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Optimal setting of FACTS devices for voltage stability improvement using PSO adaptive GSA hybrid algorithm

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This paper presents a novel technique for optimizing the FACTS devices, so as to maintain the voltage stability in the power transmission systems. Here, the particle swarm optimization algorithm (PSO) and the adaptive gravitational search algorithm (GSA) technique are proposed for improving the voltage stability of the power transmission systems. In the proposed approach, the PSO algorithm is used for optimizing the gravitational constant and to improve the searching performance of the GSA. Using the proposed technique, the optimal settings of the FACTS devices are determined. The proposed algorithm is an effective method for finding out the optimal location and the sizing of the FACTS controllers. The optimal locations and the power ratings of the FACTS devices are determined based on the voltage collapse rating as well as the power loss of the system. Here, two FACTS devices are used to evaluate the performance of the proposed algorithm, namely, the unified power flow controller (UPFC) and the interline power flow controller (IPFC). The Newton–Raphson load flow study is used for analyzing the power flow in the transmission system. From the power flow analysis, bus voltages, active power, reactive power, and power loss of the transmission systems are determined. Then, the voltage stability is enhanced while satisfying a given set of operating and physical constraints. The proposed technique is implemented in the MATLAB platform and consequently, its performance is evaluated and compared with the existing GA based GSA hybrid technique. The performance of the proposed technique is tested with the benchmark system of IEEE 30 bus using two FACTS devices such as, the UPFC and the IPFC.

1. Introduction

A multipart system generally characterizes an existing power system which comprises the transmission lines that link the entire generator stations, transformers, and the entire loading points in the power system [1]. The maintenance of the voltage within the tolerable levels is the major responsibility of a reliable power system, so as to ensure the superlative quality of customer service, leading the client to the zenith of delight [2]. However, it is unfortunate that the issue of voltage stability has loomed large as an ever-zooming restraining factor in the development and the functioning of the power systems [3,4]. The thorny issue of the voltage failure may be deemed as the inability of the power system to distribute the reactive power or by way of an avoidable absorption of the reactive power [5]. In this regard, there are different ways in which the voltage fluctuation hassle is successfully tackled. While the first strategy is devoted to the mitigation of the dilemma, the second strategy invests its attention on fine-tuning the Voltage Stability Margin (VSM) of the system for the selected functional scenarios [6]. The only option to keep the system free from the voltage failure is to scale down the reactive power load or attach added reactive power before arriving at the point of the voltage failure [6]. To accomplish a safe and cost-effective function, the Flexible AC Transmission System (FACTS) devices are appropriately installed in the system [7]. Outstanding among the entire FACTS devices offered are the united compensators like the unified power flow controller (UPFC) and the interline power flow controller (IPFC), which are deemed as the highly leading and the flexible ones [8]. The deft deployment of these FACTS devices leads to the incredible improvement in various features such as the voltage stability, the balanced state and the fleeting stabilities of a complex power system [9,10]. In order to employ the FACTS devices in the optimal location, several innovative techniques like the genetic algorithm, swarm techniques, SOL algorithm, differential evolution algorithm and the simulated annealing are elegantly employed [11]. Further, various algorithms are intended for ascertaining the optimal location of the FACTS devices. In the document, the PSO adaptive GSA technique is effectively employed for

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finding the optimal location of the FACTS devices by improving the voltage magnitude. The proposed technique was investigated to improve the stability of the transmission system based on the voltage and the power loss. The objective of the paper is to find the optimal location and sizing of FACTS devices for improving voltage stability of the system. The remainder of the document proceeds as follows. The contents of Section 2 discuss the details of the modern research works, whereas Section 3 elegantly elucidates the innovative technique in a comprehensive way. The voltages and the power loss of IEEE 30 bus benchmark system are sketched in Section 4. The concluding portion of the paper is given in Section 5.

2. Recent research works

A feast of various investigation works for successfully managing the voltage fluctuation issues in the transmission systems is available in the literary domain. Recounted below is an earnest evaluation of some of the most notable ones. With the intention of addressing the voltage inconsistency dilemmas, various methods like the genetic algorithm, fuzzy logic, gravitational search algorithm and other parallel techniques are utilized in the literature.

Dharmbir Prasad et al. [12] have presented symbiotic organisms search (SOS) algorithm for the conclusion of optimal power flow (OPF) issue of power system attached with Flexible AC Transmission Systems (FACTS) devices. Stimulated by dealing between organisms in ecosystems, SOS algorithm was a present population based algorithm which does not necessitate any algorithm particular control parameters unlike other algorithms. The process of the projected SOS algorithm was examined on the modified IEEE-30 bus, and IEEE-57 bus test systems integrated two types of FACTS devices, namely, thyristor controlled series capacitor and thyristor controlled level shifter at permanent positions. The OPF issue of the current work was calculated with four various goal functions viz. (a) fuel cost minimization, (b) transmission active power loss minimization, (c) emission reduction, and (d) minimization of combined economic and environmental cost.

Pratap Chandra Pradhan et al. [13] have explained a Firefly Algorithm (FA) optimized fuzzy PID controller for Automatic Generation Control (AGC) of multi-area multisource power system. First, a two area six units power system was used and the profits of the fuzzy PID controller were optimized, handling FA optimization technique using an ITAE condition. The majority of the projected FA optimized fuzzy PID controller have been established by differentiating the conclusion with some freshly published methods like the optimal control and Differential Evolution (DE) optimized PID controller for the identical unified power system. Then, physical constraints such as Time Delay (TD), reheat turbine, and Generation Rate Constraint (GRC) were incorporated in the system form, and the majority of FA was established by differentiating the conclusion across DE, Gravitational Search Algorithm (GSA), and Genetic Algorithm (GA) optimization methods for the similar unified power system. Moreover, a Unified Power Flow Controller (UPFC) was positioned in the tie-line, and Superconducting Magnetic Energy Storage (SMES) units were considered in both places. Simulation conclusion show that the system processes were developed radically with the projected UPFC and SMES units. Sensitivity analysis of the system was processed by changing the system parameters and operating load situation from their ostensible values.

In order to discover the optimal placement and the parameter setting of the UPFC, a technique taking cues from the Differential Evolution (DE) was offered by Husam I. Shaheen et al. [14]. D. Mondal et al. [15] had their heydays when they green-signaled an innovative Particle Swarm Optimization (PSO)-based approach to select the optimal location and set the parameters of the SVC (Static Var Compensator) and the TCSC (Thyristor Controlled Series Compensator) controllers. K. Ravi et al. for elegantly launched an improved Particle Swarm Optimization (IPSO) for optimizing the power system presentations [16]. Notwithstanding the fact that the modern techniques were able to offer the optimal results, they were unduly plagued by several constraints in achieving the optimal settings of the FACTS devices also. Further, the time-frame involved for the processing was found to be unduly prolonged and moreover, the voltage stability had become a casualty. With the intent to overshoot these problems, we have deployed an innovative Gravitational Search Algorithm (GSA), which has emerged one of the most modern stochastic population-based meta-heuristics motivated by the Newtonian laws of gravity and motion [17]. In the gravitational search algorithm, the global solution invariably relies on the gravitational constant in relation to time. In spite of the fact that the GSA has given the optimal results for solving the optimization problems, it suffers from a vital deficiency in choosing the gravitational constant in an effective manner. The gravitational constant, in essence, is modified in accordance with the changes in the solution and therefore leads to a situation in which the agents go away from the best position. Hence, it is adversely affected by the unforeseen convergence, in addition to allowing a sluggish convergence. In the document, the PSO technique is effectively employed to optimize the gravitational constant of GSA and hence, the searching performance is incredibly increased. The underlying motive of the innovative technique is invested in the optimization of the location and the size of the FACTS tools.

3. Problem formulation

The voltage stability of the system is mainly dependent on the real power, voltage magnitude and the angle, and hence it is maintained by controlling the above-mentioned parameters. Also, the problem of locating and sizing of the FACTS controller can be formulated as a multi-objective problem with the following objectives and constraints.

$$\text{Min}\, S(x,u) \tag{1}$$

$$\text{Subject to}\, h(x,u)=0 \tag{2}$$

$$p(x,u)\le 0 \tag{3}$$

Where, S is the objective function, h is the equality constraint and p is the inequality constraint that depends on the control variables x and u. The generation limits of the generating units are divided in the upper and lower bounds, which lie in between the actual limits. The equality and inequality constraints are employed for identifying the optimal location and sizing of the FACTS devices. A detailed account of the relative constraints is furnished in the following section.

a) Equality constraints

The real power balancing condition is given by Equation 4:

$$P_{inj,n}=P_{g,n}-P_{L,n} \tag{4}$$

The reactive power balancing condition is furnished by Equation 5:

$$Q_{inj,n}=Q_{g,n}-Q_{L,n} \tag{5}$$

Where, $P_{inj,n}$ characterizes the real power injected into bus n, $P_{g,n}$, the real power produced by n^{th} generator and $P_{L,n}$, the real power of the n^{th} load bus. Similarly, $Q_{inj,n}$, represents the reactive power injected into bus$n$, $Q_{g,n}$, the reactive power produced by n^{th} generator and $Q_{L,ni}$, the reactive power of the n^{th} load bus.

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b) Inequality constraints

The generation limits of the generating units are segregated in the upper and lower bounds which are situated in between the real limits. The real and reactive power, voltage magnitude and the reactance constraints of TCSC are detailed as follows:

$$P_{g,n}^{\min} \le P_{g,n} \le P_{g,n}^{\max} \tag{6}$$

$$Q_{g,n}^{\min} \le Q_{g,n} \le Q_{g,n}^{\max} \tag{7}$$

$$V_n^{\min} \le V_n \le V_n^{\max} \tag{8}$$

Where, $P_{g,n}^{\min}$ and $P_{g,n}^{\max}$ represent the real power flow limits of the n^{th} bus, $Q_{g,n}^{\min}$ and $Q_{g,n}^{\max}$, the reactive power flow limits of the n^{th} bus, and, $V_n^{\min}$ and $V_n^{\max}$, the voltage magnitude limits of the n^{th} bus. The index for voltage stability is described as follows:

$$L = \max_{j \in \alpha L}(L_j). \tag{9}$$

Where, $L_j = \left|1 - \frac{\sum_{i \in \alpha G} F_{ij} V_i}{V_j}\right|$

In the above equation, αL and αG are the set of consumers and the set of generator nodes, respectively. Here, L_j determines the bus bar from where the collapse may originate. The power loss is calculated using the following formula.

$$P_L = \sum_{j=1}^{N} |V_i||V_j||Y_{ij}|\cos(\theta_{ij} - \delta_i + \delta_j) \tag{10}$$

Where, $i = 1,2,...n$. Based on the above equations, the objective function of the paper is described as follows:

$$O_b = \begin{cases} \max(V, P_r) \\ \min(Q_r, P_L) \end{cases}. \tag{11}$$

Where, $V = \sum_{i=1}^{NP} v_i$, $P_r = \sum_{i=1}^{NP} p_i$ and $Q_r = \sum_{i=1}^{NP} q_i$. For the placement of the FACTS devices, the optimal location and sizing is determined based on the above equation. In the paper, the contribution is to find the optimal location and sizing of FACTS devices for improving the voltage stability of the system. Here, the minimum power loss and maximum voltage profile of the system are achieved after fixing the FACTS devices. Based on the voltage profile values, the stability is improved. The proposed technique is explained in the following section.

3.1. PSO adaptive GSA technique for identifying the optimal location and sizing of the FACTS device

In the paper, the PSO adaptive GSA technique is proposed to find the optimal location and sizing of the FACTS devices. From the power flow study, the bus voltages, the active power, the reactive power and the power loss of the system are found out. The voltage stability is enhanced, while satisfying a specified set of the equality and inequality constraints. In the proposed technique**,** the PSO algorithm is used to optimize the gravitational constant of the GSA algorithm. Here, the inputs of the proposed algorithm are the bus voltage (V), the power loss (P_L), the real power (P_r) and the reactive power (Q_r). The minimized power loss, the real as well as the reactive power injections can be evaluated from the inputs. The optimal location (FD_{loc}) and the capacity (FD_{sz}) of the FACTS devices are determined based on the evaluated inputs. At first, the traditional GSA working process is explained and then the procedure for the proposed algorithm is briefly elucidated.

3.1.1. Gravitational search algorithm (GSA)

GSA is one of the stochastic search algorithms which are based on the Newtonian laws of gravity and mass interaction. In the GSA, the agents' performance is measured by their masses which are taken into consideration as the objectives. The gravitational force of attraction between the objects causes an overall movement of all the objects toward those with heavier masses. As a result, the heavier masses have higher fitness values. In addition, the good solution to the problem is moving more gradually than the lesser ones representing worst solution [18].

Initially, consider N set of agent masses and define the position of these N set of values as i which is represented in Eq. (14). Then, the mass and acceleration of each agent are calculated. For evaluating the acceleration of an agent, a set of total force from the heavier masses is applied which should be considered based on the arrangement of the law of gravity.

Then, the velocity change of the searching strategy of the i^{th} agent and the direction d at time t+1 are represented as follows:

$$n_i^d(t+1) = n_i^d(t) + v_i^d(t+1) \tag{12}$$

$$v_i^d(t+1) = rand_i\{v_i^d(t) + a_i^d(t)\}. \tag{13}$$

Where, $rand_i$ characterizes the uniform random number which is generated between 0 and 1, $n_i^d(t+1)$, the position of the i^{th} agent at time t+1 and $v_i^d(t+1)$, the velocity of i^{th} agent at time t+1. Then, the gravitational constant $G(t+1)$ is determined as follows:

$$G_n = G_0\left\{\exp\left(-\delta \frac{t}{t_{\max}}\right)\right\}. \tag{14}$$

Where, $G_0(t)$ represents the initial velocity, $G_n(t+1)$, the n^{th} updated velocity, δ, the constant, t, the current iteration, and $t_{\max}$, the maximum iteration. The initial performance of the GSA is controlled by the values of δ and G_0.

3.1.2. PSO adaptive GSA technique

From the original GSA, the gravitational constant is varied according to the variation of solution, hence it is possible, that the agents tend to move away from the best position. Thus, it is affected by the precipitate convergence and permits a slower convergence. In the paper, PSO algorithm is used to optimize the gravitational constant of GSA and thus the searching performance is improved. The proposed algorithm optimized the location and size of FACTS devices. The optimal location and size of FACTS devices is computed which depends on the real power, voltage and power loss of the system. The procedure of proposed algorithm is explained as follows:

a) Procedure of Proposed algorithm

Step 1: In this step, the inputs are the bus voltage (V), the power loss (P_L), the real power (P_r) and the reactive power (Q_r), and all of them are initialized randomly. Here, the inputs are considered as the agents. The position of the agents is defined by the following equation.

b) $$S = (s_i^1, \ldots, s_i^d, \ldots s_i^n) \tag{15}$$

Where, n corresponds to the search space dimension of the problem and s_i^d, the position of the i^{th} agent in the d^{th} dimension. The inputs are specified as certain limit functions such as, the minimum and the maximum, i.e., $[V_{\min}, V_{\max}]$, $[P_r^{\min}, P_r^{\max}]$ and $[Q_r^{\min}, Q_r^{\max}]$.

Step 2: The fitness function of the agents is evaluated as their maximum range (values) of voltage. The real as well as the reactive powers of the system are evaluated as the minimum power loss in the system. The fitness function of the agent is calculated as follows:

$$\text{fitness function} = (O_b) \quad (16)$$

Where, O_b is denoted as the objective function. Subsequently, the force of the agent is calculated.

Step 3: The masses of the agents are defined randomly and the forces of each agent determined. Here, the force acting on the mass i from the mass j can be determined with the following equation.

$$f_{ij}^{d}(k) = g(t)\left(\frac{M_i(k) * M_j(k)}{r_{ij}(k) + \in}\right)\left(s_j^d(k) - s_i^d(k)\right) \quad (14)$$

Where, $M_i(k)$ and $M_j(k)$ are the masses of the agent i and j, respectively. Here, $g(k)$ represents the gravitational constant, $\in$, a small constant and $r_{ij}(k)$, the Euclidian distance between the i^{th} and the j^{th} agents. The gravitational constant of the agent is calculated using the following formula:

$$g(k) = g_0 * e^{\left(\frac{-\alpha k}{t_r}\right)}. \quad (17)$$

From the above equation, t_r represents the total number of iterations involved in the algorithm, g_0, the initial value and α, the user specified constant.

Step 4: The total force acting on the agent in k^{th} dimension is calculated as follows:

$$f_i^d(kt) = \sum_{i=1 j \neq i}^{N} rand_i f_{ij}^d(k). \quad (18)$$

Where, $rand_j$ represents a random number that fall in the interval [0, 1] and then, the acceleration is calculated.

Step 5: The acceleration of any mass is equal to the force acted on the system, divided by the mass of inertia and it is given below:

$$\alpha_i^d(k) = \frac{f_i^d(k)}{M_i(k)}. \quad (19)$$

3.2. Step 6: optimize the gravitational parameters using the PSO algorithm

The PSO is a robust optimization technique that is based on the swarm intelligence, which implements the simulation of the social behavior [17,19]. In this algorithm, each member is seen as a particle and each particle is a potential solution to the problem. Here, the gravitational parameters of GSAs are controlled using the PSO algorithm. The gravitational parameters such as the gravitational constant ($g(k)$) and acceleration ($\alpha_i^d(k)$) are optimized. The procedure for implementing the PSO algorithm is explained in the following section.

3.3. Steps of the PSO algorithm

1. In the PSO algorithm, initialize the positions and the velocity vectors of all the GSA controlling parameters randomly. Here, each parameter is considered as a particle and for each particle, the position vector is $x_i^k = (x_{i1}^k, x_{i2}^k, \ldots.. x_{in}^k)$ at iteration k and the corresponding velocity vector is $v_i^k = (v_{i1}^k, v_{i2}^k, \ldots.. v_{in}^k)$.
2. The best solution achieved by i^{th} particle in iteration k is defined as $P_{besti}^k = (p_{bset,i1}^k, p_{best,i2}^k, \ldots.. p_{best,in}^k)$.
3. Evaluate the fitness function of the particles as follows:

$$\text{fitness function} = \min(g(k)). \quad (20)$$

Where, $(g(k))$ is calculated with Eq. (13). Here, the minimum value of the gravitational parameter is taken as a fitness function. Equation (18) is used to control the gravitational constants.

4. Compare the personal best P_{besti}^k of every particle with its current fitness value. If the current fitness value is better, then assign the current fitness value to the P_{besti}^k coordinates.
5. Establish the current best fitness value in the whole population and its coordinates. If the current best fitness value is better than the global best $g(best)$, then assign the current best fitness value to $g(best)$ and assign the current coordinates to the $g(best)$ coordinates.
6. Update the velocity and the position of the d^{th} dimension of the i^{th} particle using the following equations:

$$V_i^{k+1} = w * V_i(k) + C_1 \times rand \times \alpha_i^d(k) + c_2 \times rand(g(best) - G_i(k)) \quad (21)$$

$$X_i^{k+1} = X_i(k) + V_i(k+1)). \quad (22)$$

Where, $acc_i(k)$ is the acceleration of agent i at iteration k. Finally, the agents' positions are updated.

7. Repeat the process, until the termination is reached. Otherwise, terminate the algorithm.

Step 7: New positions for the agents, the gravitational constants and the inertia masses are updated using the following equations:

$$m_i(k) = \frac{fit_i(k) - worst(k)}{best(k) - worst(k)} \quad (23)$$

$$M_i(k) = \frac{m_i(k)}{\sum_{j=1}^{N} m_j(k)}. \quad (24)$$

Where, $fit_i(k)$ represents the fitness value of the i^{th} agent at iteration k.

Step 8: The velocity of each mass is calculated and the new position for the masses is considered. Update the agent's velocity as well as the position using the following equation:

$$V_i^d(k+1) = rand \times v_i^d(k) + \alpha_i^d(k). \quad (25)$$

When the acceleration and the velocity of each mass are calculated, the new positions of the masses are considered as follows:

$$s_i^d(k+1) = s_i^d(k) + v_i^d(k+1). \quad (26)$$

Where, $V_i^d(k)$ and $s_i^d(k)$ are the velocity and the position of an agent at the k time and d dimension, respectively, and $random_i$ is the random number in the interval of [0, 1].

Step 9: When the maximum iteration is reached, the process is terminated. Otherwise, the steps from step 3 to step 9 are repeated. Here, the best voltage, the real as well as the reactive powers are calculated. Based on the fitness function, the FACTS' location and sizing are optimally identified. The flowchart of proposed PSO based GSA algorithm is illustrated in the Fig. 1. Then, the analysis part is discussed in the following section.

4. Results and discussion

In the paper, the PSO adaptive GSA technique is proposed to optimize the location and sizing of the FACTS devices and to maintain the voltage stability of the system. The proposed PSO adaptive GSA technique is implemented in the MATLAB working platform. The

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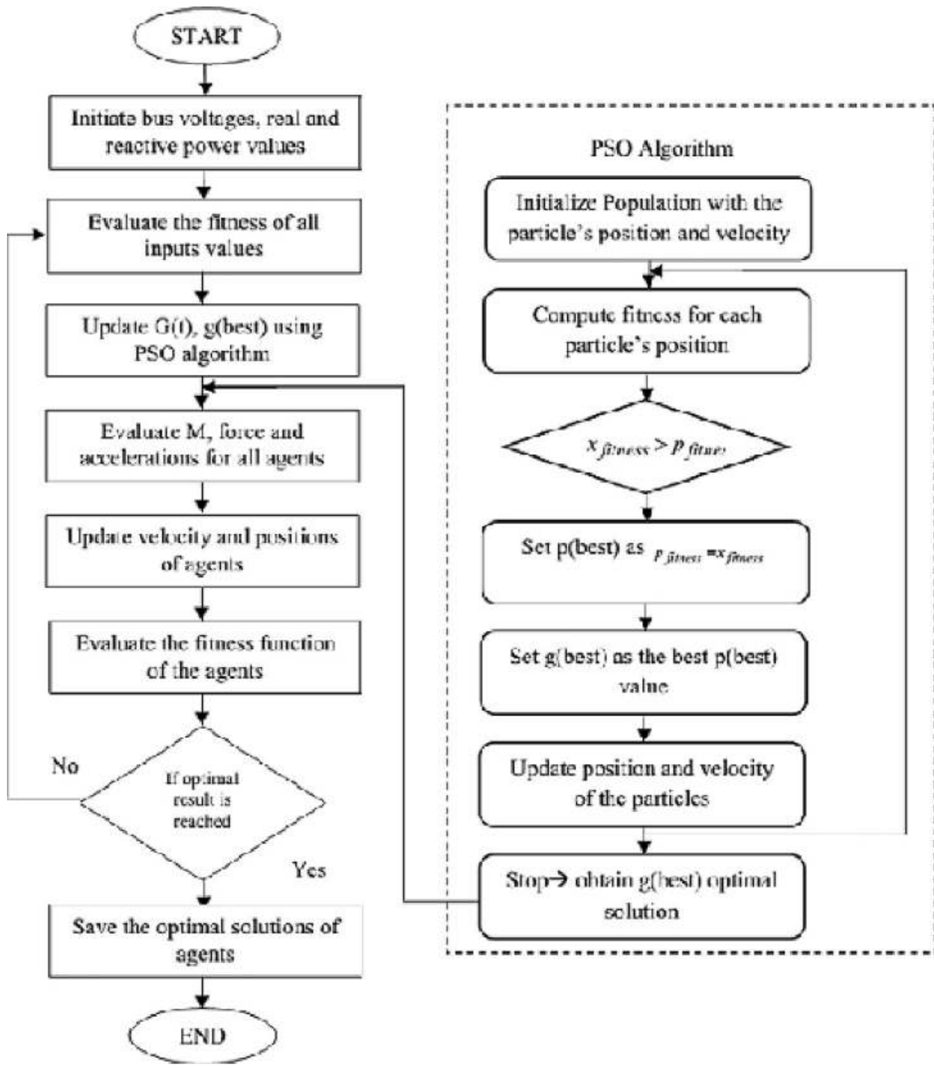

Fig. 1. Flow chart of proposed PSO based GSA algorithm.

performance of the proposed technique is tested with the bench mark system of IEEE 30 bus using two FACTS devices such as the UPFC and the IPFC. Initially, the normal bus voltages and normal power losses are evaluated. Then, the injected voltage and power loss are calculated. According to the variation in the power loss and voltage collapse, the optimal location of the FACTS is determined. After placing the FACTS, the voltage of the system is examined. The implementation parameters are tabulated in Table 1.

4.1. Performance analysis and evaluation metrics in IPFC

The performance of the proposed algorithm is analyzed for getting the best voltage and the minimum power loss, when the IPFC is connected. Here, the IPFC is connected in the IEEE 30 bus system in the line of bus number is 12-15-16 which is illustrated in Fig. 2. After connecting the IPFC, the voltages in 30 buses are calculated and the normal as well as the collapsed time bus voltages are tabulated in Table 2. Also, the normal and the minimum power loss of the bus system are calculated. Then, the power loss and the iterations of the proposed method are analyzed. The performances are illustrated in Fig. 3.

After placing the IPFC, the normal voltage and the injected voltage of the bus system are tabulated as shown in Table 2. For instance, in bus 1, usually the normal voltage is 1.06p.u and the injected bus voltage is about 0.988p.u. The proposed technique attains the voltage profile of about 0.9914p.u. Similarly, by placing the UPFC, the normal and the injected voltages of the various buses are noted as depicted in Table 3.

Initially, the voltage and power losses of the buses are analyzed by connecting the IPFC when the load gets varied, and then the GSA technique is applied. From the above figure, the load changes are found to vary highly in bus 12, and the voltage instability problem is developed. By using the GSA, the voltage instability problem is reduced. The power loss and voltages of the bus system are analyzed with the GSA, and their performances are illustrated in Figs. 4 and 5.

Fig. 6(a) represents the graphical illustration of bus voltage in stressed condition. Under the stressed condition, the voltage values are increased 1.09 at the bus 12, and the instability problem

Table 1
Implementation parameters of the proposed PSO adaptive GSA technique.

Parameters	Values
Number of iterations in PSO	25
Dimension of particles	10×30
Number of iterations in GSA	100
Minimum and maximum Search space (Xmin, X_{max})	(0.9, 1.06)

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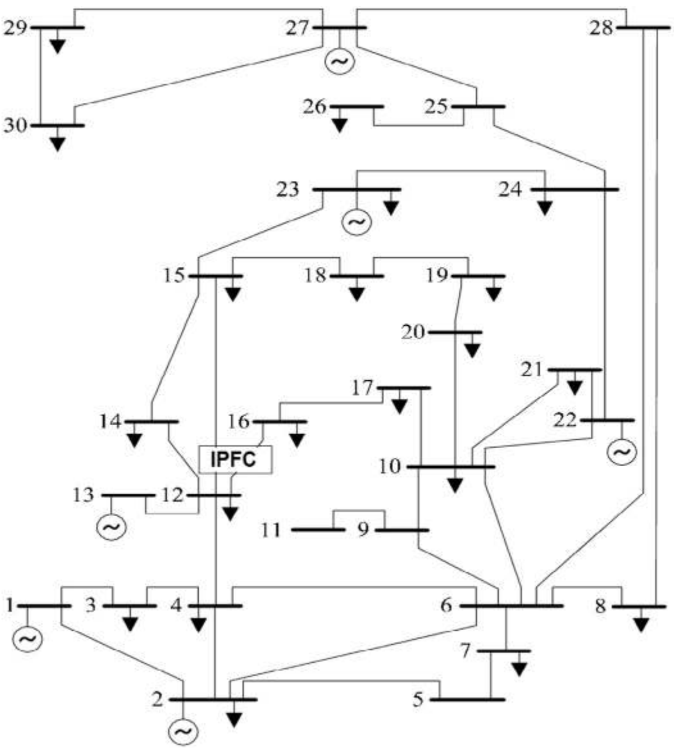

Fig. 2. IEEE 30 bus system with IPFC connected to the line of bus numbers 12, 15, and 16.

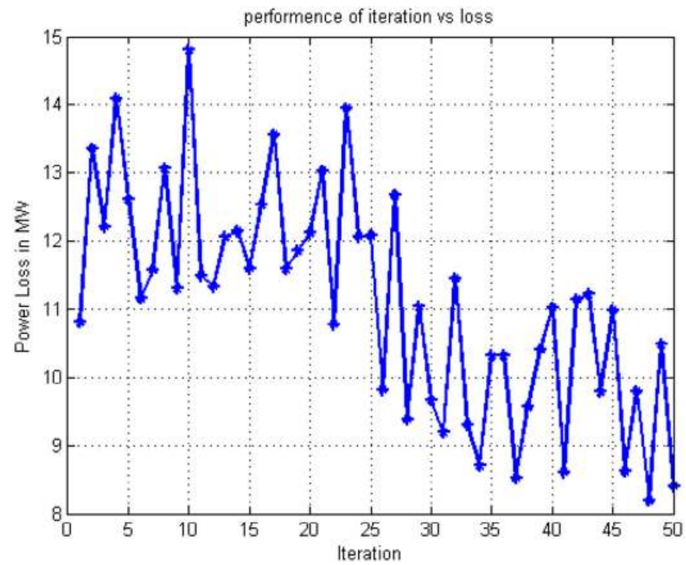

Fig. 3. Plot between power loss and iteration after connecting the IPFC.

occurred in the buses. Here, the voltage increases in load demonstrating more threatening operating condition since voltage collapse happens even at higher voltage magnitude. Along these lines, it is conceivable to make note of system status change in a better way in the proposed system. The FACTS devices show the enhanced voltage profile, however, its real importance lies in its ability of taking care of increased power flow and consequently increased stability even under stressed condition. The bus voltage magnitude in Fig. 6(c) illustrates that the voltage corresponding to the weakest bus is step by step diminishing and subsequently approaches voltage

Table 2
The normal and injected voltage of the bus system after placing the IPFC.

Bus number	Normal voltage in p.u.	Injected bus voltage in p.u.	Voltage obtained after using the proposed technique (p.u.)
1	1.06	0.988	0.9914
2	1.033	1.002	1.06
3	1.0228	0.99373	1.023
4	1.0136	0.99493	1.0243
5	1.0044	0.98673	1.035
6	1.01	1.007	1.054
7	0.99993	0.99082	0.99173
8	1.0103	1.0097	1.00724
9	1.0458	1.059	1.057
10	1.0367	1.0378	1.0363
11	1.0771	1.0705	1.06
12	1.0572	1.0372	1.0571
13	1.071	1.032	1.055
14	1.0414	1.0197	1.035
15	1.0355	1.0164	1.044
16	1.0411	1.023	1.028
17	1.0326	1.0209	1.06
18	1.0236	1.008	1.042
19	1.0198	1.0062	1.044
20	1.0232	1.0108	0.9923
21	1.0228	1.0125	1.028
22	1.03	1.026	1.02
23	1.0229	1.0122	1.032
24	1.0158	1.0116	1.021
25	1.0069	1.0177	1.033
26	0.98903	1	1.017
27	1.01	1.03	1.015
28	1.0094	1.0087	1.033
29	0.98987	1.0103	1.016
30	0.97823	0.99891	1.022

Table 3
After placing the UPFC bus voltages.

Bus number	Normal voltage in p.u.	During voltage collapse in p.u	Voltage obtained after using the proposed technique (p.u.)
1	1.06	0.989	0.99174
2	1.033	0.995	1.0016
3	1.0228	0.98997	1.056
4	1.0136	0.99003	1.06
5	1.0044	0.98047	1.053
6	1.01	1.002	1.0054
7	0.99993	0.98524	0.99933
8	1.0103	1.0021	1.0095
9	1.0458	1.0272	1.057
10	1.0367	1.0122	1.0363
11	1.0771	1.059	1.06
12	1.0572	1.0241	1.0371
13	1.071	1.028	1.025
14	1.0414	1.0094	1.015
15	1.0355	1.0048	1.014
16	1.0411	1.0106	1.028
17	1.0326	1.0062	1.06
18	1.0236	0.99483	1.042
19	1.0198	0.99218	1.044
20	1.0232	0.99636	0.99921
21	1.0228	0.99655	1.018
22	1.03	1.001	1.02
23	1.0229	0.99621	1.0123
24	1.0158	0.98948	1.012
25	1.0069	0.98684	1.0133
26	0.98903	0.96859	1.017
27	1.01	0.994	1.015
28	1.0094	1.0004	1.033
29	0.98987	0.97351	1.016
30	0.97823	0.96166	1.026

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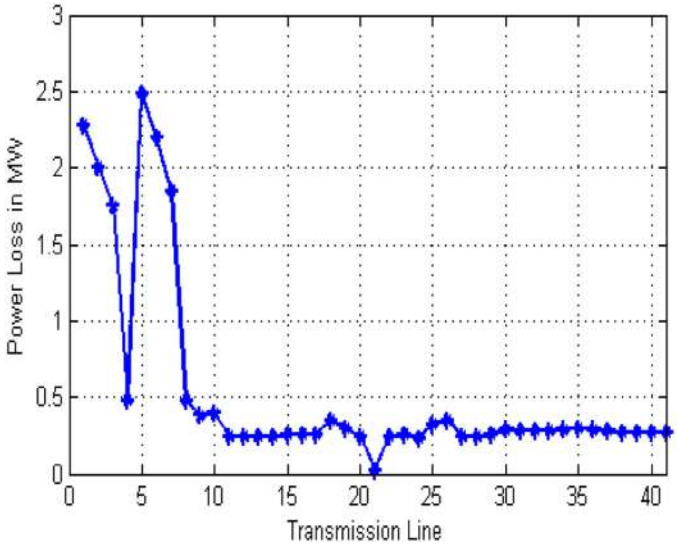

Fig. 4. Performance analysis of power loss using GSA method.

instability for increase in system loading. A flatter voltage profile is conceivable where FACTS device is connected at the weakest bus of the system with better load handling limit.

Therefore, the voltage stability is improved by using the proposed technique. The voltage values of the buses are evaluated by connecting the IPFC, when the load gets changed and then, the proposed technique is applied. The performances are compared, which are illustrated in Fig. 6. From the above figure, the load changes are found to vary highly in bus 12, and the voltage instability problem is developed. By using the GSA, the voltage instability problem is reduced. Subsequently, the power loss performances are evaluated and compared with those of the N-R approaches, the load variation and the proposed method with the IPFC. The performance comparison of the transmission line power loss is illustrated in Fig. 7.

By using the proposed method, the optimal location of the FACTS device is evaluated. Here, when calculated, the normal loss of the bus system is 10.8095 *MW* and the injected bus power is 3.803 *MW*. Now, the injected power loss is 13.3525 *MW*. After connecting the IPFC in between bus 10 and bus 22, the minimized power loss and the cost are evaluated using the proposed algorithm. Then, the minimized power loss of the system is found to be 8.191 *MW* and the cost of the IPFC is found as $187.7329. Similarly, the best line buses are evaluated and computed by their minimum losses and costs. From the above illustrations, the proposed method is proven to achieve better results than the N-R approaches and the load variation. Similarly, the UPFC is connected in between the two buses for carrying out the analysis. Then, the performance of the proposed method with the UPFC is evaluated.

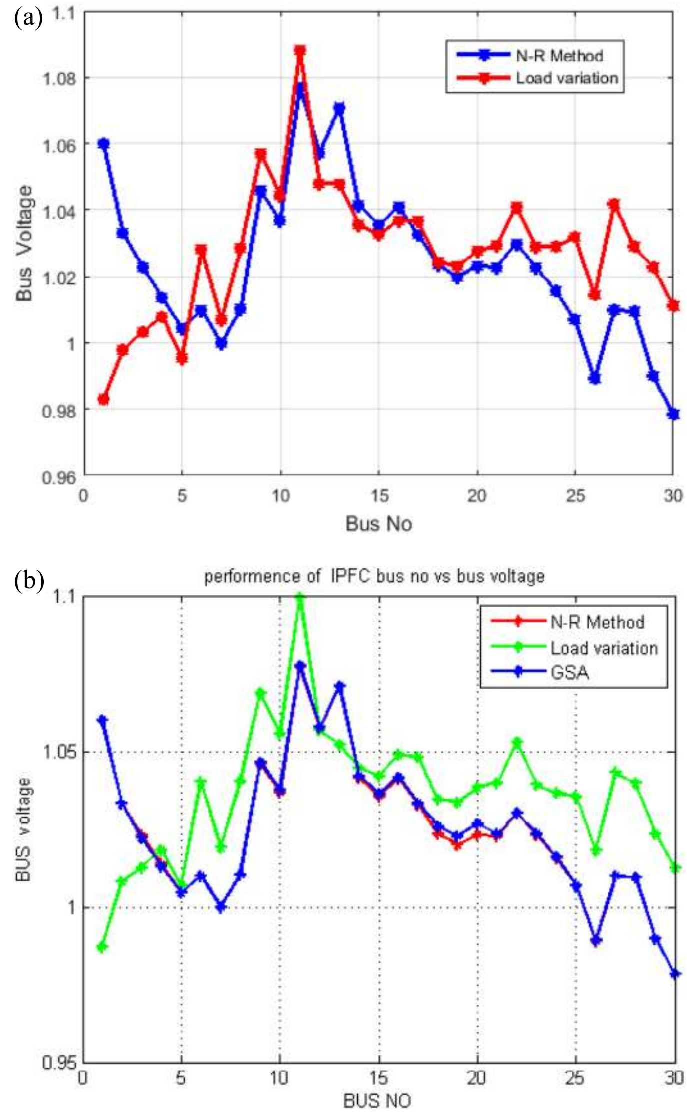

Fig. 6. Performance of voltage (a) in stressed condition and (b) comparison analysis of various approaches.

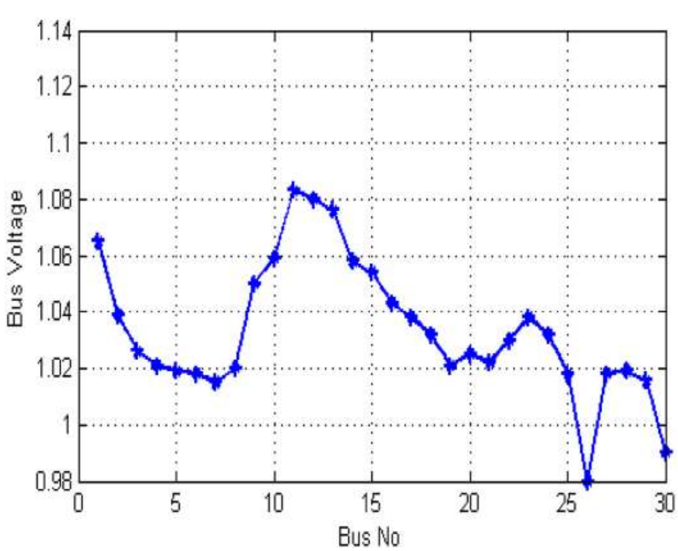

Fig. 5. Performance analysis of bus voltages using GSA method.

4.2. Performance analysis and evaluation metrics in UPFC

Here, the optimal voltage and the minimum power loss are analyzed by connecting the proposed method with the UPFC. The magnitudes of the voltages from bus 30 are evaluated and tabulated in Table 3. During the normal as well as the voltage collapse period, the power loss in the bus system is calculated. In the IEEE 30 bus system, the UPFC is connected to the line of bus numbers 12–15 as shown in Fig. 8. After connecting the UPFC in between the buses, the minimized loss is evaluated. By utilizing GSA technique, the performance analysis of voltage and power loss is analyzed

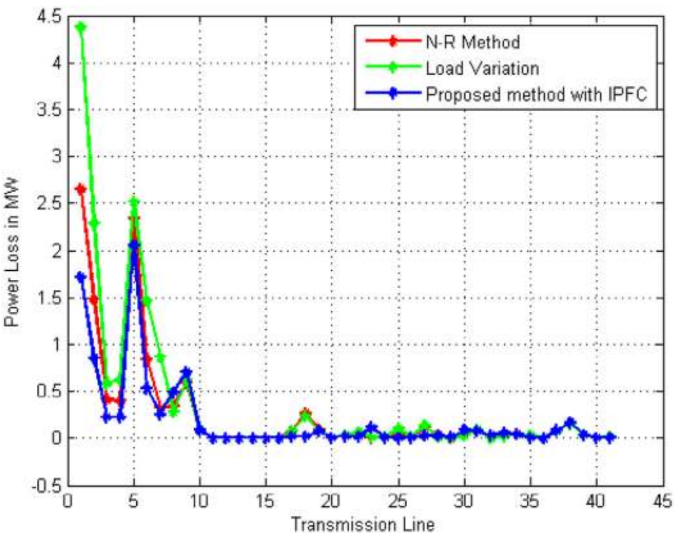

Fig. 7. Performance comparison of power losses after connecting the IPFC.

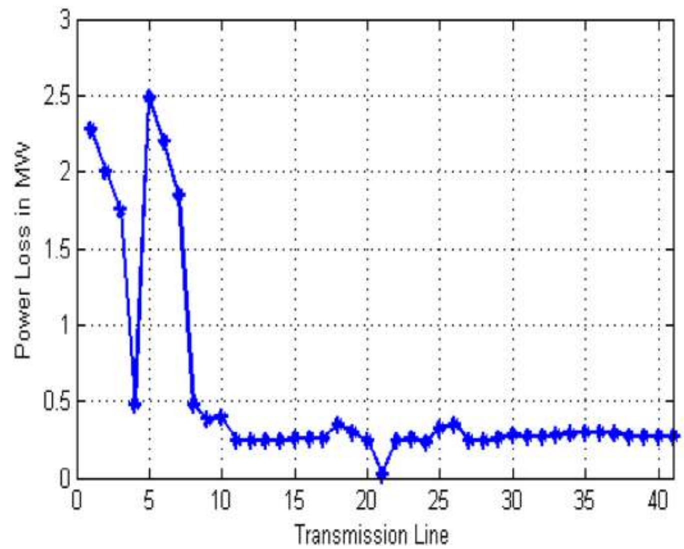

Fig. 9. Performance analysis of power loss after applying GSA technique.

and illustrated in Figs. 9 and 10, respectively. Then, the performances of the proposed method in terms of power loss and the number of iterations are analyzed and illustrated in Fig. 11. Then, the voltage values are evaluated with the N-R method, and the performances are compared with those of the proposed method.

The voltage values of the buses are evaluated by connecting the UPFC, load changes, and after applying the N-R approaches. Subsequently, the power loss performances are evaluated and compared with the N-R approaches, load variation, and the proposed method with the IPFC. The performance comparison of power loss and voltage in the transmission line is illustrated in Figs. 12 and

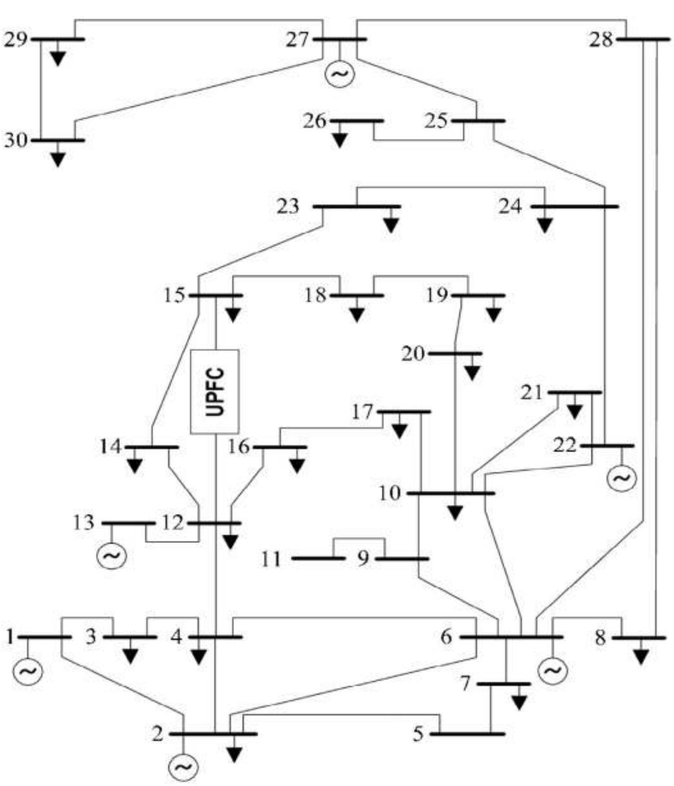

Fig. 8. IEEE 30 bus system with the UPFC connected to the line of buses 12–15.

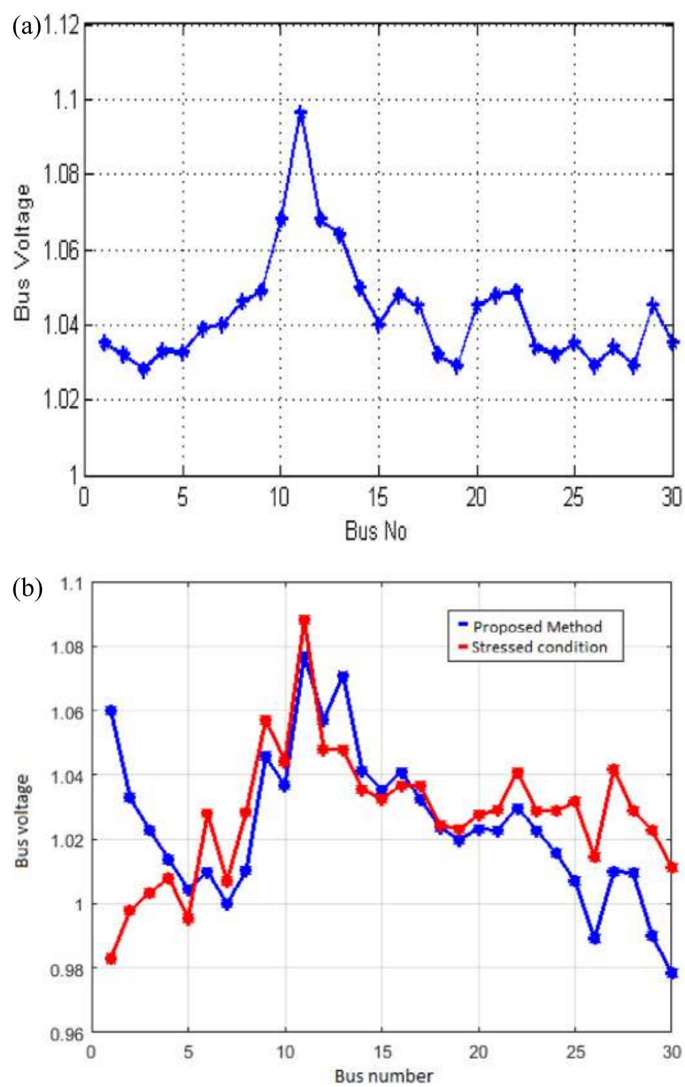

Fig. 10. Performance analysis of bus voltages (a) after applying GSA technique and (b) voltage under stressed condition.

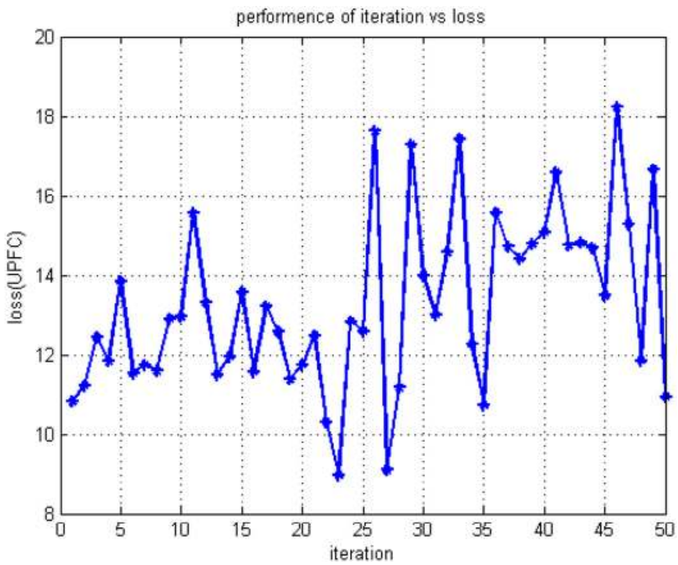

Fig. 11. Plot between power loss and iteration after connecting the UPFC.

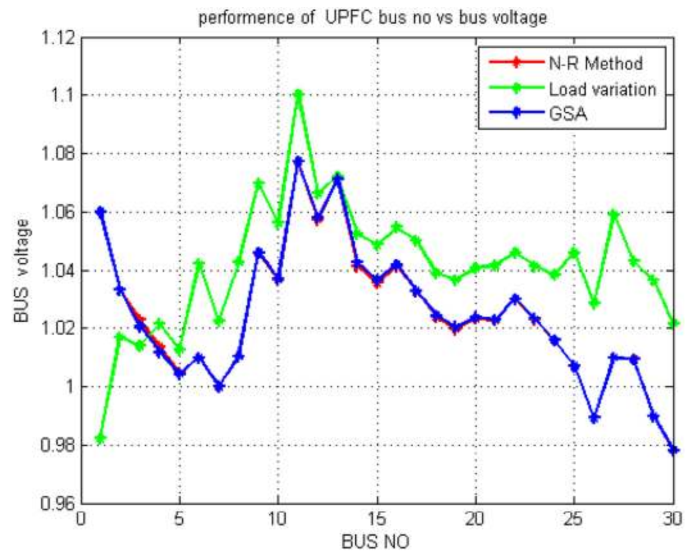

Fig. 13. Performance comparison of bus voltages after connecting the UPFC.

13. Here, when calculated, the normal loss of the bus system is 10.8095 *MW* and the injected bus power is 1.556 *MW*. The injected bus number is 16 and the injected power loss is 12.9151*MW*. After connecting the UPFC in between bus 12 and bus 15, the minimized power loss and the cost are evaluated using the proposed algorithm. Then, the minimized power loss of the system is found to be 9.7167*MW* and the cost of the UPFC is $188.22. Similarly, the best line buses are evaluated and calculated by their minimum losses and costs. From the above illustrations, the proposed method is found to achieve better results when compared to the N-R approaches and the load variations. Then, the performances of the proposed method with the IPFC and the UPFC are evaluated and illustrated in Fig. 14.

In the system, the reference set of L stability index value is 0.1251. Then, it can be concluded that the placement of the IPFC in between bus 10 and bus 22, the best L stability index with the reference set of 0.1356. After the installation of the IPFC at these buses, the minimum real power loss and L stability index are achieved. On comparison with the performance of the existing methods, it is seen that the proposed algorithm is able to considerably decrease the real power loss and decrease the L stability index of the system. The proposed algorithm yields better performance. Similarly, the UPFC is connected in between the two buses for carrying out the analysis. Then, the performance of the proposed method with the UPFC is evaluated. The performance of L stability index values of proposed method is compared with the existing methods and tabulated in Table 4.

From the above Fig. 15(a) and (b), the voltage collapse and the voltages from the proposed method are evaluated. Here, the voltage

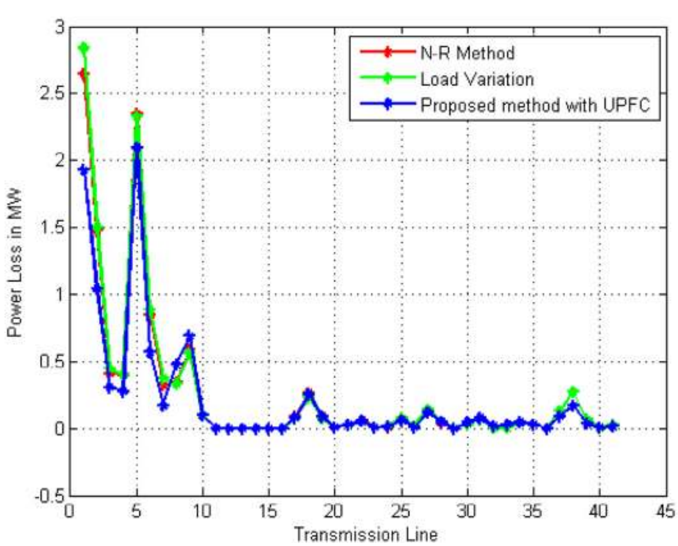

Fig. 12. Performance comparison of power losses after connecting the UPFC.

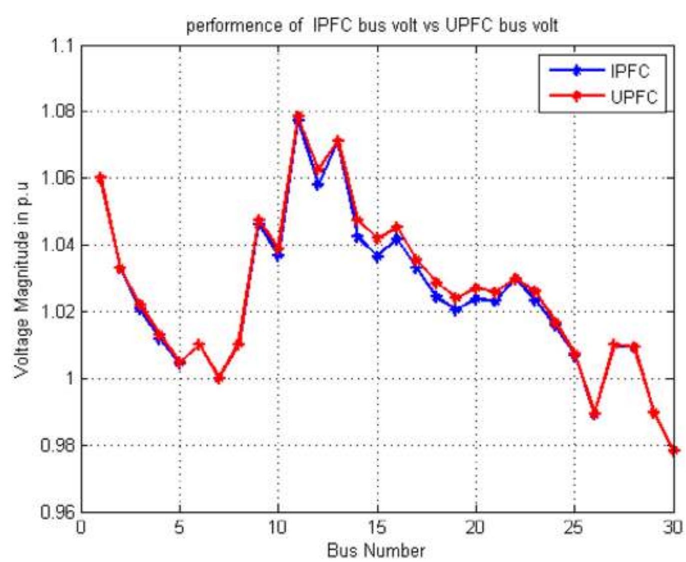

Fig. 14. Performance comparison of the voltages in the UPFC and the IPFC.

Table 4
L stability index values for proposed and existing methods.

Methods	L stability index			
GA based GSA hybrid technique	Before IPFC	0.1356	After	0.1342
PSO based GSA hybrid technique		0.1428	IPFC	0.1293
GA based GSA hybrid technique	Before UPFC	0.1389	After	0.1296
PSO based GSA hybrid technique		0.1435	UPFC	0.1208

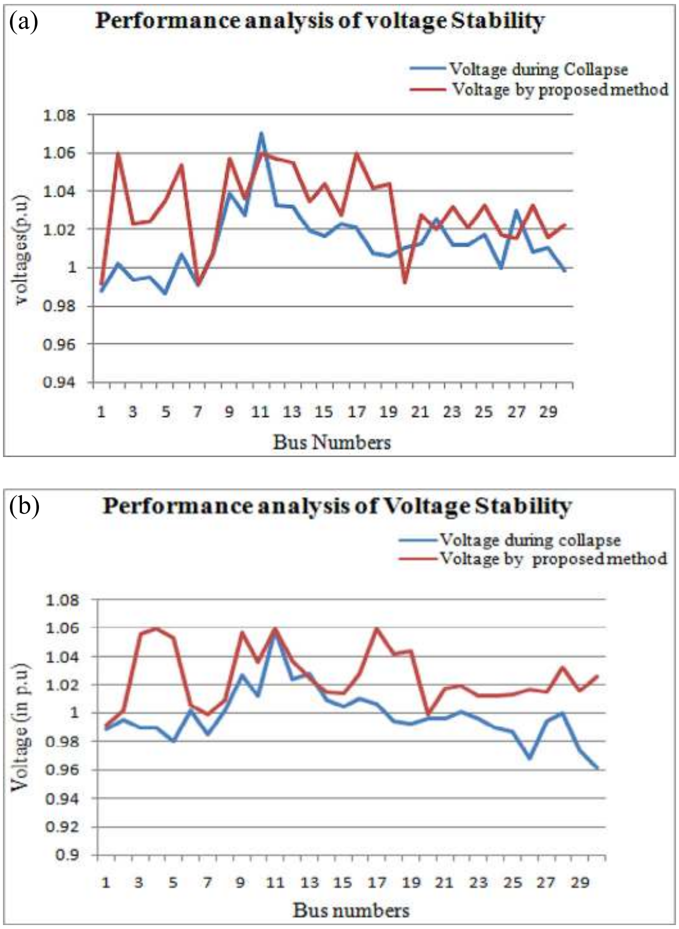

Fig. 15. (a) Performance analysis of voltage stability obtained from the IPFC-based proposed method. (b) Performance analysis of voltage stability obtained from the UPFC-based proposed method.

stability of the system is improved by connecting the IPFC as well as the UPFC and the power loss is also evaluated. Then, the performance comparison of the power losses is determined. The proposed system has reduced the power loss after the IPFC is connected and it is compared with the power loss without connecting the IPFC based on the performances. Similarly, the voltage stability of the system is enhanced by connecting the UPFC. Now, the UPFC achieves better results. The performance comparison of the voltages of the IPFC and the UPFC is illustrated in Fig. 14. The IPFC is used to control the multiline in an effective manner and the losses as well as the costs are reduced. However, the UPFC controls the transmission line between two buses efficiently.

The conventional GSA is not used for getting the optimal results of the searching capability, as it takes more processing time. In the existing method, the GA based GSA method is used for finding the optimal location and the capacity of the FACTS devices. For evaluating the processing time, a conventional GSA-based IPFC and GSA-based UPFC are considered. Here, the time consumed for choosing the best location and the time capacity of the UPFC is determined. Then, the total computation time is also calculated. Therefore, it is usually hard to find the nearest optimal location for fixing the FACTS device. For this reason, an optimization algorithm based on GSA is used to find the near-optimal location for such devices. Here, the PSO based GSA algorithm is used to find the optimal location for the FACTS devices and to improve the searching performance of the GSA. Then, the proposed algorithm is used for controlling the gravitational search parameters. Thereafter, the computation time for the

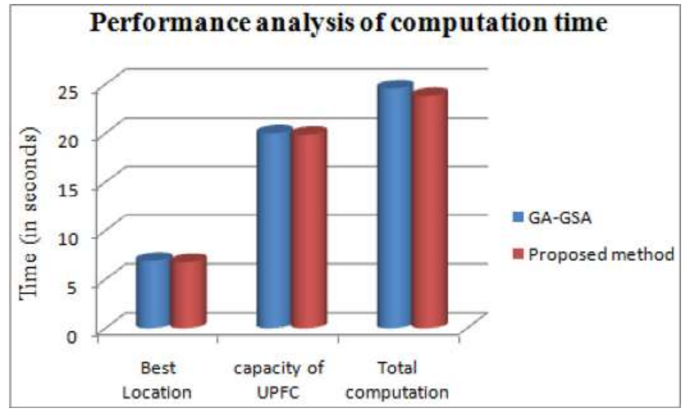

Fig. 16. Performance analysis of computation time in the UPFC.

optimal location and the optimal sizing of the FACTS device are evaluated. Also, the overall computation time is evaluated. Therefore, an enhanced GSA is used for getting the optimal results. The comparison analysis of computation time in proposed and existing method is illustrated in Figs. 16 and 17.

From the performances analysis of the GA–GSA method, the time required for choosing the best location is found to be 6.885 seconds and that for calculating the capacity of the UPFC is 19.9905 seconds. Then, the total evaluation time is estimated to be 24.5849 seconds. In the same way, the evaluated time for choosing the best location and the capacity of the IPFC are 6.9157 seconds and 18.6417 seconds, respectively. Then, the computation time for the process is found to be 22.4994 seconds. Similarly, the computation time of the FACTS devices is calculated using the proposed method and the corresponding evaluated time for choosing the best location, the time capacity of the UPFC and the total computation time are 6.7518 seconds, 19.8517 seconds and 23.8155 seconds, respectively. The computation time is evaluated for choosing the best location of the IPFC, the time capacity of the IPFC, and the total computation time. Their values in order are 6.3411 seconds, 16.4481 seconds, and 22.7892 seconds. From the performance analysis, the proposed technique takes lesser processing time compared to that of the GA based GSA. Therefore, the proposed technique is easy to control the gravitational parameters and detect the optimal location of the FACTS devices. Thus, the proposed technique is more efficient when compared to the existing methods.

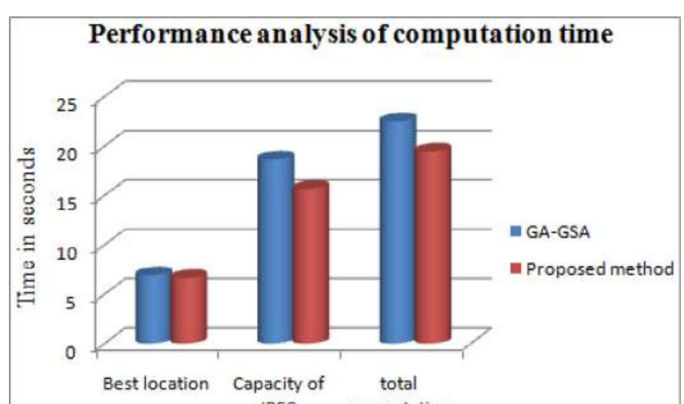

Fig. 17. Performance analysis of computation time in the IPFC.

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5. Conclusion

The proposed technique was implemented in the MATLAB platform. It was used to find the optimal location and the power rating of the FACTS devices based on the voltage and the minimum power losses. Here, the PSO adaptive GSA technique was investigated to improve the stability of the transmission system based on the voltage and the power loss. The proposed technique was tested with the IEEE 30 bus benchmark system. Initially, the voltage collapse rating of the system was analyzed and determined by the optimal location of the FACTS device. From the location, the injected power rating of the FACTS was determined depending on the voltage magnitude and the angle. Then, the UPFC and the IPFC were placed on that location and the stability of the system was analyzed. Subsequently, the power loss and the injected voltages were analyzed and their corresponding results were discussed. By connecting the IPFC in between two buses, the voltage values and their power losses were evaluated. Similarly, by connecting the UPFC between two buses, their magnitudes were calculated. In the GA–GSA and in the proposed technique, the computation time was evaluated based on their performance analysis. From the performance analysis, the elapsed time for the proposed technique was less compared to that of the GA–GSA method. Therefore, the proposed technique was able to achieve better results for improving the voltage stability and reducing losses. In future work, the objective of the paper is modified and the optimal placement of FACTS device is identified using latest optimization algorithm. However, the optimal placement of the FACTS device was chosen more accurately.

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