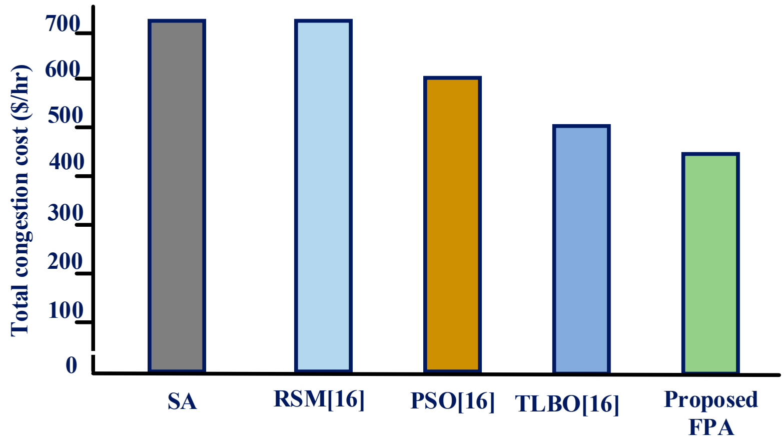

Figure 10. Effectiveness of proposed FPA with other optimization techniques.

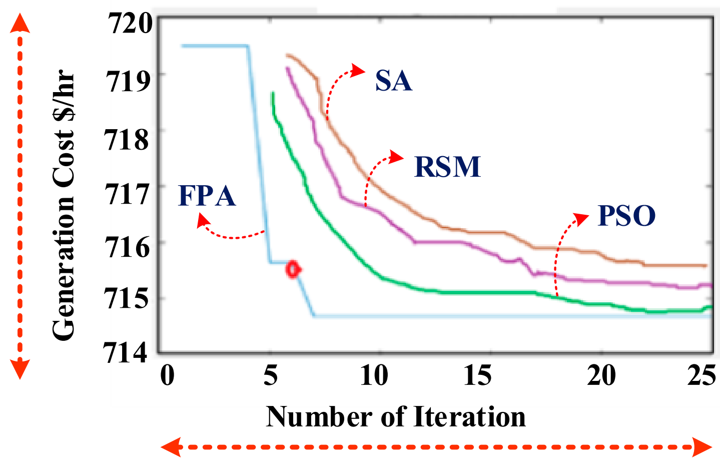

Figure 11. Convergence curve for managing congestion using FPA'.

Table 6. Parametric settings proposed FPA with other optimization techniques.

SA [16]	RSM [16]	PSO [16]	TLBO [26]	FPA
Start Set Temperature = 900 °C; End Set Temperature = 900 °C;		No. of swarms = 20	No. of learners = 6	No. of flowers = 6
No. of iter. = 1000	No. of iter. = 1000	No. of iter. = 300	No. of iter. = 30	No. of iter. = 25
		$C_1 = 2$; $C_2 = 2$; $\omega_{min} = 0.4$; $\omega_{max} = 0.9$		$\Lambda = 1.6$; $\Upsilon = 0.12$; p = 0.80

6. Congestion Management with PHSU

In this proposed work, to replenish the varying load demand nature, a PHSU unit has been incorporated with the test system. PHSU is operated in generator mode when there is power inadequacy while operated in pumping mode where there is power sufficiency. Thus PHSU helps in minimize the cost of congestion while maintaining the voltage figuration, The test case considering the modified IEEE 30 bus system has been simulated with a line outage 1–2 so as to create the contingency and results in violations of power flow between lines 1–3, 2–6, and 4–6, respectively. Considering this outage, BSF are then computed for different load buses. The bus with the highest negative index is chosen to be the optimal location for PHSU placement. Here, it is evident from Table 7 that the ideal location for PHSU placement is obtained at bus 4. This is pictorially depicted in Figure 12 The feasible location of PSHU placement is attained assuming sufficient availability of water resource and reservoir area. GSF is then calculated for rescheduling active power of generators. Thus the placement of PHSU at bus 4 yields the minimized congestion cost of 361.450 \$/hr as compared to bus 16 with 756.03 \$/hr higher cost of congestion. This infers the efficiency of FPA in terms of congestion cost reduction. Active powers of the generators are then rescheduled through the computed GSF as inferred from Table 8 Generators with the highest negative sensitivities are opted for participation in rescheduling Table 9.

Table 7. Sensitivity factor without PHSU.

Load Bus No.	2	3	4	5	7	8	16	20	23
BSF	−0.0179	0.0315	−0.192	0.0107	0.0315	0.1532	0.0016	0.0804	0.0413

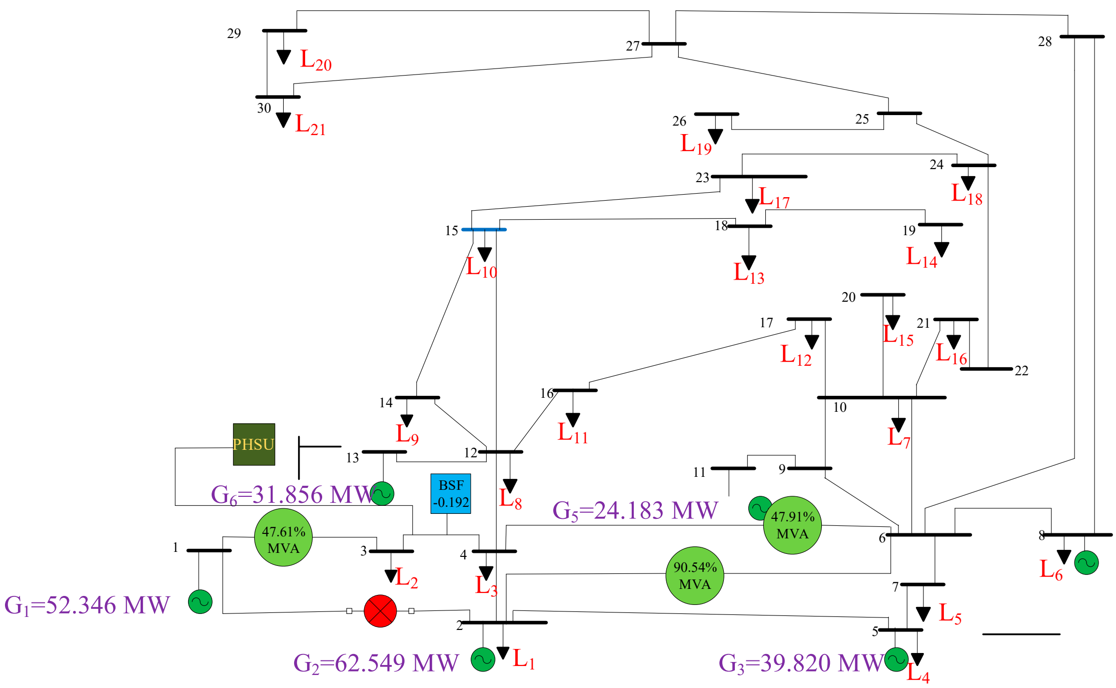

Figure 12. FPA-based suitable choice of PHSU for managing congestion.

Table 8. Sensitivity factor without PHSU.

Generators	G1	G2	G3	G4	G5	G6
GSF	−0.5563	−0.4217	−0.5326	−0.4862	−0.4326	−0.511

Table 9. Rescheduling with PHSU.

Generator No.	Before Rescheduling (MW)	After Rescheduling (MW)	Increment in Generation (ΔPgi)
1	138.590	52.346	−86.244
2	57.560	62.549	4.989
3	24.560	39.820	15.260
4	35.000	27.729	−7.271
5	17.910	24.183	6.273
6	16.930	31.856	14.926

Figure 12 interprets the incremental changes in value of rescheduling of real powers of the generators with the incorporation of PSHU. This facilitates meeting the objective of yielding minimum cost of congestion. The results gained from the implementation of FPA for alleviation of congestion influencing other network criterion is tabulated in Table 10. This investigates the effective minimization of power losses and security enhancement after employing EPA. The total loss in the system was 8.177 MW, which was also reduced to 5.217 MW after conducting congestion management, and further reduced to 4.208 MW after the incorporation of PHSU. Further the considerable improvement in voltage portrait is also tabulated.

Table 10. Influence of FPA on other network criterion in the test case.

Other Network Criteria	Rescheduling without Applying FPA	Rescheduling Applying FPA	Rescheduling Applying FPA Incorporating PHSU
Power loss (MW)	8.177	5.217	4.208
Voltage (p.u)	0.930	0.939	0.947

The PHSU is placed at load bus number 4 which is selected based on the most sensitive bus sensitivity factor. The PHSU is connected to the bus 16 and the results are tabulated. The generation cost is 736.426 $/hr and the congestion cost incurred to the consumer is 361.450 $/hr after the implementation of the pumped storage hydro unit at bus 4, as pictorially depicted in Figure 13. Table 11 infers the alleviation of congestion after the incorporation of PHSU employing FPA.

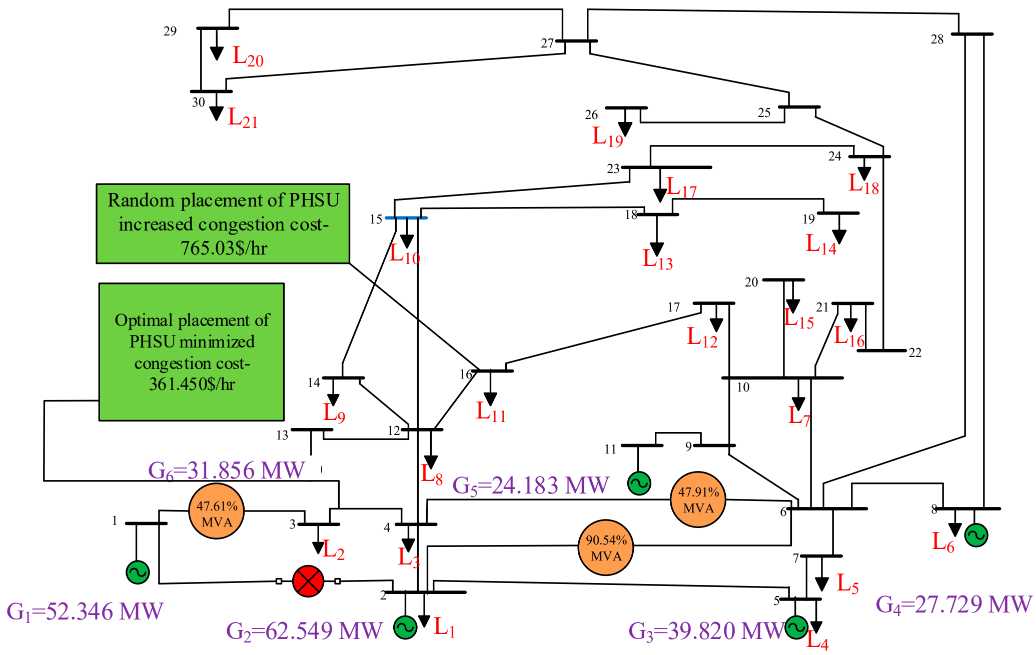

Figure 13. FPA-based cost comparison in placement of PHSU for managing congestion.

Table 11. FPA-based MVA line flow with and without PHSU.

Congested Line	Limit (MVA)	Before Applying FPA (MVA)	After Applying FPA (MVA)	After Applying FPA Incorporating PHSU (MVA)
1–3	130	148.0636	63.5146	61.9052
2–6	65	138.6385	60.6178	58.8522
4–6	90	90.5903	43.2578	43.1241

From Table 12, it is inferred that the rescheduling cost using FPA is considerable reduced by 1.27% with the PHSU placement. Furthermore, the superiority of the FPA is shown in terms of congestion cost reduction of 2.04% after the application of FPA algorithm employing PHSU placement as depicted pictorially in Figure 14. Thus the effectiveness of the FPA algorithm is proven in terms of minimized congestion cost and other parameters that influence the network framework criterion.

Table 12. Cost comparison with and without PHSU employing with and without FPA.

Parameter	Rescheduling Applying FPA without Incorporating PHSU	Rescheduling Applying FPA Incorporating PHSU
Congestion cost($/hr)	460.616	361.450

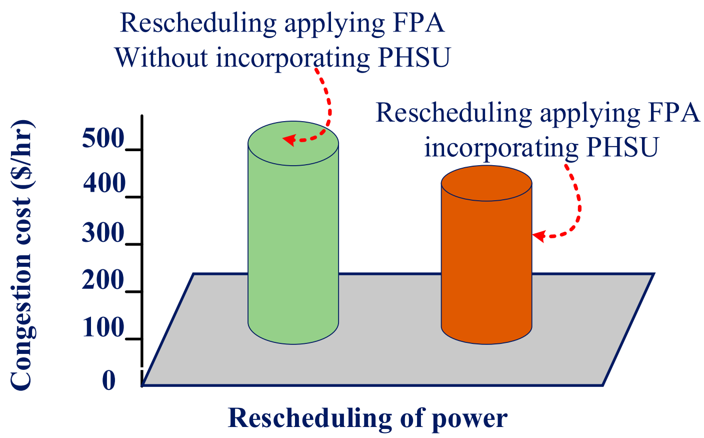

Figure 14. FPA-based cost comparison with and without placement of PHSU for managing congestion.

7. Conclusions

To relieve the congestion and recognize the congestion management's importance in the power system, an attempt using FPA has been carried out in this paper. Generator rescheduling is used in this work for congestion management with that to reduce the transmission congestion cost. Here a study has been carried out to solve the congestion problem by generator rescheduling with the help of flower pollination algorithm aimed at reducing transmission congestion cost. Then the algorithm is compared with the other optimization techniques taking the same constraints and outage. The efficacy of FPA in benefitting the ISO in reliving the congestion in terms of minimized congestion cost. It is marked that there is a considerable amount of decrease in congestion cost by the incorporation of pumped storage unit and is validated effectively by Flower Pollination Optimization. Furthermore, the effects of other network parameters like system losses and voltage has been computed. The result obtained proves effectiveness of the algorithm in terms of minimized cost convergence as compared with other recent trendsetting reported optimization techniques.

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List of Symbols and Abbreviations

e^n	Reservoir pumped storage energy level at interval n
e^{final}	Reservoir final limit
η_{Ps}	Pumping operation efficiency
η_{Hs}	Generation operation efficiency
$P^n{}_{Ps}$	Pumped storage power generation at interval n
P^n_{Hs}	Pumped storage power consumption at interval n
P^{min}_{Ps}	Minimum limit of power consumption
P^{max}_{Ps}	Maximum limit of power consumption
P^{min}_{Hs}	Minimum limit of power generation
P^{max}_{Hs}	Maximum limit of power generation
e^l	Reservoir lower limit
e^u	Reservoir upper limit
FPA	Flower Pollination Algorithm
GA	Genetic Algorithm
SA	Simulated Annealing
RSM	Random Search Method
HAS	Harmony Search Algorithm
PSO	Particle Swarm Optimization
TLBO	Teaching Learning-based Optimization
UC	Unit Commitment
EDRP	Emergency Demand Response Program

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