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# Enhance power system security with FACTS devices based on Mayfly Optimization Algorithm

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## Abstract

Security of power systems can be defined as their ability to withstand severe disturbances and survive the transition to an acceptable new steady-state condition. The introduction of a flexible AC transmission system (FACTS) in a power system improves stability, reduces power losses, reduces the cost of generation, and improves the system's load ability. In this paper, technological development with modelling of Facts devices is shown to provide system stability, reduce the losses, and reduce the fuel cost. Facts devices like static synchronous compensator (STATCOM), Interline Power Flow Controller (IPFC), unified power flow controller (UPFC) and Thyristor-Controlled Series Compensation (TCSC) are fitted in a proper location of the transmission line to reduce the losses. The best location of Facts devices is hard to identify due to the enormous lines present in the IEEE bus system. An optimization is utilized to find the proper location of Facts devices accurately, leading to improving the power system security. In the proposed method, Mayfly Optimization Algorithm (MA) is applied to determine the optimal location of Facts devices in a power system. Find the best location and reduce outage losses based on the multiple objective functions. The proposed method is tested with the IEEE 30 bus, IEEE 118 bus, and 300 bus systems. The corresponding line loading, line limits, generator limits, bus voltage impact, etc. The projected method is executed in MATLAB and tested with various cases. The proposed method provides a high power demand and system steadiness. It reduces the fuel cost compared to the existing techniques of Particle Swarm Optimization (PSO), Firefly optimization, and Yin-Yang-Pair Optimization (YYPO).

***Keywords***: *Facts devices*; *fuel cost*; *Mayfly Optimization Algorithm (MA)*; *power losses; system security.*

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## 1. Introduction

Recently, power system management and control are challenging tasks for enabling security, reliability, and stability under contingency conditions (Pavella, Ernst, & Ruiz-Vega, 2012). The power system has been greatly harassed due to heavy load demand, which creates problems in transmission lines such as system collapse conditions, bus voltage violations, security issues and line overloading (Spellman, 2016; Goel, & Hong, 2015). Based on heavy load demand, the power system transactions create hidden failure, unexpected events and weak connections in protection systems. Additionally, human errors and other reasons may initiate system balance fault and catastrophic failures in the power system. Due to the increase of power transfer, the system operation is more difficult as well as less secure in order to meet the demand of load as well as fulfil the steadiness and reliable conditions of the system, for adding a new line or using an existing transmission line. A new line added to the system takes more time, and it is rarely possible due to atmospheric issues. So, security enhancement is the main research that has to be carried out in an energy management system to compute the stability and security of the system under contingency conditions (Yorino, El-Araby, Sasaki, & Harada, 2003). Hence, the dynamic security analysis is an essential task to enable proper reliable and stable operation of power system operation under various operating conditions. The power system industries have concentrated on designing and implementing corrective and preventive measures of problems for enabling security constraints (Wood, Wollenberg, & Sheblé, 2013).

Normally, Security Constraints Optimal Power Flow (SCOPF) is utilized to analyze and enable proper security of the power system through Q-V curves. This power flow technique is used to identify the various contingency conditions in the power system (Capitanescu, Glavic, Ernst, & Wehenkel, 2007). However, it is not concentrating on correcting the problems of an outage, loadings and so on. Many techniques are available to maintain the system in a stable condition by the corrective method, but these methods are not considered the security constraints of the system (Xue, Van Cutsem, & Ribbens-Pavella, 1988). Mostly, Flexible Alternating Current Transmission System (FACT) is an effective solution to empower the security and stability in the power system (Bayod-Rújula, 2009). Fact devices are installed in a power system to enable stability and reliability. The Fact device installation empowers the system parameters such as complete system losses, power flow in transmission lines and voltage magnitudes. Fact devices can play the main consideration in controlling congestion in the transmission line as well as demand management (Singh, & David, 2001). Facts devices have a meshed network structure, and the devices are placed in a suitable location to allow power flow control and improve the system's security and load ability.

Different types of Fact devices are available in a system, such as Static Synchronous Compensator (STATCOM) (Pateriya, Saxena, & Tiwari, 2012), Static VAR Compensator (SVC) (Biswas, & Das, 2011), Unified Power Quality Controller (UPQC) (Sudeep Kumar, & Ganesan, 2006, November), Unified Power Flow Controller (UPFC) and Interline Power Flow Controller (IPFC). The Fact devices are combined with SCOPF, which empowers preventive and corrective problems. To empower the security constraints of the system by using Fact devices, objective functions are defined based on the Fact device's optimal location and capacity for proper stability operations such as power loss, voltage deviation, installation cost and so on. Security constraints, equality and non-equality constraints are also considered in security enhancement (Chen, Lu, & Zhang, 2018). These objective functions are solved by utilizing meta-heuristic optimization. Many different types of algorithms are available to solve the objective functions for enabling security, reliability and stability problems in power systems such as Genetic Algorithm (GA), Improved Teaching Learning-based Optimization (ITLO) (Lenin, Reddy, Kalavathi, 2013), Modifier Salp Swarm Optimization (MSSO) (Cheng, 2020) and so on. One of the previous methods contains a simple generic optimization to find the best location of TCSC and SVC devices. Both Facts devices maintain voltage stability and bus voltages. Another technique presents a heuristic optimization to locate the best place of five various Facts devices, and it is simulated and validated in IEEE 30 bus system. In the proposed work, Mayfly Optimization Algorithm (MA) is utilized for solving the optimal problem of objective functions to identify the best location of Facts devices. MA is the most recently developed optimization algorithm, and it offers a balanced power flow among generation and consumer and rapid working to find the best location of Facts device.

Without secured power system contain voltage collapse issues related to the problem of reactive power and analysis of contingency. The analysis is based on finding where the best reactive power assets are present in the system. In the traditional method, planning of reactive power contains two types of limitations, namely, voltage stability limitation and voltage feasibility limitation. In voltage stability conditions, secure the network against voltage imbalance, and in voltage feasibility conditions, ensure the voltage of the bus in allowed limits. The goal of the reactive-power (VAR) planning challenge is to create as a few new reactive-power supplies as possible while satisfying just the voltage feasibility restrictions in normal and post-contingency states.

### 1.1 Contribution

The security guard of four Facts devices is applied to reduce the losses in the power system by using a mayfly optimization algorithm.

- IEEE buses like 30, 118 and 300 are designed to analyse the security condition in case of an error duration.
- Four Facts devices are integrated into the system for reducing the error. A mayfly Optimization algorithm is modelled to optimally select the size and location of Facts devices.
- Determine the bus position and size of Facts devices to choose a suitable device amongst these four Facts devices that decrease the loss and the mayfly optimization algorithm's initial population.
- A formulation of the objective function to discover the ideal site for Facts device placement is included in the Mayfly optimization algorithm. Six objective functions are addressed in the proposed work: Power loss, Voltage deviation, Investment cost, Fuel cost, Severity function, and Line overload security index, which are utilised to discover the appropriate equipment for addressing the transmission line issue.
- The advanced system outcome is validated for with and without Facts devices, in addition, contrast with previous methods like Firefly, PSO and YYPO

The remaining part of the paper is organized as follows; section 2 provides the recent research related to security enhancement in the power system. Section 3 provides the system configuration with the objective functions of security constraints. The performance of the proposed method is evaluated and presented in section 4. The conclusion, as well as the future scope of the research, is presented in section 5.

## 2. Recent related works

Many research works are available to enhance the security of the power system. Some of the works are reviewed in this section.

Kumar et al., 2020, have developed Biogeography Based Optimization (BBO) for solving power system security constraints (Kumar, Alli Rani, & Sundaravazhuthi, 2020). To meet the power system security, multi-Fact devices were used in the power system. The designed method with Fact device was applied variance bus voltage magnitude as well as transmission line loadings. With the utilization of Fact devices, the transmission system security was achieved through objective functions such as severity index and fuel charges. The objective functions were evaluated in the contingency circumstances of the transmission network and generator. The presented method completely reduced the heavy stress in the transmission line and maintained the system's power flow. The BBO provided the best results compared to the existing methods such as GA and Particle Swarm Optimization (PSO).

Kumar Kavuturu and Narasimham, 2020a, have presented Adaptive Cuckoo Search Algorithm (ACSA) for solving multi-objective economic operations under weather variations in the modern power system (Kumar Kavuturu & Narasimham, 2020a). In this method, the transformer/transmission line resistance values, solar photovoltaic generation and transformer resistances values were considered in ambient temperature effects. Based on temperature variations, the economic schedule was obtained by objective functions such as average voltage deviation index, average voltage collapse point indicator index, real power loss and complete operating cost. In the dispatching problem in the transmission system, various operating constraints were handled within the limits of the optimal unified power flow controller. The superiority of the presented method was evaluated by comparison of the Cuckoo Search Algorithm (CSA) and PSO algorithm. The presented method was evaluated by using various case studies such as IEEE 118 bus system, IEEE 30 bus system and IEEE 14 bus system.

Kumar Kavuturu and Narasimham (2020b) have presented the CSA algorithm for security management in transmission lines under (N-1) line contingency (Kumar Kavuturu, & Narasimham, 2020b). This research was provided with information about Renewable Energy Sources (RES) and Optimal Unified Power Flow Controller (OUPFC) on the severity of contingency (N-1) in the transmission line. The performance of OUPFC was tested in the single line contingency conditions. The contingency problems were solved by optimal power flow with objective functions, which were Line collapse, Proximity Indicator (LCPI) and real power loss. Initially, the OUPFC location was computed based on objective functions, and the contingency conditions were checked at various RES generation stages. The presented CSA algorithm worked under different conditions, such as exponentially improving switching parameters (CSA2) and dynamically improving switching parameters in the power system. The presented method was evaluated by using the standard IEEE 30 bus system.

Ain et al. (2020) have investigated the Thyristor Control Series Compensator (TCSC) and Static Synchronous Series Compensator (SSSC) for stability enhancement of the system under various fault conditions (Ain, Jamil, Hameed, & Naqvi, 2020). This research provided information on TCSC and SSSC modelling as well as operation in multi-machine conditions. The effectiveness of the Fact controller in different types of fault scenarios was considered. In a large system, a power system stabilizer (PSS) was used for maintaining stable operation. The Fact devices of TCSC and SSSC were combined with PSS to enable stable operation. The Fact devices completely enhanced the stability by mitigating the power system oscillations, which empowers the overall system efficiency.

Kumar and Ramaiah (2020) have presented a Modified Salp Swarm Optimization Algorithm (MSSA) for identifying the optimal location of UPFC to motivate stable operation (Kumar & Ramaiah, 2020). The main objective functions of the presented method were reduced complexity, random reduction and improved searching ability. The presented MSSA algorithm is used to determine the optimal location of the UPFC when a power generator fault happens in the system. The MSSA computes the greatest power line loss related to the optimal location of UPFC as per the objective functions. To find out the objective functions, the inequality and equality constraints were considered in the power system. The voltage deviation, power loss, and optimum capacity of UPFC were considered as the objective function.

S. Surender Reddy and James A. Momoh (2015) have presented the best-fit day-ahead schedule by minimising both real-time and day-ahead adjustment costs, together with revenue from renewable energy certificates, by taking into account the effect of uncertainties in solar PV, wind, and load forecasts, and providing the best-fit day-ahead schedule by reducing both real-time and day-ahead adjustment costs, together with revenue from renewable energy records (Reddy & Momoh, 2015). Using a generic algorithm to find the best-fit day-ahead schedule to reduce the cost, this method is validated for the IEEE 30 bus system.

Reddy, 2017, has suggested maximising specific objective functions. CSA is utilised to identify the ideal settings of regulating variables, namely transformer tap positions, generator voltages, and the quantity of reactive compensation required (Reddy, 2017). The method is simulated and validated for examined on standard Ward Hale 6 bus, IEEE 30 bus, 118 bus, 57 bus, and 300 bus systems. This method is more effective and efficient to give a better outcome.

Reddy and Bijwe, 2016, have presented the meta-heuristic algorithms that were used to solve the Optimal Power Flow (OPF) problem in three efficient ways (Reddy & Bijwe, 2016).. The number of load flows/power flows to be done significantly reduced when these methodologies were used, resulting in a significant increase in solution speed. This system was able to handle discontinuities in the objective function, complex nonlinearities, multi-objective optimization, and discrete variables handling. The system was designed and validated in IEEE 30, 118 and 300 bus systems.

Reddy, 2019, has suggested the Hybrid Differential Evolution and Harmony Search (Hybrid DE-HS) algorithm was used to solve an Optimal Power Flow (OPF) with non-convex and non-smooth generator fuel cost characteristics (Reddy, 2019). The OPF answer was calculated using objective functions: transmission loss, generator fuel cost, and voltage stability index. The system was verified in EEE 30, 118 and 300 bus systems as well as compared with existing techniques related to this work.

Reddy and Bijwe, 2019, have developed a concept of incremental load flow model based on sensitivity and some heuristics, fresh evolutionary-based multi-objective optimization (MOO) techniques for solving the optimal power flow (OPF) problem (Reddy & Bijwe, 2019). This method was more effectively handled discontinuities, complex non-linearities, discrete variables, and multiple objectives function. This method was designed and verified in IEEE 30 bus system.

Reddy, 2018, has presented a method for determining the best position for Flexible AC Transmission System (FACTS) controllers in the restructured electrical power system for Congestion Management (CM) (Reddy, 2018). Total system losses and power flows are used to calculate performance indexes. The method was designed and validated for IEEE 30 bus system as well as effectively finding the optimal FACTS controller position.

Kumar et al., 2020, presented BBO for solving the security issues in the power system under contingency conditions (Kumar et al., 2020). However, it may fail in convergence characteristics to meet the major objective functions. Kumar Kavuturu and Narasimham, 2020a, have presented ACSA for solving multi-objective economic operations (Kumar Kavuturu & Narasimham, 2020a). It is not considered the Fact device for oscillation reductions in the power system (Kumar Kavuturu et al., 2020a). Kumar Kavuturu and Narasimham, 2020b, have presented the CSA algorithm for security management in the power system (Kumar Kavuturu & Narasimham, 2020b). However, it is not tested with the large area bus system. Ain et al., 2020, has investigated the TCSC and SSSC for stability enhancement of the system under various fault conditions (Ain et al., 2020). This method has not cleared the faults optimally due to optimal location failure. Kumar and Ramaiah, 2020, have presented MSSA for identifying the optimal location of UPFC to motivate stable operation (Kumar & Ramaiah, 2020). However, three types of objectives were only considered in the system. Reddy and Momoh, 2015, explain the best-fit day-ahead schedule to reduce costs (Reddy & Momoh, 2015). Reddy, 2017, uses the CSA method to solve the optimization problem, which is very good for solving the problem (Reddy, 2017). Reddy and Bijwe, 2016, use a meta-heuristic algorithm to solve the optimal power flow problems, which effectively reduces the problem (Reddy, & Bijwe, 2016). Reddy, 2019, explains a Hybrid DE-HS algorithm to solve the optimal power flow issues (Reddy, 2019). It is a new hybrid method for solving the OPF problem, and it gives a better accuracy as compared to another. Reddy and Bijwe, 2019, explain the multi-objective optimization (MOO) techniques for solving the optimal power flow (OPF) problem (Reddy & Bijwe, 2019). This method gives a good outcome and very effectively solve the problems. Reddy, 2018, explains the approach of Congestion Management (CM) to find the best place of Facts device. This technique is not making a rapid operation to find the place (Reddy, 2018). The abovementioned drawbacks are overwhelmed by designing the new method with Fact devices.

## 3. Problem formulation

### 3.1 Power loss

In a transmission line, a part of power is lost due to wind, atmosphere, dielectric loss, heating of resistive elements, etc., so the consumer cannot get the specified amount of power. The security devices are used to minimize power loss. The equation of power loss is given in Eq. (1).

$$F1=P_{loss}=\sum_{\substack{K=1\\ J\neq i}}^{NL} G_{kj}[V_k^2+V_j^2-2V_k.V_j\cos\left(\delta_k-\delta_j\right) \qquad (1)$$

where, $\delta_k$ is the angle of $k$ bus; $\delta_j$ is the angle of $j$ bus; $V_j$ , $V_k$ is a voltage magnitude of $j$ bus and $k$ bus respectively; $G_{kj}$ is conductance among the buses $k$ and $j$ respectively; $P_{loss}$ is system power loss.

### 3.2 Voltage deviation

Voltage deviation is defined as the mean difference between the voltage in the given instant point and the reference point of the power system. Some security devices are used to control the deviation. The mathematical expression of voltage deviation is,

$$F2=V_{div}=\sum_{i=1}^{NL}/V_i-V_i^*/ \qquad (2)$$

where, $V_{div}$ is voltage deviation; $V_i$ is voltage magnitude at $i$ bus; $V_i^*$ is reference voltage magnitude value.

### 3.3 Investment cost

The Fact devices investment cost is regarded as the third objective function. In this paper, four Fact devices are analysed, namely STATCOM, UPFC, IPFC and TCSC. The cost function of each device is given in Eq. (3), Eq. (4) and Eq. (5),

$$F3=Cost_{UPFC}+Cost_{IPFC}+Cost_{TCSC} \qquad (3)$$

where, $Cost_{UPFC}=0.0003S^2+0.026922S+188.22$

$$F3=Cost_{STATCOM}+Cost_{UPFC}+Cost_{IPFC} \qquad (4)$$

where, $Cost_{STATCOM}=0.0003s^2-0.3051s+127.38$;
$Cost_{UPFC}=0.0003s^2-0.026911s+188.22$

$$F3=Cost_{IPFC}=Cost_{IPFCA}+Cost_{IPFCB} \qquad (5)$$

where, $Cost_{IPFCA}=0.00015s_i^2-0.01345s_i+94.11$
$Cost_{IPFCB}=0.00015s_j^2-0.01345s_j+94.11$

### 3.4 Fuel cost

In cost of a power system contain two components, such as fixed cost and variable cost (fuel cost and maintenance cost). The Facts devices are used to minimize the total generator fuel cost and limit the parameters. The Triangle method of cost calculation is given in Eq. (6),

$$\cos(Q) = a^n Q^2 + b^n Q + C^n \ (\$/hr) \qquad (6)$$

where, $a^n b^n c^n$ are constant.

### 3.5 Severity function

Line loading and voltage deviation are the most effective problem to cause power loss in the power system. Both of the parameters are considered while assessing the severity of the transmission line. Facts devices are used to solve this type of incident. The composite severity index formula is shown in Eq. (7),

$$F5=CSI_{ij}=w_1 \times LUF_{ij}+w_2 \times FVSI_{ij} \qquad (7)$$

where, $w_1 \& w_2$ are weighting factor; the value of $w_1$ and $w_2$ is 0.5; $w_1+w_2=1$

Line Utilization Factor, $LUF_{ij}=\frac{MVA_{ij}}{MVA_{ij\ max}}$

Fast Voltage Stability Index, $FVSI_{ij}=\frac{4z^2 Q_j}{V_1^2 X}$

### 3.6 Line overload sensitivity index

The sensitivity index finds the proper location of Facts devices in the transmission line and also analyze the performance of the devices.

Equation of sensitivity index is,

$$F6=a_{ij}=\frac{\partial Q_l}{\partial x_{ij}}=\left[\left(V_i^2+V_j^2\right)-2V_iV_jG_{ij}\cos\delta_{ij}\right]\left[\frac{r_{ij}^2-x_{ij}^2}{\left(r_{ij}^2+x_{ij}^2\right)^2}\right] \qquad (8)$$

where, $V_i$ and $V_j$ are voltage magnitude of bus $i$ and bus $j$; $\delta_{ij}$ is the voltage difference between bus $i$ and bus $j$, i.e $\delta_{ij}=\delta_i-\delta_j$; $x_{ij}$ is the reactance of transmission line between bus $i$ and j; $r_{ij}$ is the resistance of transmission between bus $i$ and $G_{ij}$ is susceptance of transmission line between $i$ and $j$.

The above objective functions are important for finding the best locations where the Facts devices are placed in the system. Because the devices are not only safe the system, they also reduce the voltage deviation, power loss, stable power, and regulate the reactive power. Moreover, it reduces the cost of fuel during the outage period.

## 4. Proposed methodology of optimal placement of Facts device

In a power system, many losses arise between the transmission line of generation and distribution, so the consumer cannot get enough power. The power losses are caused by wind, heating of resistive elements, dielectric loss, atmosphere, etc. The Facts devices are used to control this problem. Facts devices are more flexible in the power system and control operation, thus improving the existing power usage. There are many types of facts devices used based on the operation and the capability of the transmission line.

The concept of Facts devices was first introduced by NG. Hingorani in the USA in 1988 (Mahdad, Bouktir, & Srairi, 2006). The application of Facts devices in the power system is to control the power flow, to increase stability, reduce the voltage fluctuation, power factor correction and reduce the power losses. Thyristor controlled series capacitor (TCSC) and Static VAR compensator (SVC) are most commonly used in the power system. The transmitted power through a line is inversely proportional to the transfer impedance.

In this paper, we have to propose a simple method based on heuristic and practical rules of the optimal places of four different Facts devices, such as Static Synchronous Condenser (STATCOM), Unified Power Flow Controller (UPFC), Interline Power Flow Controller (IPFC), and Thyristor Controller Series Compensator (TCSC) with specific characteristics. These Facts devices are used to minimize the error, which is occurred in the power system. The main focus of this paper is to find the correct location of the Facts devices and analysis the performance by using a simple algorithm.

By using these Facts devices, the consumer gets the specified amount of power. The sensitivity index analyses the week transmission lines and gets the correct location where the Facts devices are fitted. The best location of the devices is identified by multiple objective functions that are explained in the above section. The objective function is power loss, voltage deviation, investment cost, fuel cost, severity function and line overload sensitivity index. These objectives are important to reduce since they create more economical and power losses directly or indirectly. A simple and effective algorithm of mayfly optimization is used to find the weakest transmission line and the correct location of Facts devices.

The mayfly algorithm is based on the life cycle of the mayfly insect. This algorithm is used in many fields to solve many problems. The result of this algorithm satisfies the discrete problem compared to another optimization. Mayfly optimizes the objective functions to identify the best location where the Facts devices are fit. Mayfly provides the best working to accurately identify the suitable place of device, which is more useful for reducing outage losses and fuel cost. The proposed method and mathematical simulation are shown below

### 4.1. Modelling of Facts devices

In a power system, the Facts devices are used to balance the power between the generating side and the distribution side. There are four types of Facts devices that are commonly used in power systems; they are STATCOM, UPFC, IPFC, and TCSC. These devices are most well to balance power quality. In this paper, these four Facts devices are briefly studied.

### *4.1.1 STATCOM*

The static synchronous compensator (STATCOM) is also known as a static synchronous condenser. It is based on a voltage source converter. These devices are used to transfer alternating current to the power system. Usually, this device is used in an area that contains poor power factors and poor voltage regulators. The equivalent circuit diagram is shown in Figure 1.

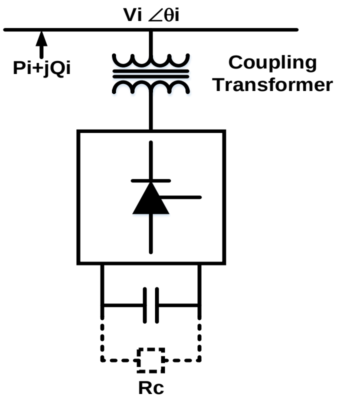


**Figure 1** Equivalent circuit of STATCOM

The STATCOM devices contain two steady-state operations such as capacitive and inductive. The voltage source converter converts dc to ac output voltage, and it is connected to the secondary side of the coupling transformer. The coupling transfer steps down or steps up the power to transfer the bus bar.

Let, $V_{bus}$ =*bus bar voltag*
$V_{OSTA}$ = STATCOM output voltage
$X_l$ = Inductive voltage
$V_{dc}$ = Capacitor dc voltage

The equation of STATCOM in real and reactive power is,

$$P = (V_{bus} \times V_{OSTAT} \div X_l) \sin \alpha \tag{9}$$

$$Q = \left(V_{bus} \times \frac{V_{bus}}{X_l}\right) - (V_{bus} \times V_{OSTAT} \div X_l) \cos \alpha \tag{10}$$

where, $X_l = R + j\omega l$

### *4.1.2. UPFC*

UPFC stands for Unified Power Flow Controller. It provides fast-acting reactive power compensation on a high voltage electricity transmission network and controls the active & reactive power flows in a transmission line. It contains a back-to-back connection of two converters, i.e., one is connected in series, another one is connected in parallel. The equivalent circuit diagram is shown in Figure 2.

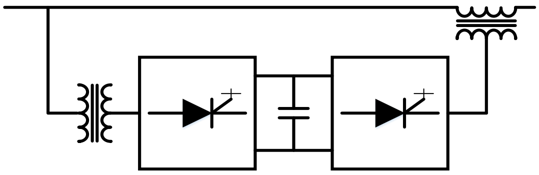


**Figure 2** Equivalent diagram of UPFC

In Figure 2, the voltage source converter 1 & 2 is connected to the coupling transformer, respectively. The coupling transformer transfers voltage from VSC2 to the transmission line, which is connected in series. Current 'I' in transmission line travel through this voltage source to provide real and reactive power interchange UPFC and transmission line. The equation is,

$$V_{sr} - V_{sr1} = R_{sr} I_{sr1} + I_{sr}{}^{d}_{dt} \qquad (11)$$

where, $V_{sr}$ is series voltage; $I_{sr}$ is series current

The real and reactive power equation is,

$$\begin{bmatrix} P_0 \\ Q_0 \end{bmatrix} = \begin{bmatrix} V_{od} & V_{oq} \\ -V_{oq} & V_{od} \end{bmatrix} \qquad (12)$$

### *4.1.3. IPFC*

IPFC stands for Interline Power Flow Controller. This device is used to control power flow and improve power system stability. It is the latest device in the Facts family. IPFC have the ability to control power flow in two or more transmission lines at the same time. The equivalent circuit diagram is shown in Figure 3.

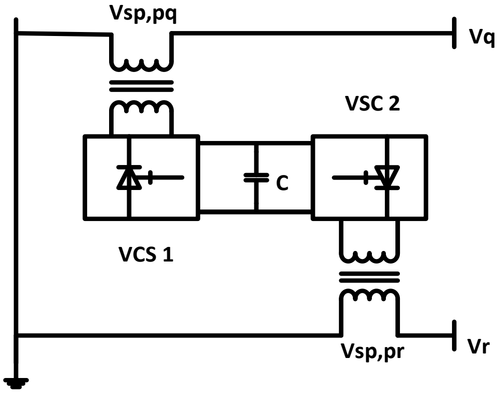


**Figure 3** Equivalent diagram of IPFC

In Figure 3, there are two voltage sources connected in parallel. The real and reactive power equation is given in Eq. (13) and Eq. (14)

$$P_{ir} = \frac{V_r}{|Z|} \left[ V_{ipq} \, sin\left(\frac{\delta}{2} + \theta_{ipq} - \varphi\right) + V_1 \;\; sin\left(\varphi - \frac{\delta}{2}\right) \right] \qquad (13)$$

$$Q_{ir} = \frac{V_r}{|Z|} \left[ V_{ipq} \; cos\left(\frac{\delta}{2} + \theta_{ipq} - \varphi\right) + V_1 \; cos\left(\varphi - \frac{\delta}{2}\right) \right] \qquad (14)$$

$$V_1 = V_r - V_s$$

$$\varphi = Cos^{-1}\left(\frac{R}{\sqrt{R^2 + (L\omega)^2}}\right)$$

where $i$ represent line index, $\theta_{ipq}$ is the phase difference between $V_{ipq}$ and $V_1$.

### *4.1.4. TCSC*

The word TCSC is derived from Thyristor Controlled Series Controller. It is the first method of AC transmission system. It is used to control the line impedance through the induction in thyristor controlled capacitor in series. TCSC is connected series in the transmission line conductor. The equivalent diagram is shown in Figure 4.

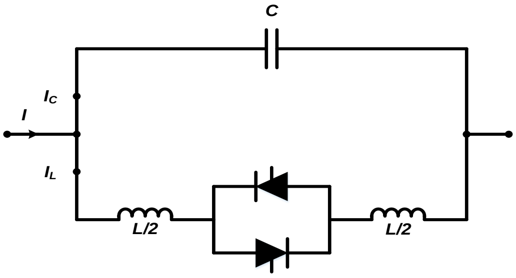


**Figure 4** Equivalent diagram of TCSC

Figure 4 contain a series capacitor bank, and a thyristor is connected between the inductors. It is naturally commutated, and the switching frequency is also low, containing insufficient energy storage and no dc port. The result of this operation is to improve angular and voltage stability.

$$P = V_1 V_2 \sin\varphi / x \qquad (15)$$

$$V = f(P, Q)$$

where, $V_1, V_2$ is denote voltage either the interconnection; $\varphi$ is Angular differenc

## 4.2 Mayfly optimization

### *4.2.1 Mayfly algorithm*

Zervoudakis and Tsafarak have developed the Mayfly algorithm by miming the behaviour of mayflies for resolving many optimization problems

(Bhattacharyya et al., 2020). This algorithm is a hybrid algorithm developed by merging the advantages of traditional optimization algorithms like Firefly Algorithm (FA), Genetic Algorithm (GA) and Particle Swarm Optimization (PSO). This MA algorithm will have enhanced performance over a large- and small-scale set of features. The behaviour of mayflies will be explained in detail as follows.

### *4.2.2 Behaviour of mayfly*

The mayflies are a kind of insect that comes under the order Ephemeroptera. These insects belong to the group of insects called Palaeoptera. The presence of this insect in the UK will be in May month so, this insect was named a mayfly. The immature mayflies will grow as aquatic nymphs for many years until they become adult mayflies. The adult mayflies will be found on the surface of the water. Especially the male adults will be present a few metres above the water as a swarm in order to attract females. The male adults will perform a dance known as a nuptial dance that consists of up and down movement creating a pattern. The female adults will approach these swarms in order to carry out mating. The process of mating will exist for a few seconds. They are following that the eggs will be dropped in the water, and this cycle will continue.

### *4.2.3 Movement of male mayfly*

The male mayflies will gather in a swarm, and the position of each male will be adjusted based on its neighbour or its own experience. The position of a male adult is updated based on the following equation.

$$x_i^{t+1} = x_i^t + v_i^{t+1} \tag{16}$$

In the above equation, $x_i^t$ represent the current position and $x_i^{t+1}$ implies the updated position obtained by adding the velocity with the current position. As explained previously, these male mayflies will remain a few metres above the water surface. Therefore, they cannot create greater speed, so they move constantly. The velocity of the male mayfly is calculated as follows.

$$v_j^{t+1} = g \times v_j^t + a_1 \times e^{-\beta r_p^2} \times \left(pbestt_j - x_j^t\right) + a_2 \times e^{-\beta r_g^2} \times \left(gbestt_j - x_j^t\right) \tag{17}$$

where $g$ signifies the gravitational coefficient, $v_j^t$ is the velocity of a male mayfly at time $t$ and $x_j^t$ represent the position of a male adult at time $t$. $a_1$ and $a_2$ denotes the positive attraction constant. And they were used for calculating the social and cognitive components. $pbestt_j$ denotes the optimal position that was not yet visited by the mayfly and $gbestt_j$ denotes the global best position of male mayflies, and $\beta$ represents the fixed visibility coefficient that retains the visibility of mayflies to others. On considering the minimization function, it is calculated as follows.

$$pbestt_j = f(x) = \begin{cases} x_j^{t+1}, \&if\, x_j^{t+1} < pbestt_j \\ remains\ the\ same,\ otherwise \end{cases} \tag{18}$$

where, $x_j^t$ denotes the fitness position value, and it helps us to evaluate the quality of the solution. At last $r_p$ represents the Cartesian distance between $x_j$ and $pbest$ and $r_g$ represents the Cartesian distance between $x_j$ and $gbest$. The mathematical equation used for calculating the Cartesian distance is given as follows.

$$|x_k - X_k| = \sqrt{\sum_{j=1}^{n} (x_{kj} - X_{kj})^2} \tag{19}$$

where, $x_{kj}$ denotes the position of mayfly and $X_k$ denotes $pbest$ or $gbest$. The best mayfly will perform the nuptial dance, and it is considered significant for the constant functioning of the algorithm. So, the velocity of the best mayfly will keep changing.

### *4.2.4 Movement of female mayfly*

The female mayflies will not gather in swarm-like males; rather, they move towards the male mayflies for breeding. The position of a female adult is updated based on the following equation.

$$y_i^{t+1} = y_i^t + v_i^{t+1} \tag{20}$$

In the above equation, $y_i^t$ represent the current position and $y_i^{t+1}$ implies the updated position obtained by adding the velocity with the current position. The attraction process between male and female mayfly will be based on the current solution (i.e.) the best female will be attracted to the best male. On considering the minimization function, the velocity of the female is calculated as follows.

$$v_{ij}^{t+1}=\begin{cases} v_{ij}^{t}+a_1 \times e^{-\beta r_{mf}^{2}}\left(x_i^t - y_i^t\right),\ if\ f(y_i) > f(x_i)\ \& \\ v_{ij}^{t}+fl*r,\ if\ (y_i) \leq f(y_i) \end{cases} \tag{21}$$

In the above equation, $v_{ij}^{t}$ is the velocity of a female mayfly at time $t$ and $x_{ij}^{t}$ represent the position of a female adult at time $t$. $a_1$ and $a_2$ denotes the positive attraction constant. And they were used for calculating the social and cognitive components. $\beta$ represents the fixed visibility coefficient that retains the visibility of mayfly to others. $r_{mf}$ denotes the Cartesian distance among male and female mayflies. $fl$ denotes the random walk coefficient utilized when the female is not attracted to the male, and it moves randomly, $r$ signifies the random value [-1, 1].

### *4.2.5 Mating of mayflies*

The process of mating is performed in the following manner. The male and female mayflies are selected from the population. The selection process is done on the basis of fitness value. Two offspring are generated as a result of mating, and it is represented as follows.

$$offspring1=s*male+(1-s)*female \tag{22}$$

$$\text{offspring2}=\text{s}*\text{female}+(1-\text{s})*\text{male} \tag{23}$$

In Eq. (22) and Eq. (23), $male$ represent the male parent, and $female$ represents the female parent. $s$ represent random value. The velocity of offspring is set at zero initially.

### *4.2.6 Steps by step procedure of mayfly algorithm for optimal placement of Facts*

**Step1:** Start the process

**Step 2:** Initialize the population of male mayfly $x_i=1....N$ and velocity $v_m$ i.e. Eq. (16) and Eq. (17) and also initialize the population of female mayfly $y_i=1....N$ and velocity $v_f$ i.e. Eq. (20) and Eq. (21). Here consider two dimensions, namely bus number and size of the Facts devices.

**Step 3:** Fix the objective function and evaluate the solution to find the global best. Then update the position and velocity of a male and female mayfly. Then the objectives are calculated by the multiplication of the above formulation. The mathematical expression of the objective is given below,

$$objective=F1\times F2\times F3\times F4\times F5\times F6 \tag{24}$$

where $F1$ is a power loss, $F2$ is voltage deviation, $F3$ is investment cost, $F4$ is fuel cost, $F5$ is severity function index, $F6$ is line overload sensitivity index.

**Step 4:** Rank the mayflies based on fitness value and then make them mate. Eq. (18) to find the rank of mayflies.

**Step 5**: After the process of mating, the offspring are obtained. The mathematical expression of mating is shown in Eq. (22) and Eq. (23). The male and female offspring are separated randomly.

**Step 6:** Finally, the worst mayflies are replaced with the best solution.

**Step 7:** The best solution is found after replacing, and the process ends. If not found, the process continues from step 2.

Mayfly optimization is very suitable for finding the best location of Facts devices in IEEE 30, 118 and 300 bus systems. Flow chart of mayfly algorithm is illustrated in Figure 5. Mayfly is a recently developed optimization technique for solving optimization problems rapidly. The optimization separates the male and female mayfly to find the best one individually to make a mating process. Likewise, the Facts device's best locations are selected based on the six objective functions to increase the power transfer capability as well as secure the system. The key advantage of using mayfly optimization is rapid operation to find the best location and balance the system power from generation to consumption.

*Flow chart of the mayfly algorithm:*

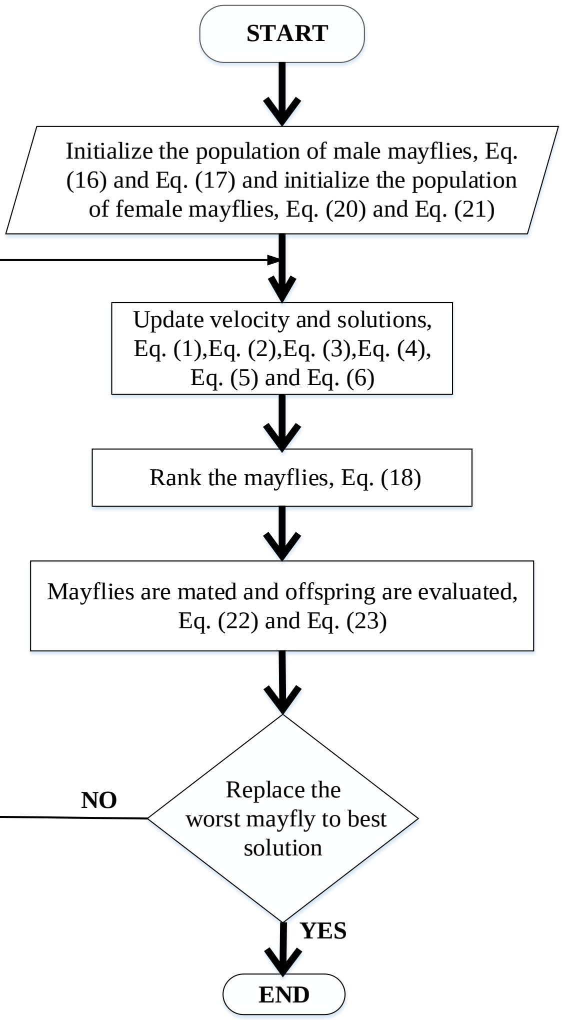


**Figure 5** Flow chart of mayfly algorithm

## 5. Result and discussion

In this paper, the security guard of four Facts devices, namely STATCOM, UPFC, IPFC, and TCSC, is used to calculate the transmission line losses. The first step is to find a proper location of Facts devices that were ensured to reduce the losses and carry a maximum amount of reactive power. And also consider three bus systems such as IEEE 30, 118, 300 bus systems. The Facts devices are placed in the incorrect location of these test buses on computing. Based on the Mayfly Optimization Algorithm, the location of Facts devices is obtained properly, and the performance of test bus IEEE 30, 118 and 300 bus calculates with or without Facts devices. The performance of the proposed Mayfly optimization algorithm parameters is shown in below Table 1. In the YYPO algorithm, description is considered for dimension, alpha, $I_{max}$, $I_{min}$ and number of iterations, and its ranges are 20, 0.5, 5, 10 and 20, respectively.

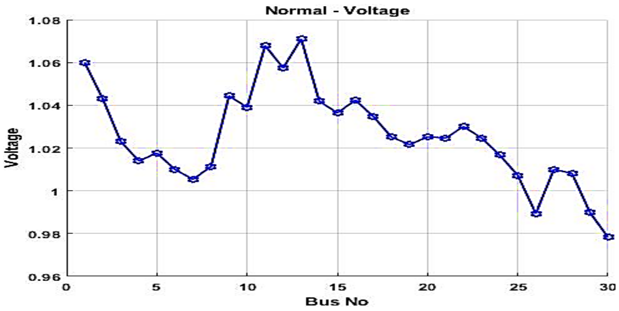
Similarly, the parameters of PSO are dimension, the number of indexes and iterations. Its ranges are 20, 20 and 20 individually. Likewise, the parameter of firefly is also observed. Descriptions of the firefly algorithm are dimension, alpha, gamma, beta-min and the number of iterations, and its values are 20, 0.5, 1, 1 and 20, respectively. And the parameter of the proposed algorithm is dimension, $I_{max}$, $I_{min}$ and number of iterations, and its ranges are taken as 20, 12, 10 and 10, respectively.

**Table 1** Parameter of Mayfly Optimization Algorithm

| Description | Algorithm | Ranges |
|---|---|---|
| Dimension | YYPO | 20 |
| Alpha | | 0.5 |
| $I_{max}$ | | 5 |
| $I_{min}$ | | 10 |
| Number of iteration | | 100 |
| Dimension | PSO | 20 |
| Number of indexes | | 20 |
| Number of iteration | | 100 |
| Dimension | FA | 20 |
| Alpha | | 0.5 |
| Gamma | | 1 |
| Beta-min | | 1 |
| Number of iteration | | 100 |
| Dimension | MA | 20 |
| $I_{max}$ | | 12 |
| $I_{min}$ | | 10 |
| Number of iteration | | 100 |

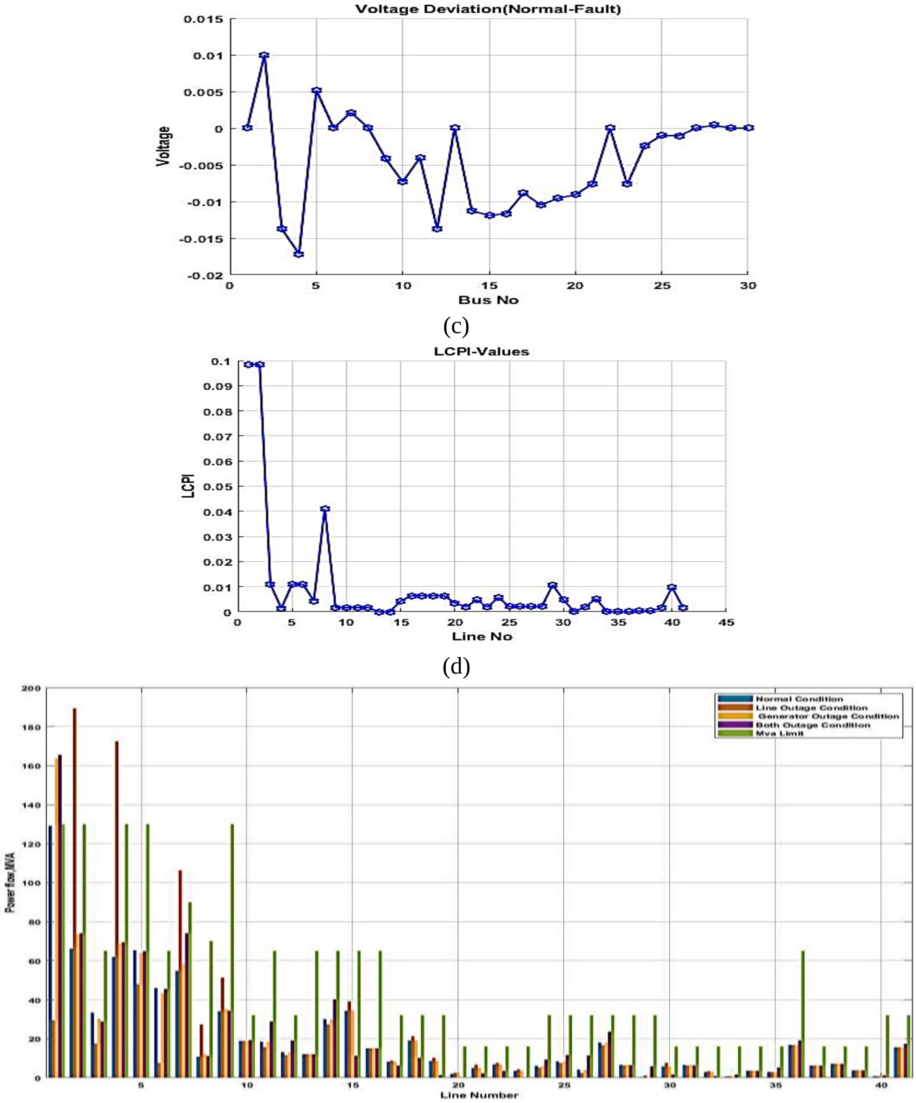
5.1 Analysis of the performance of the IEEE 30 bus system

The proposed method of the Mayfly algorithm is most effectively working to solve the power flow issues in the transmission line. It is the successful beginning of the proposed method. Several tests are carried out in a single device to visually analyse the power flow and fault, and the indirect losses are analysed by the advanced mayfly optimization method. A detailed review of the proposed method is given in the resulting section. In a transmission line, power may cause loss due to external disturbances. Voltage loss, power loss and voltage deviation under normal conditions are shown in Figure 6 (a), (b) and (c).



(a)

(b)



(c)

(d)

(e)

**Figure 6** Base case result of IEEE 30 bus system under normal condition (a) Voltage loss; (b) Power loss; (c) voltage deviation; (d) Variation of LCPI values; and (e) Variation of power flows in system severity function

Figure 6 (a) explain the transmission line voltage loss. Voltage losses are not constant, and they may vary depending on the fault occurring in the transmission line. The fault occurs in a line, reducing the voltage up to the end. Power loss is the important fault in a transmission line, which creates power cut, uninterrupted, and low-required power. Figure 6 (b) shows the power loss result under normal operation. The effect of both losses is occurring up to the end-users. Voltage deviation is the difference between the voltage at a point and the reference voltage. Under the normal operating condition, no voltage deviation occurs in the transmission line. Similarly, the Line collapse proximity index (LCPI) and power flow in severity function were also analysed.

## 5.2 Performance analyzed after placing the Facts devices

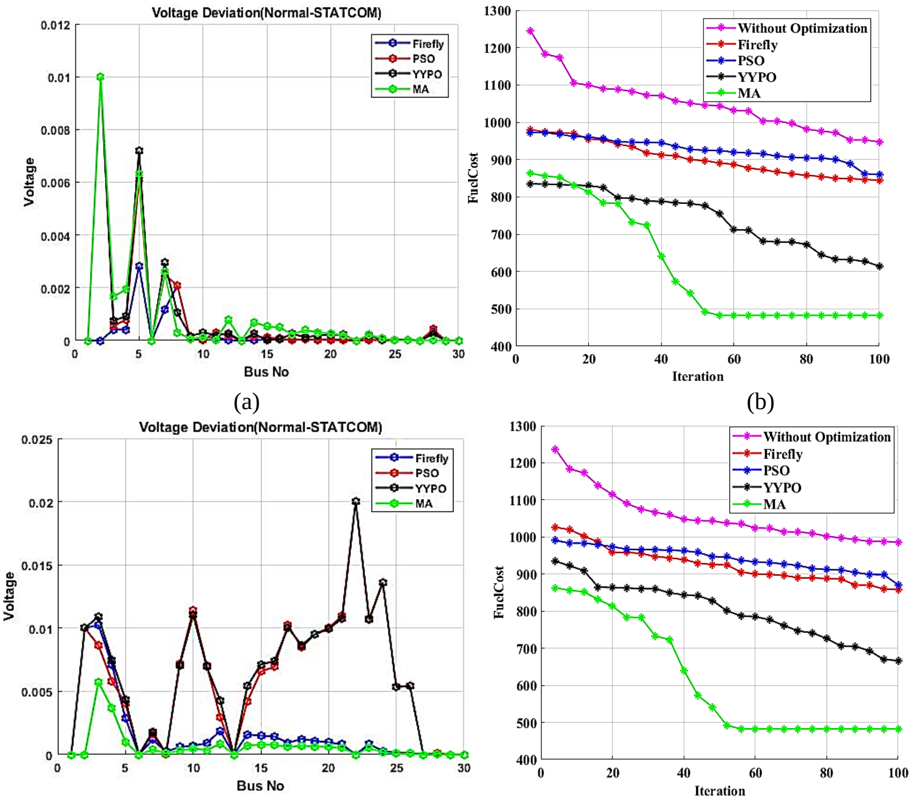
The four Facts devices are fitted in the proper locations of the transmission line. Every device is fitted in the system to analyse the performance using the Mayfly algorithm. These four Facts devices are divided into five different categories. Namely, single-type Facts allotment like STATCOM, dual-type Facts allotment like

UPSC, triple-type Facts allotment like IPFC, quadruple-type Facts allotment like TCSC and the last one is multi-type Facts allotment denoted by STATCOM, UPFC, IPFC and TCSC suitably used in Mayfly optimization algorithm. In addition, the scenario is divided into four various categories, namely,

**Case 1:** STATCOM device using Mayfly algorithm
**Case 2:** UPFC device used in Mayfly algorithm
**Case 3:** IPFC device used in Mayfly algorithm
**Case 4:** TCSC device allotment in algorithm

### Case 1:

STATCOM is one of the commonly used Facts devices. STATCOM should be placed in the proper location of the transmission line were needed to reduce the power loss. Here the Facts device of STATCOM was carrying in the Mayfly optimization algorithm to reduce the cost, losses and deviation. Figure 7 shows the graphical explanation of voltage deviation after connecting the STATCOM device. Voltage deviation and fuel cost of generation outage in proposed and existing methods are illustrated in Figure 7 (a) and (b), respectively. In the proposed approach, initially, the voltage loss is high after a few seconds, the STATCOM takes rapid action to minimize the loss and reduce the fuel cost below 600. Similarly, the voltage deviation and fuel cost in line outage are shown in Figures 7 (c) and (d). Compared to existing methods, the voltage deviations and fuel cost are more minimized in the proposed approach. Loss is reduced to 0 voltage as well cost of fuel is reduced below 700. Figure 7 (e) and (f) present the voltage deviation and fuel cost graphical model in both outages. As compared to previous methods, MA rapidly solves the error and more effectively reduces the fuel cost.

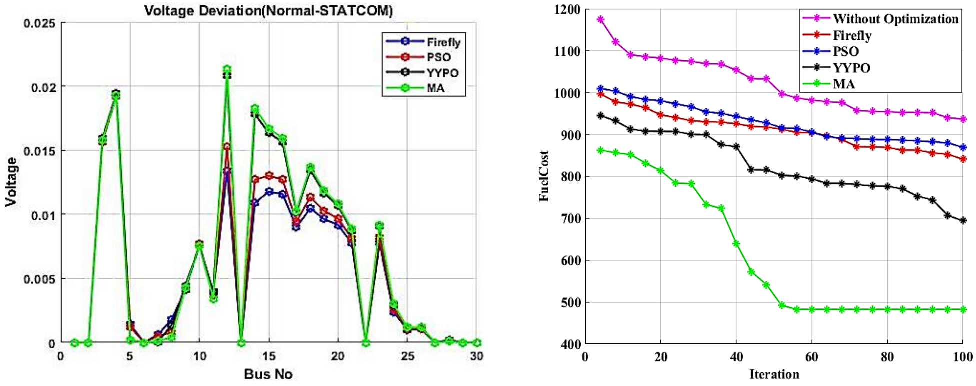


(a)

(b)

(c)

(d)



(e) (f)

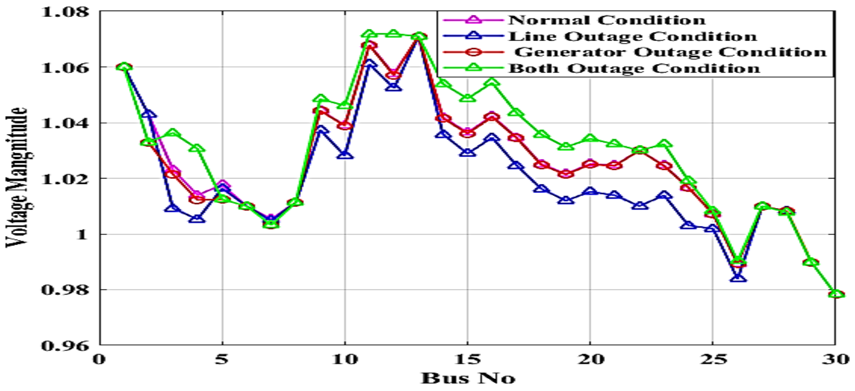
**Figure 7** Analysis of after connecting STATCOM device in IEEE 30 bus system (a) Voltage deviation in generation outage; (b) Fuel cost in generation outage; (c) Voltage deviation in line outage; (d) Fuel cost in line outage; (e) Voltage deviation in both outage; and (f) Fuel cost in both outage

5.3 Compare to existing methods

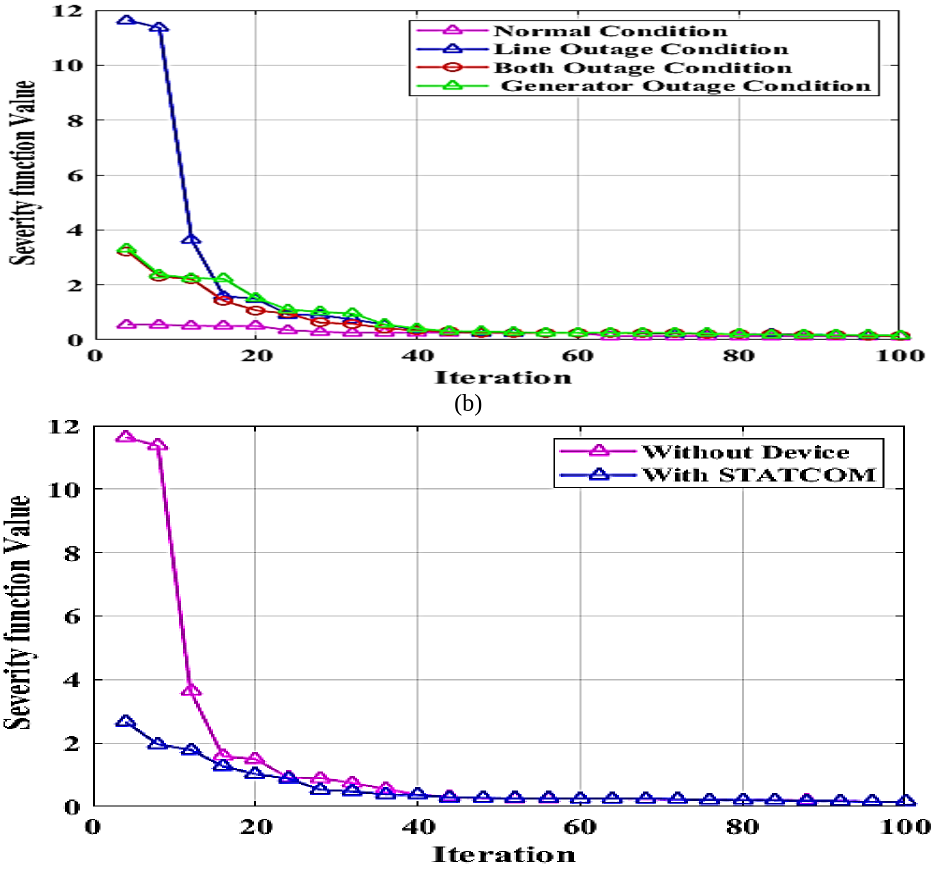
The novel mayfly optimization algorithm applied STATCOM device effectively reduces the loss and voltage deviation. The proposed method of STATCOM fitting transmission line increases the power demand because it absorbs or generates the reactive power depending on the output voltage of the AC system. Table 2 contains the STATCOM performance in present and previous approaches. Performance of STATCOM is analysed for without device and with the device. At the circumstance of STATCOM, four optimization approaches are used to analyse the system performance.

**Table 2** Performance of STATCOM placement

| **Algorithm** | **Generation Outage** | | | **Line Outage** | | | **Both Outage** | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Bus no** | **Power loss** | **Fuel cost** | **Bus no** | **Power loss** | **Fuel cost** | **Bus no** | **Power loss** | **Fuel cost** |
| Without facts devices | - | 10.8856 | 810.845 | - | 10.8856 | 601.5602 | - | 10.8856 | 814.14 |
| Fire fly | 2, 4 | 9.2825 | 498.8075 | 2, 4 | 23.9828 | 489.1577 | 5,7 | 11.7863 | 462.205 |
| PSO | 2 ,4 | 9.47 | 470.4895 | 10, 21 | 22.8158 | 489.1577 | 15, 18 | 12.2342 | 435.4097 |
| YYPO | 2, 5 | 10.9379 | 432.6385 | 25, 27 | 25.657 | 505.0818 | 12, 15 | 9.2464 | 537.5167 |
| MA | 2 ,4 | 12.0418 | 447.6052 | 10, 20 | 18.2873 | 511.7535 | 5,7 | 9.53 | 592.6951 |



(a)



(b)

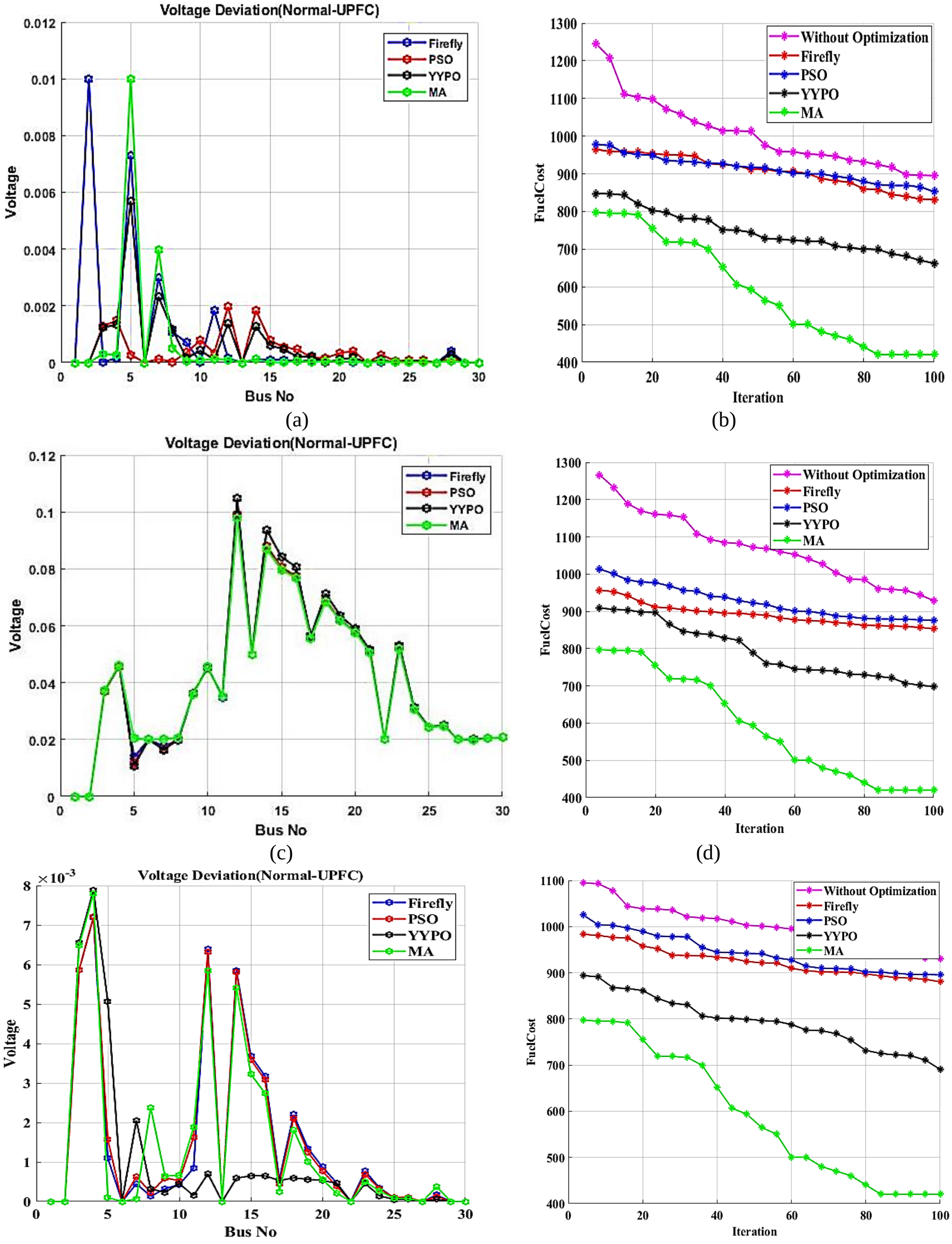
(c)

**Figure 8** Analyze various conditions of STATCOM connected IEEE 30 bus system (a) Voltage deviation; (b) characteristics of system severity function; and (c) System severity function with and without device

Figure 8 presents voltage deviation comparison of system severity function characteristics and severity function with or without the device. Four various optimizations are used to analyse the performance of the system severity function. Among four optimizations, MA gives a better outcome, reduced to nearly zero value. Figure 8(c) shows the severity function with or without the device. For the absence of device, the severity function is more in the first iteration, i.e. 11.8 value in the first iteration; during the presence of the device in the system, severity value is low in the first iteration, that is severity value is 3 in the first iteration.

**Case 2:**

In this case study, another Facts device of Unified Power Flow Controller (UPFC) interacts in the transmission line to reduce the losses. UPFC provide fast-acting reactive power on a high voltage transmission network. UPFC contain two back to back converter. Both of them are connected with the AC structure due to inductive reactance communicating through the Voltage Source Converters transformer. UPFC's best location is selected for the mayfly optimization algorithm. It selects the best location based on the six objective functions in a 30 bus system where find the high objective function value that is the best location of UPFC integration.



(a) (b)

(c) (d)

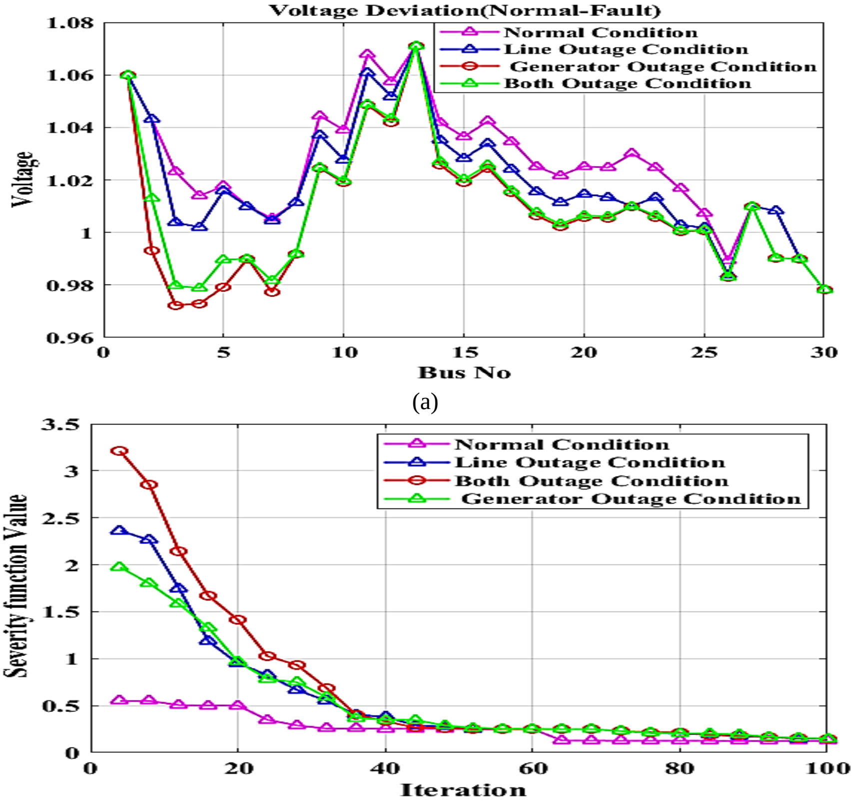
(e) (f)

**Figure 9** Analysis of after connecting UPFC device in IEEE 30 bus system (a) Voltage deviation in generation outage; (b) Fuel cost in generation outage; (c) Voltage deviation in line outage; (d) Fuel cost in line outage; (e) Voltage deviation in both outage; and (f) Fuel cost in both outage

After linking the mayfly optimization-based UPFC device on a transmission line, the voltage deviation is reduced compared to the existing method of firefly, PSO and YYPO. Figure 9 compares the proposed method and the existing methods with generation outage, line outage and both outage. For generation outage, line outage, and both generation and line outage, the cost of fuel is low in the MA optimization approach. Without optimization approach in both outage circumstances, the cost is low to 1100 at the 10th iteration. But in MA optimization, the cost is reduced to below 700 in the 10th iteration. Table 3 shows the performance outcome of UPFC at various optimization approaches. Three conditions are used to analyse the UPFC performance: generation outage, line outage, and both outages.

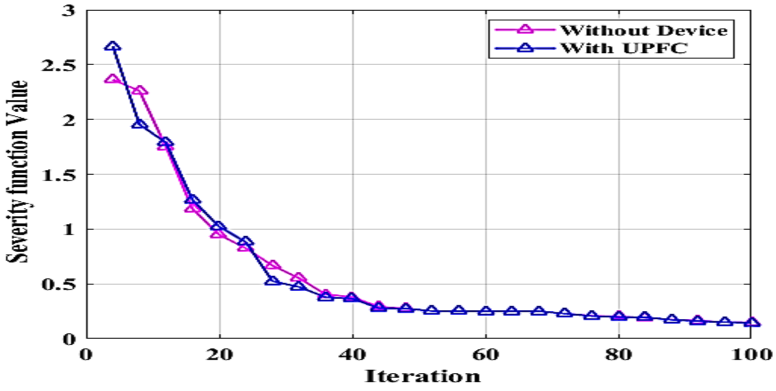
**Table 3** Performance of UPFC placement

| Algorithm | Generation Outage | | | Line Outage | | | Both Outage | | |
|---|---|---|---|---|---|---|---|---|---|
| | Bus no | Power loss | Fuel cost | Bus no | Power loss | Fuel cost | Bus no | Power loss | Fuel cost |
| Without facts devices | - | 10.8856 | 810.845 | - | 10.8856 | 693.5203 | - | 10.8856 | 988.2569 |
| Fire fly | 22, 24 | 9.3178 | 512.9099 | 22, 24 | 9.3178 | 512.9099 | 10, 21 | 31.7465 | 415.4227 |
| PSO | 5, 7 | 9.8669 | 487.482 | 5, 7 | 9.8669 | 487.482 | 2, 5 | 28.6925 | 461.7777 |
| YYPO | 22, 24 | 8.2891 | 509.6814 | 22, 24 | 8.2891 | 509.6814 | 2, 6 | 29.2856 | 490.7998 |
| MA | 10, 21 | 8.5136 | 539.7487 | 10, 21 | 8.5136 | 539.7487 | 10, 21 | 24.9518 | 521.9149 |



(a)

(b)



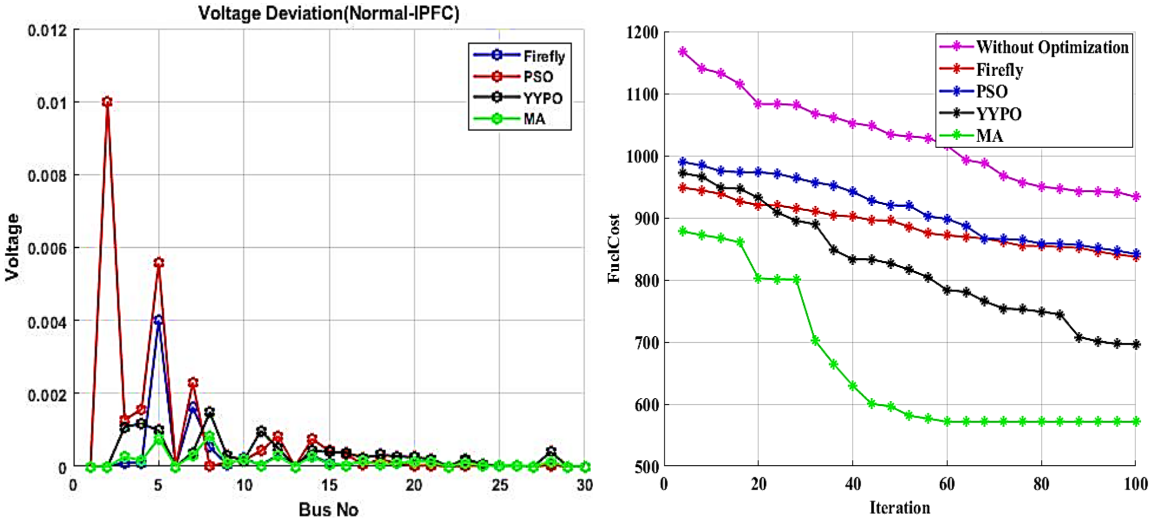
(c)

**Figure 10** Analyzed various conditions of UPFC connected IEEE 30 bus system (a) Voltage deviation; (b) characteristics of system severity function; and (c) System severity function with and without device

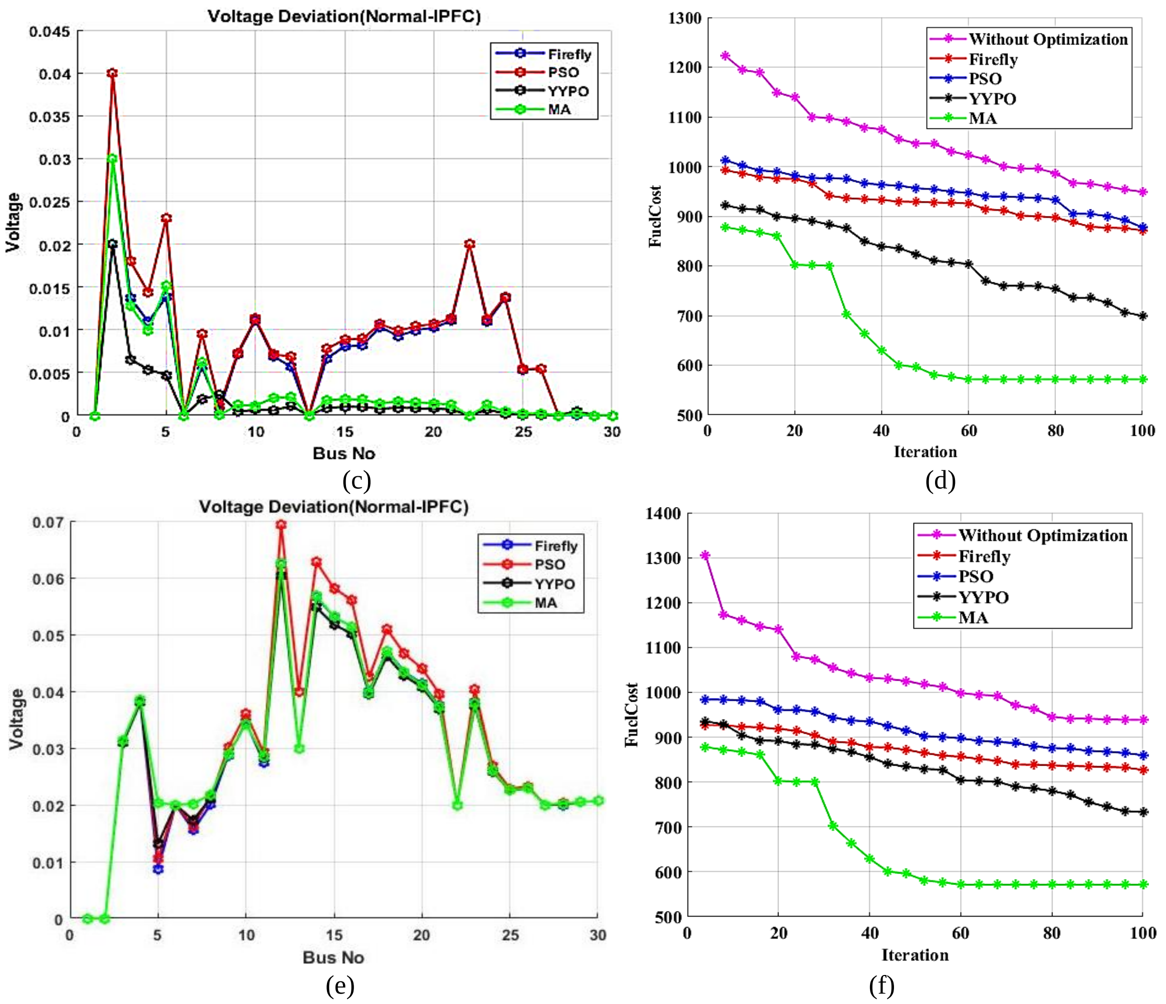
Figure 10 shows the voltage deviation, severity function characteristics, and with and without device severity function characteristics. Without the device, the severity function is not reduced. After the linkage of UPFC, the severity function is reduced much.

**Case 3:**

Here, the Facts device of the Interline power flow controller (IPFC) was interconnected in the transmission line by means of the novel mayfly optimization algorithm. IPFC adapted the two dimensions and the series voltage point to manage the power flow on a transmission line. After interacting with the IPFC device, the difference between the voltage at the point and the reference voltage is a high rating at the starting period of power flow. A few minutes later, the power flows constantly without any deviation. The devices are placed in a suitable location to reduce the voltage deviation, power outage, generation outage and fuel cost. Based on the objective function value, the MA chooses the best location for the device. Mayfly optimization-based IPFC and the existing methods are compared in a graphical representation which is shown in Figure 11.



(a) (b)



(c) (d)

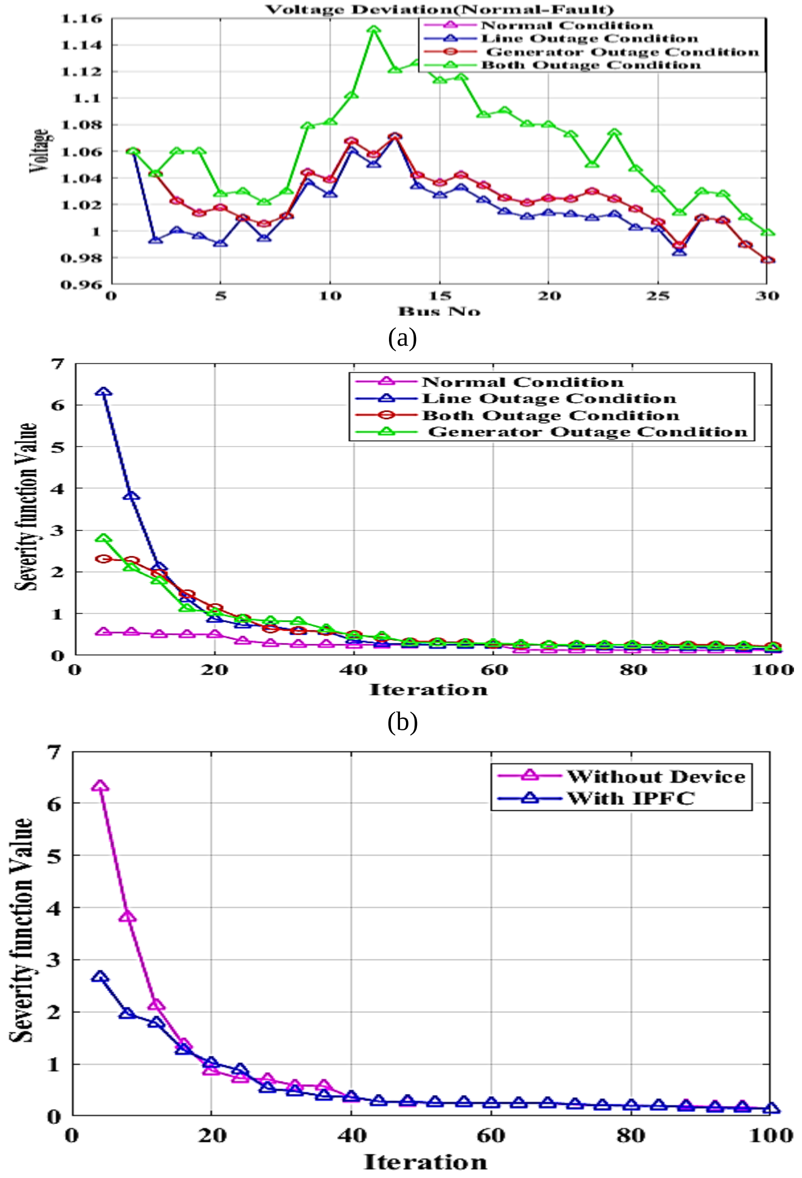
(e) (f)

**Figure 11** Analysis of after connecting IPFC device in IEEE 30 bus system (a) Voltage deviation in generation outage; (b) Fuel cost in generation outage; (c) Voltage deviation in line outage; (d) Fuel cost in line outage; (e) Voltage deviation in both outage; and (f) Fuel cost in both outage

Figure 11 illustrates the IPFC outcome of the existing and proposed MA approach at various conditions like line outage, generation outage and both outages. In three circumstance conditions, MA reduces the fuel cost very effectively as the IPFC is placed in the best location of the system. Observed values of the best location, power loss and fuel loss in previous and present approaches are shown in Table 4. IPFC connected 30 bus systems with and without severity function are sketched in Figure 12 (c) without IPFC, the severity function is 6.5 value at 1st iteration. But in IPFC based system, the initial value of severity function is 2.8.

**Table 4** Performance of IPFC placement

| **Algorithm** | **Generation Outage** | | | **Line Outage** | | | **Both Outage** | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Bus no** | **Power loss** | **Fuel cost** | **Bus no** | **Power loss** | **Fuel cost** | **Bus no** | **Power loss** | **Fuel cost** |
| Without facts devices | - | 10.8856 | 893.6317 | - | 10.8856 | 33.1721 | - | 10.8856 | 810.845 |
| Fire fly | 5, 7, 2 | 10.0016 | 424.4134 | 2, 5, 7 | 29.4319 | 468.4767 | 9, 11, 6 | 12.3021 | 441.2579 |
| PSO | 10, 20, 9 | 10.9723 | 375.2779 | 2, 5, 7 | 36.0268 | 390.7157 | 9, 11, 6 | 11.6462 | 468.8283 |
| YYPO | 6, 7, 4 | 9.216 | 496.8576 | 22,24,25 | 17.6465 | 572.3925 | 25,26,24 | 12.3698 | 479.1435 |
| MA | 6, 7, 4 | 9.0213 | 582.5857 | 10, 20, 9 | 29.5269 | 477.1114 | 12, 13, 4 | 9.4128 | 628.1952 |



(a)

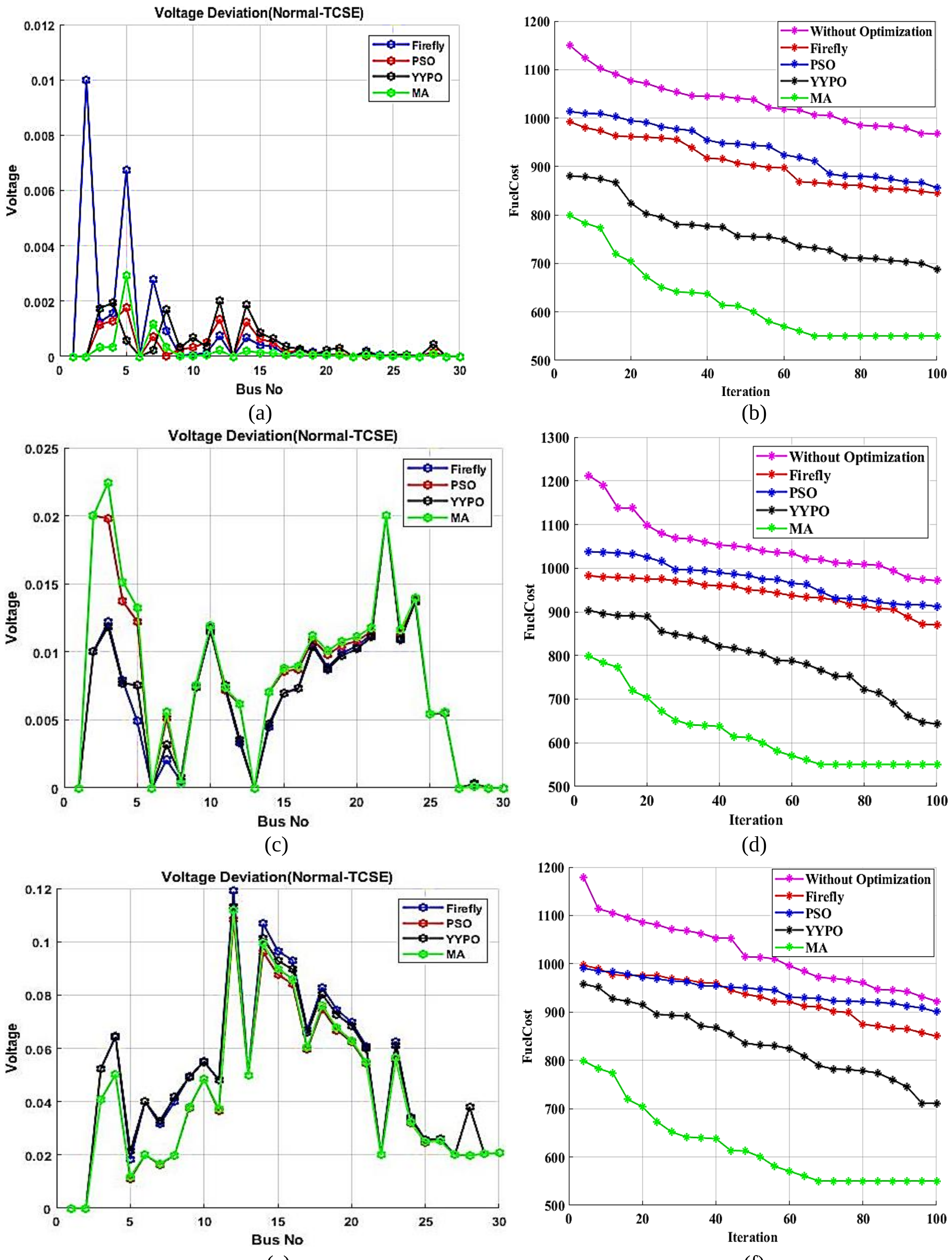
(b)

(c)

**Figure 12** Analyze various conditions of IPFC connected IEEE 30 bus system (a) Voltage deviation; (b) characteristics of system severity function; and (c) System severity function with and without device

**Case 4:**

In this case, Thyristor Controller Series Compensator (TCSC) was integrated into the transmission line to analyze its performance. Find a suitable place for fitting the TCSC device on the transmission line. As a result, improves the transmission line capacity and reduces active and reactive power loss. The best location of TCSC is identified by MA, which optimizes the six objective functions to find the best solution. Voltage deviation and fuel cost of previous and proposed approach at various conditions of line outage, generation outage, and both outages are illustrated in Figure 13. MA most effectively reduce the voltage deviation and fuel cost. For both outages, fuel cost is reduced below 700 in the MA optimization approach.



(a) (b)

(c) (d)

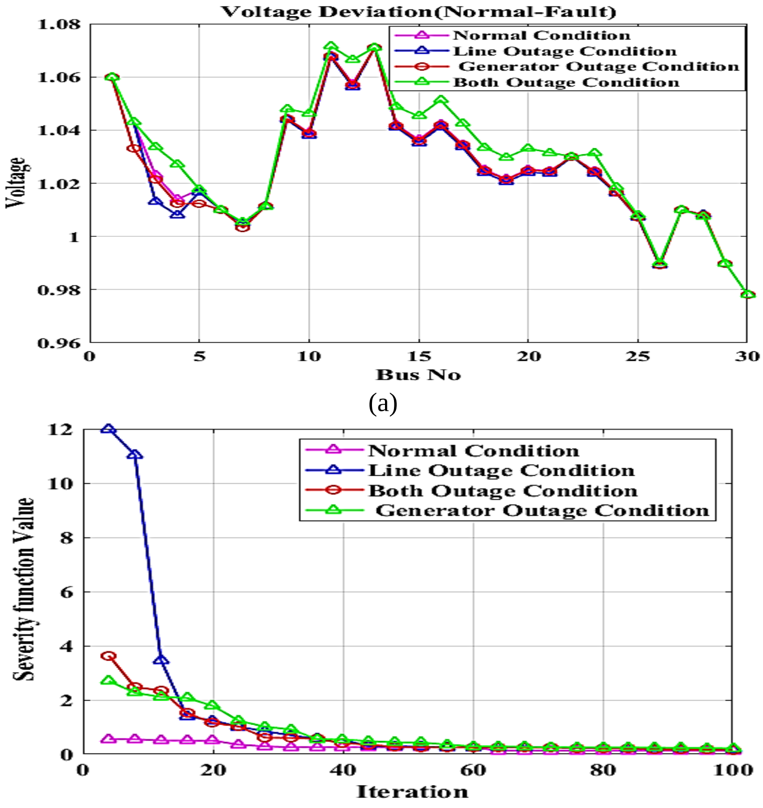
(e) (f)

**Figure 13** Analysis of after connecting TCSC device in IEEE 30 bus system (a) Voltage deviation in generation outage; (b) Fuel cost in generation outage; (c) Voltage deviation in line outage; (d) Fuel cost in line outage; (e) Voltage deviation in both outage; and (f) Fuel cost in both outage

Table 5 presents the TCSC performance with or without the device. The performance analysis is focused on the best location, power loss and fuel cost for generation outages, line outages and both outages. The best location of the proposed approach is buses no.12, 15 and 23 at generation outage. Similarly, the best location of TCSC at line outage is bus no. 2, 6, 28. And both outage period, the best location of TCSC is buses no. 2, 5, 7. Figure 14 presents voltage deviation, severity function characteristics, and severity function with and without the device. Without the device, the value of severity is 12 in 1$^{st}$ iteration, but with the TCSC device, the value of severity is 2.9 in 1$^{st}$ iteration.

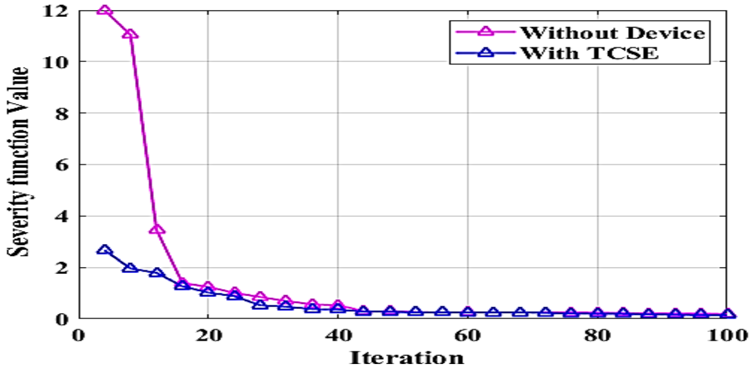
**Table 5** Performance of TCSC placement

| **Algorithm** | **Generation Outage** | | | **Line Outage** | | | **Both Outage** | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Bus no** | **Power loss** | **Fuel cost** | **Bus no** | **Power loss** | **Fuel cost** | **Bus no** | **Power loss** | **Fuel cost** |
| Without facts devices | - | 10.8856 | 810.845 | - | 10.8856 | 461.4956 | - | 10.8856 | 1250.3614 |
| Fire fly | 12, 15, 23 | 10.8881 | 473.2026 | 10, 21, 23 | 39.1142 | 547.4248 | 22, 24, 25 | 14.6625 | 470.4275 |
| PSO | 15, 23, 24 | 9.4098 | 485.703 | 10, 20, 9 | 50.9698 | 438.3922 | 2, 5, 7 | 16.1922 | 427.5711 |
| YYPO | 12, 15, 23 | 8.153 | 548.3774 | 10, 21, 23 | 38.4132 | 511.5146 | 6, 7, 4 | 15.3933 | 446.1715 |
| MA | 12, 15, 23 | 9.9369 | 466.1263 | 2, 6, 28 | 58.2935 | 443.2013 | 2, 5, 7 | 15.9171 | 536.5961 |



(a)

(b)



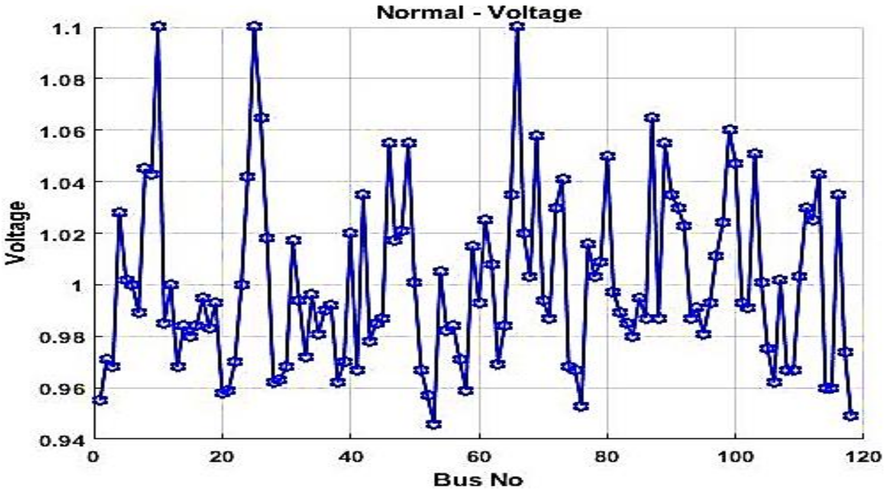
(c)

**Figure 14** Analyze various conditions of TCSC connected IEEE 30 bus system (a) Voltage deviation; (b) characteristics of system severity function; and (c) System severity function with and without device

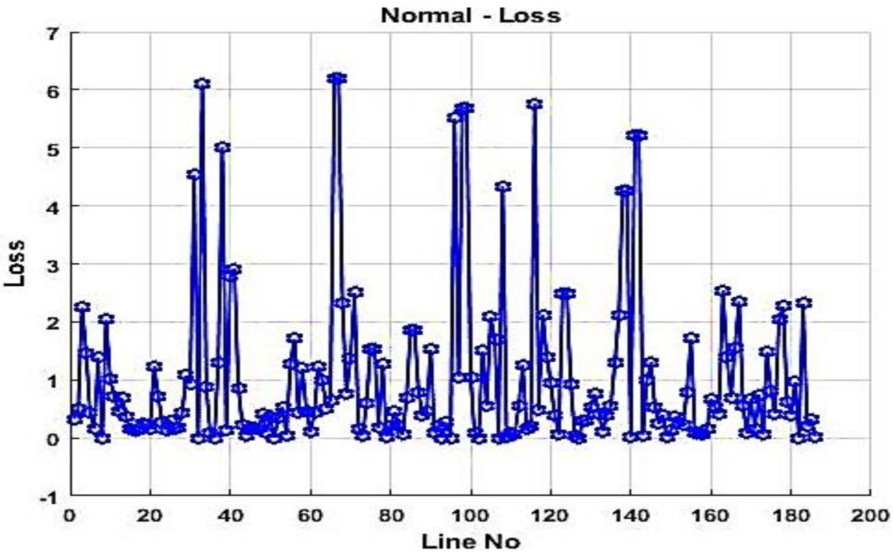
The proposed method was the most effective to reduce the fuel cost. Because the Facts devices can generate or absorb the reactive power under normal or critical conditions and stable power flows in the transmission line, there is no need to integrate an extra distribution generator. Each Facts device was separately explained graphically. Initial fuel cost is also low in the mayfly optimization-based Facts devices.

### 5.4 Analysis of the performance of IEEE 118 bus system

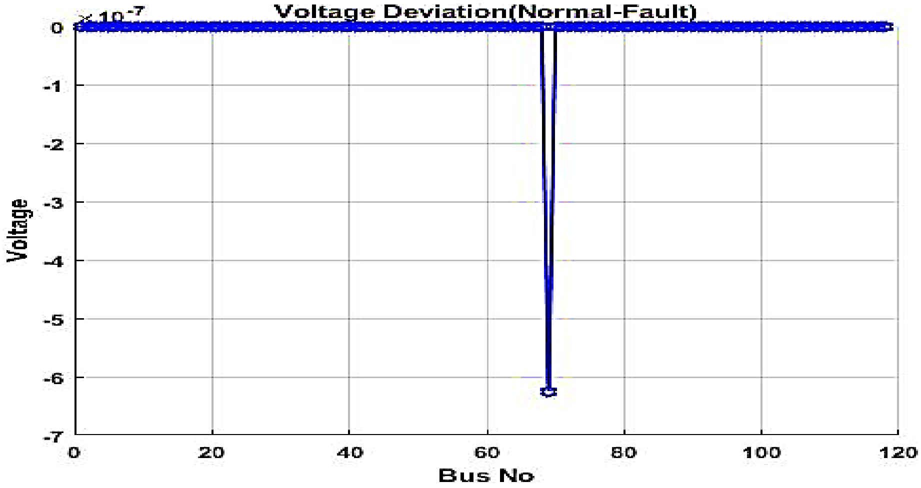
The IEEE 118 bus system contains a high-quality transformer, lines, shunt reactor and generators. Estimate the voltage, power loss, and real and reactive power parameters are effective. Normally the load demand is calculated. But in this method, the fuel cost of generation is also calculated. The data which is obtained in this bus is mostly identical. The system is analyzed without fitting the Facts devices. For the absence of Facts devices, voltage loss, power loss, voltage deviation and LCPI value are analysed, which is sketched in Figure 15. Voltage deviation reaches the peak value at the period of 70 bus.



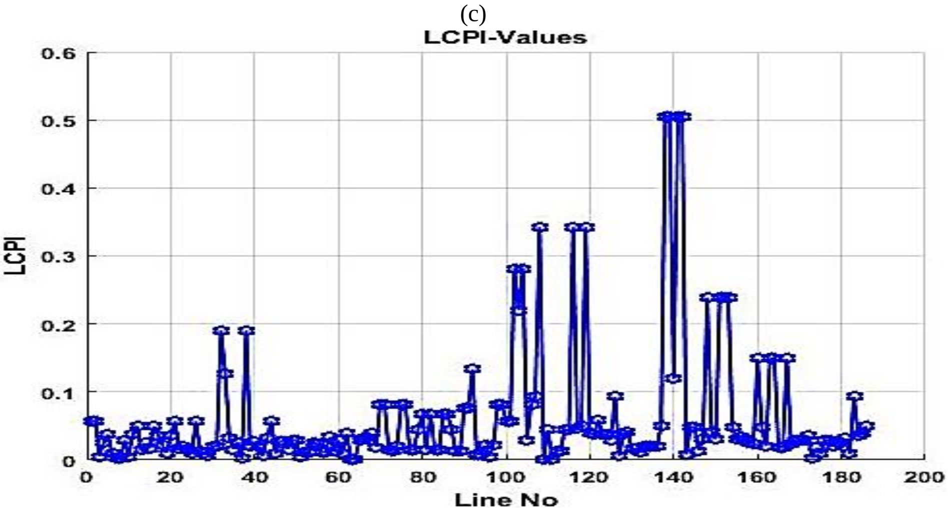
(a)


Normal - Loss
Loss
Line No
7
6
5
4
3
2
1
0
-1
0
20
40
60
80
100
120
140
160
180
200

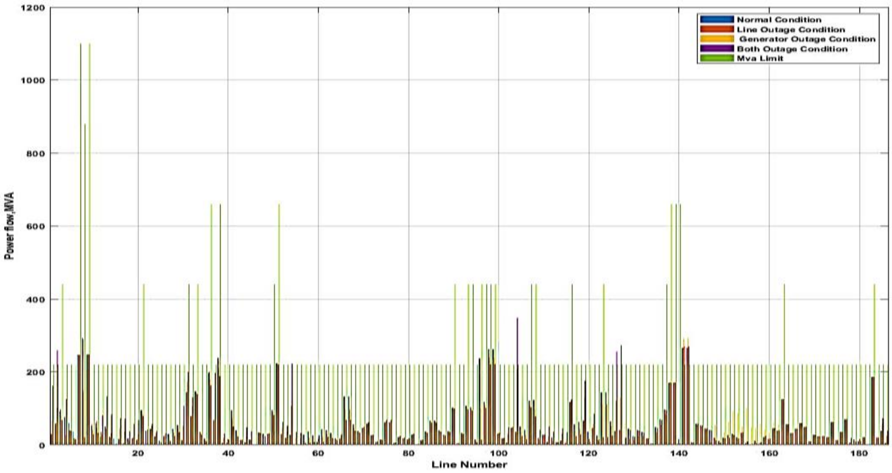
(b)


Voltage Deviation(Normal-Fault)
× 10^-7
Voltage
Bus No
0
-1
-2
-3
-4
-5
-6
-7
0
20
40
60
80
100
120

(c)


LCPI-Values
LCPI
Line No
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140
160
180
200

(d)



(e)

**Figure 15** Base case result of IEEE 118 bus system under normal condition (a) Voltage loss; (b) Power loss; (c) voltage deviation; (d) Variation of LCPI values; and (e) Variation of power flows in system severity function

## 5.5 Performance analysis after connecting Facts devices

In this section, the Facts devices fit in the proper location of the bus system. Several operations are held in each Facts device to analyze the performance achieved by the mayfly algorithm. Mayfly selects the best location for the Facts devices based on the six objectives. The main scope is to reduce the objectives via Facts devices, so the best place is taken at the highest value of the six objectives. The performance of the Facts devices is analysed individually. It is divided into four cases; all of them are performed in the mayfly optimization algorithm to find the proper location and best values.

**Case A:** Applying mayfly algorithm in STATCOM device

**Case B:** Applying mayfly algorithm in UPFC device

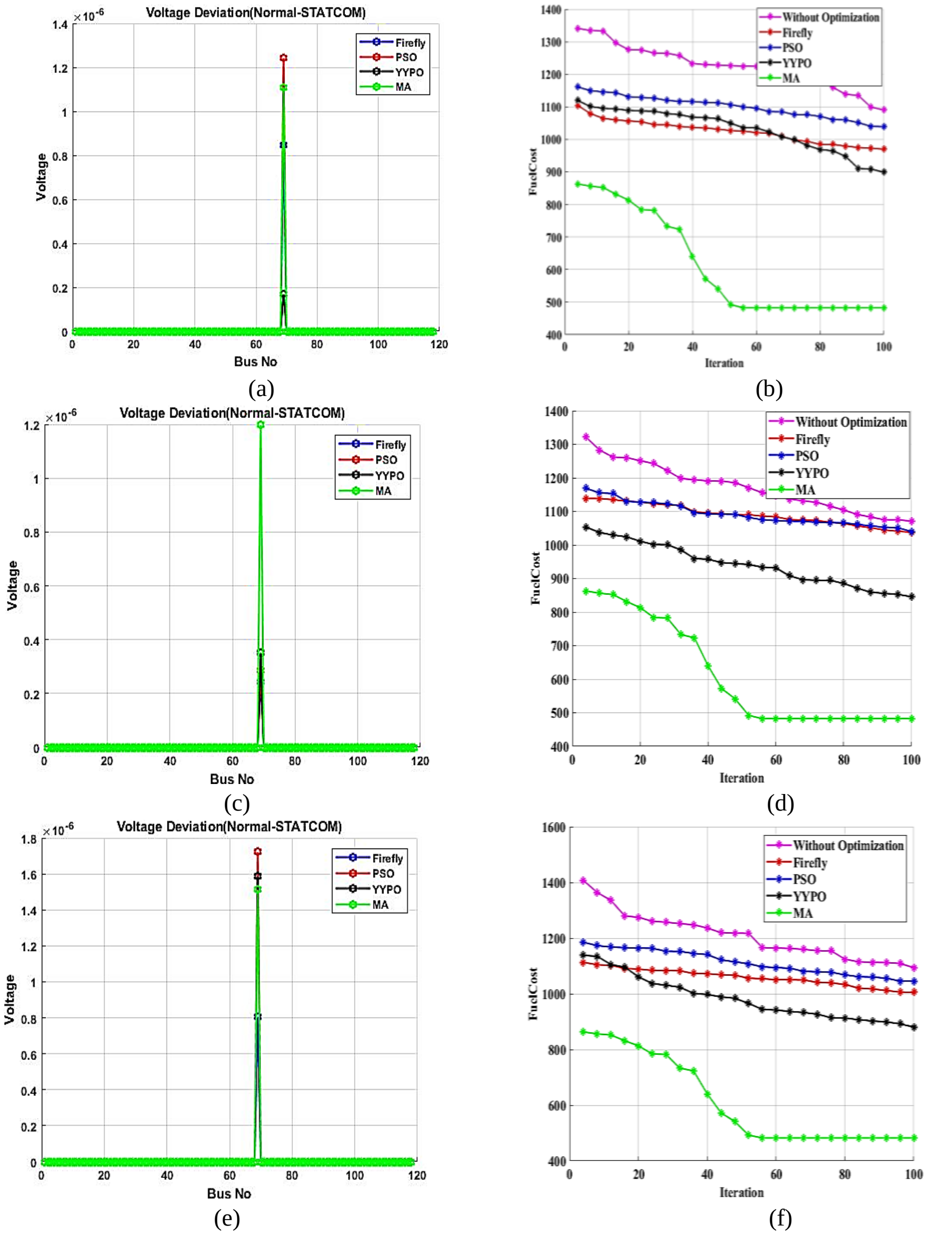
**Case C:** Applying mayfly algorithm in IPFC device

**Case D:** Applying mayfly algorithm in TCSC device

### ***Case A:*** *Applying mayfly algorithm in STATCOM device*

The STATCOM device is fitted into the proper location of the transmission line to remove the losses. The STATCOM device carried in the mayfly optimization algorithm to reduce the losses effectively. Figure 16 compares mayfly optimization-based STATCOM device performance and existing method performance. All optimization reaches the highest peak value at the bus no. 70, but the deviation is varied, PSO varied at 1.29 * $10^{-6}$, proposed MA varied from 0.1 to $1.16*10^{-6}$. Similarly, the cost of fuel is also reduced to 900. It shows the proposed method is more advantages than the existing methods.

The mayfly optimization-based STATCOM device reaches the peak value in bus no 70. STATCOM is augmenting the power system steadiness and considerably cutting down the fuel and device costs. It reduced the fuel cost at both outages below 800, which is the lowest cost compared to the existing. Table 6 shows the comparison value of the proposed STATCOM and the existing STATCOM method. Both proposed and existing techniques generation outage, line outage, and outage values are analysed. Moreover, outages fuel cost, power loss and the best location STATCOM are observed. For proposed MA, the best location of generation outage is bus no. 4 and 5, and line outage best location is bus no. 16 and 17 and the best location of both outages are bus no. 1, 2.



(a) (b) (c) (d) (e) (f)

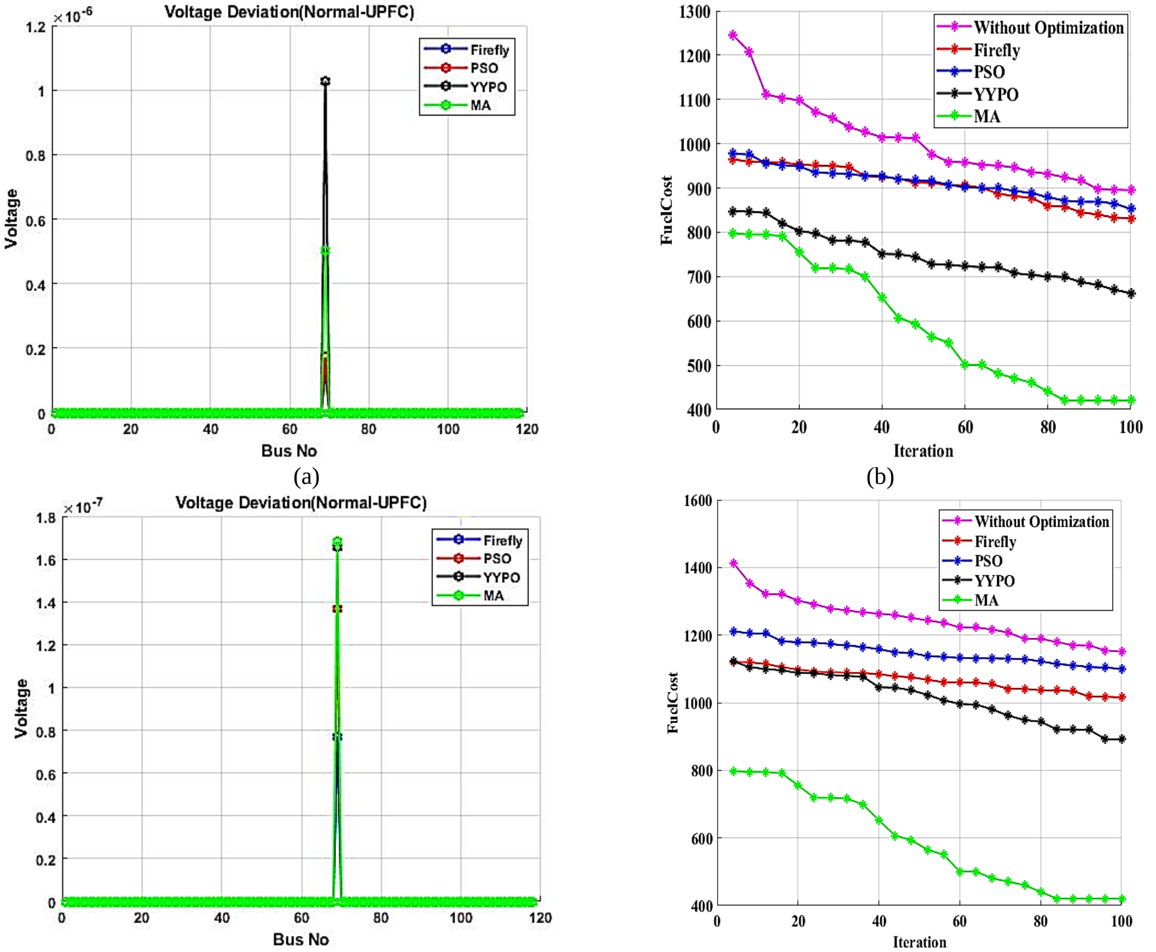
**Figure 16** Analysis of after connecting STATCOM device in IEEE 118 bus system (a) Voltage deviation in generation outage; (b) Fuel cost in generation outage; (c) Voltage deviation in line outage; (d) Fuel cost in line outage; (e) Voltage deviation in both outage; and (f) Fuel cost in both outage

**Table 6** Analysis of STATCOM performance

| Algorithm | Generation Outage | | | Line Outage | | | Both Outage | | |
|---|---|---|---|---|---|---|---|---|---|
| | Bus no | Power loss | Fuel cost | Bus no | Power loss | Fuel cost | Bus no | Power loss | Fuel cost |
| Without facts devices | - | 194.0901 | 810.845 | - | 194.0901 | 810.845 | - | 194.0901 | 678.9898 |
| Fire fly | 6, 7 | 200.5318 | 467.2114 | 5, 6 | 205.2675 | 499.8551 | 5, 6 | 198.606 | 438.785 |
| PSO | 1, 2 | 200.168 | 449.9379 | 11, 12 | 207.4351 | 467.9089 | 5, 6 | 200.8948 | 457.6742 |
| YYPO | 1, 3 | 201.057 | 549.062 | 5, 11 | 210.8121 | 536.847 | 5, 6 | 199.5968 | 405.1823 |
| MA | 4, 5 | 202.5308 | 535.0836 | 16, 17 | 206.1116 | 576.6575 | 1, 2 | 200.4055 | 469.3726 |

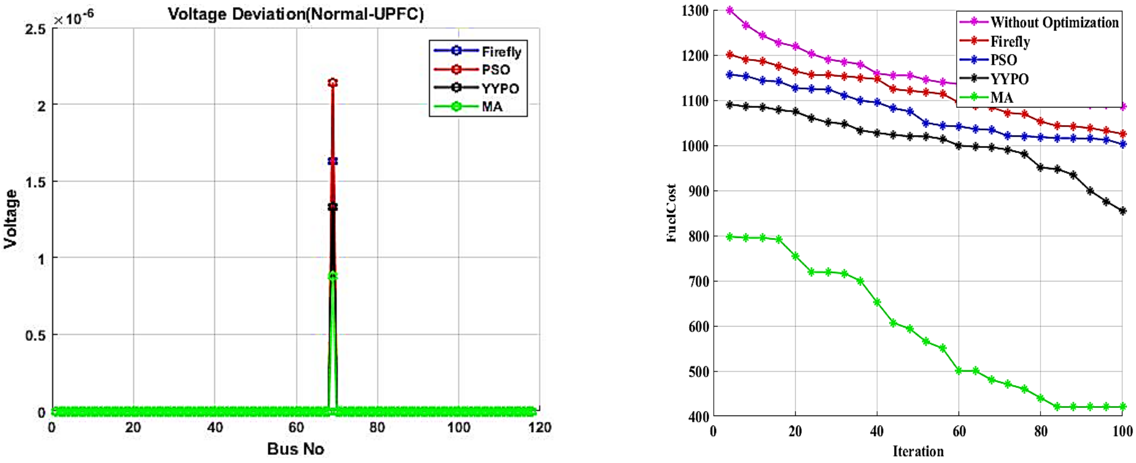
***Case B:*** *Applying mayfly algorithm in UPFC device*

Here, mayfly optimization-based UPFC is placed in the proper location of the transmission line to mitigate the losses. UPQC contain two back to back inverter sharing a common dc link. The two source inverters reduce the harmonics, voltage loss and power loss and maintain the dc-link constant. Figure 17 compares the existing and proposed methods in a graphical model. At the 70th bus, all the techniques reach the highest peak value, and firefly reaches $1.2*10^{-6}$ voltage peak value at bus no.70. In the proposed approach, the MA varied from $0.1*10^{-6}$ to $0.5*10^{-6}$ at bus no.70. After that, it maintains $0.1*10^{-6}$ constantly. For both outages, the fuel cost is reduced to below 1000, which is the lowest cost compared to the existing techniques of UPFC.



(a) (b)

(c) (d)



(e) (f)

**Figure 17** Analysis of after connecting UPFC device in IEEE 118 bus system (a) Voltage deviation in generation outage; (b) Fuel cost in generation outage; (c) Voltage deviation in line outage; (d) Fuel cost in line outage; (e) Voltage deviation in both outage; and (f) Fuel cost in both outage

The UPFC based novel approach has efficiently detected the optimal location for placement to improve the power system steadiness and decrease fuel and device costs. Table 7 represent the performance of UPFC with or without Facts devices. The performance of the UPFC with and without the device is analysed with three conditions such as generation outage, line outage, and both outages. Power loss, fuel cost, and the best location of UPFC are observed in these conditions. In the proposed MA approach, the best location of UPFC at generation outage condition bus no. 38,65, similarly, the best location of UPFC in line outage is bus no. 4, 11 and the best location of UPFC in both outages is bus no. 23, 32.

**Table 7** Analysis of UPFC performance

| **Algorithm** | **Generation Outage** | | | **Line Outage** | | | **Both Outage** | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Bus no** | **Power loss** | **Fuel cost** | **Bus no** | **Power loss** | **Fuel cost** | **Bus no** | **Power loss** | **Fuel cost** |
| Without facts devices | - | 194.0901 | 810.845 | - | 194.0901 | 903.0245 | - | 194.0901 | 742.6218 |
| Fire fly | 38, 65 | 200.1288 | 445.4143 | 2, 12 | 201.0938 | 403.5112 | 47, 69 | 201.8427 | 534.9925 |
| PSO | 42, 49 | 200.6335 | 470.0478 | 5, 6 | 202.0099 | 447.2525 | 47, 69 | 201.5684 | 470.1995 |
| YYPO | 42, 49 | 200.9173 | 499.7628 | 5, 6 | 200.8329 | 467.7693 | 42, 49 | 201.0336 | 470.711 |
| MA | 38, 65 | 199.6808 | 501.974 | 4, 11 | 203.8027 | 618.7775 | 23, 32 | 203.6598 | 624.7619 |

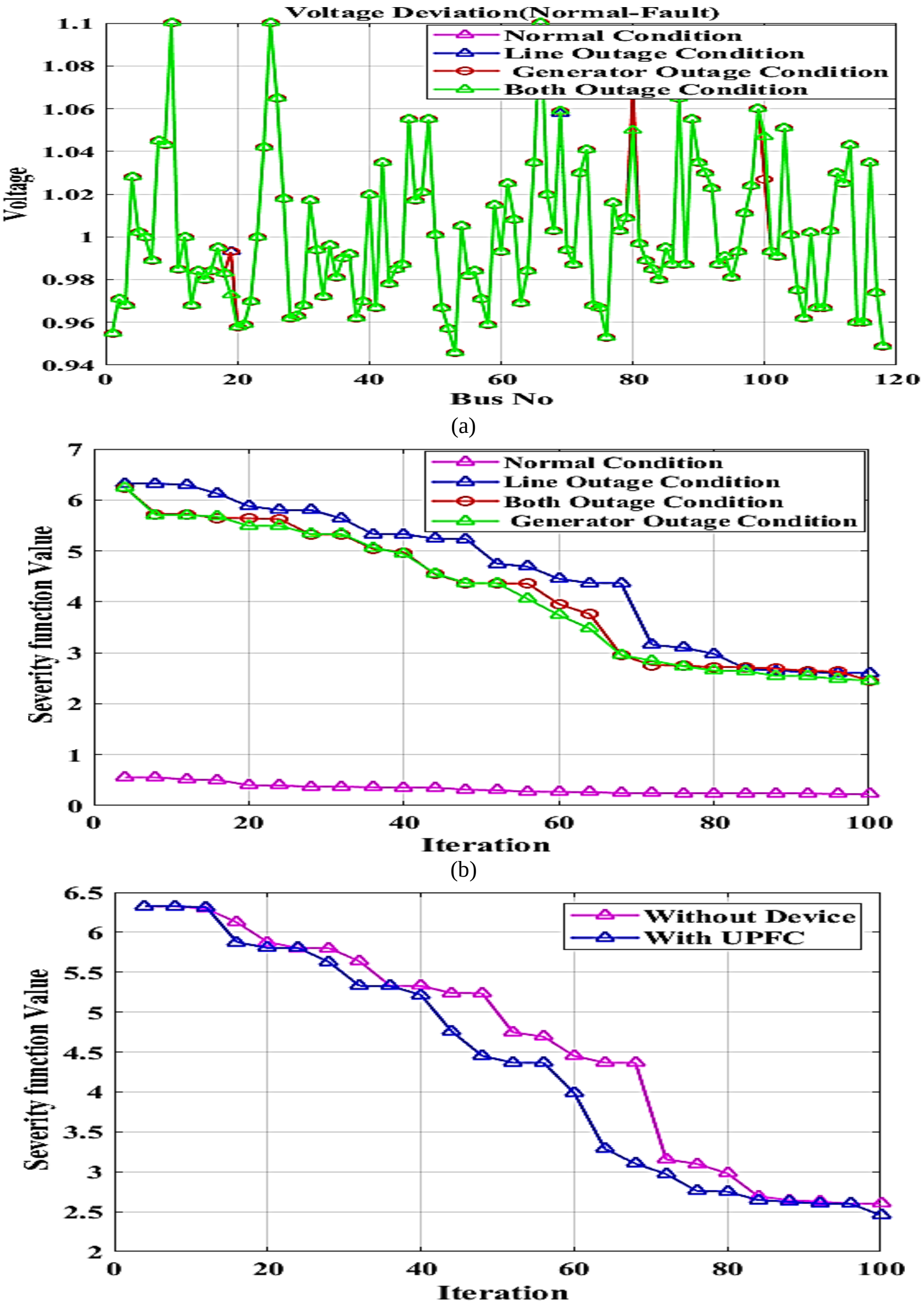
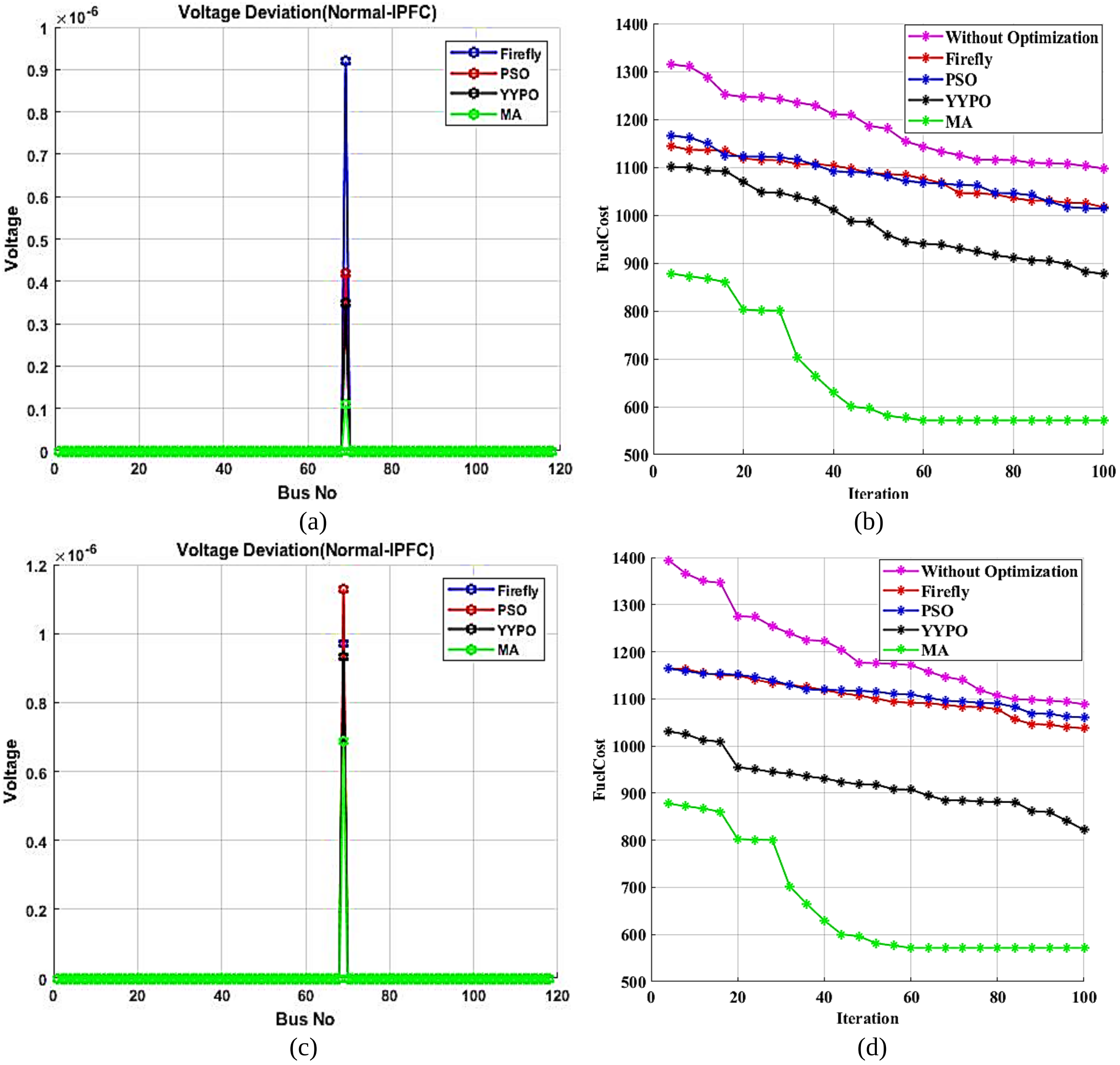


**Figure 18** Analyze various conditions of UPFC connected IEEE 118 bus system (a) Voltage deviation; (b) characteristics of system severity function; and (c) System severity function with and without device

Figure 18 shows the voltage deviation, severity function characteristics and systems severity with and without the device. In without device, the severity function is high, but after the connection of the device, the severity function is reduced, which is clearly demonstrated in the graphical comparison structure.

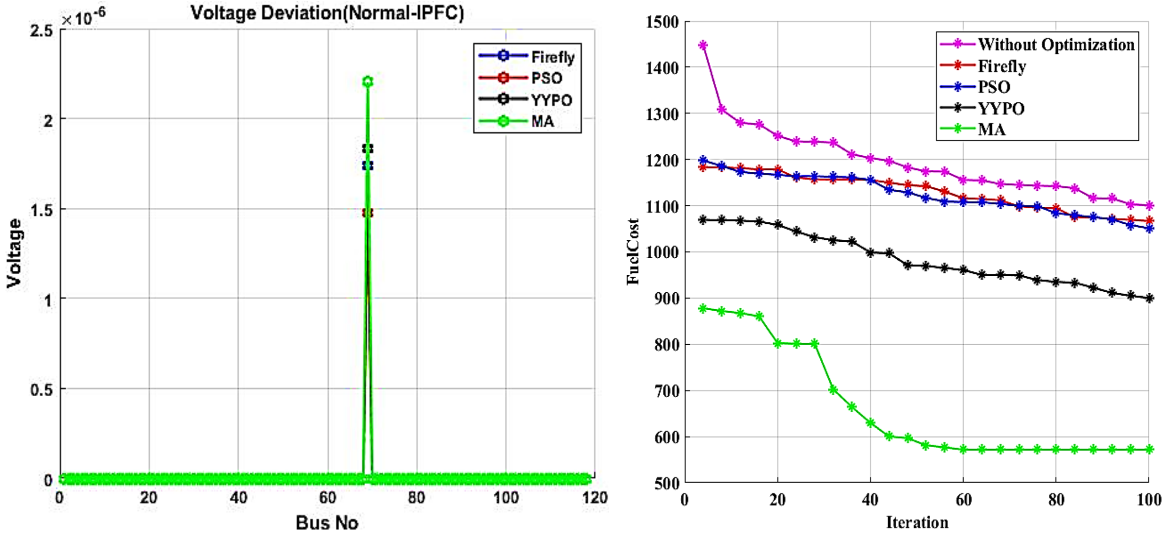
***Case C:*** *Applying mayfly algorithm in IPFC device*

Here, the allocation of IPFC appliances is efficiently carried out by means of the new mayfly optimization technique. IPFC consists of two back-to-back dc-to-ac converters, reducing the losses and improving the power system's steadiness. MA found the best location where the IPFC is integrated to secure the system as well as reduce the power loss, voltage deviation and so on. The suitable location is found via the six objective functions that are given in the MA optimizer. Optimizer analyses the objective functions, in which time the objective values are reduced that is taken as the best location to fit the IPFC device.



(a) (b)

(c) (d)



(e) (f)

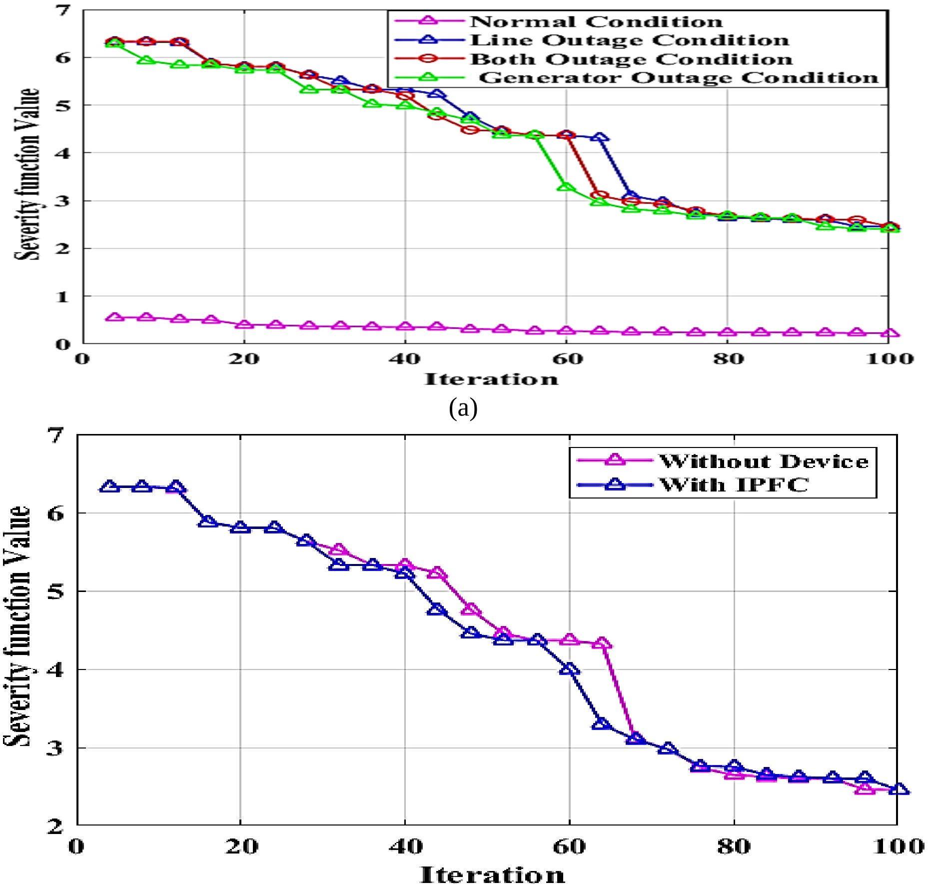
**Figure 19** Analysis of after connecting IPFC device in IEEE 118 bus system (a) Voltage deviation in generation outage; (b) Fuel cost in generation outage; (c) Voltage deviation in line outage; (d) Fuel cost in line outage; and (e) Voltage deviation in both outage (f) Fuel cost in both outage

IPFC is placed in the proper location of the transmission line to remove the losses and improve the stability of the line. On bus no. 70, IPFC reach the highest peak voltage. For both outage periods, MA reduces the fuel cost below 800, which is the lowest value in contrast to the previous techniques. Table 8 contain IPFC performance at generation outage, line outage and both outage period. During these periods, the best location of IPFC, power loss and fuel cost were also measured. The best location of IPFC in the proposed approach is bus no. 26, 30, 38 at generation outage period, bus no. 16, 17, 113 at line outage period and bus no. 38, 65, 68 at both outage periods as shown in Figure 19.

The impact of IPFC is analysed based on power flow improvement, reduction of line loss and active power generation cost.

**Table 8** Analysis of IPFC performance

| **Algorithm** | **Generation Outage** | | | **Line Outage** | | | **Both Outage** | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Bus no** | **Power loss** | **Fuel cost** | **Bus no** | **Power loss** | **Fuel cost** | **Bus no** | **Power loss** | **Fuel cost** |
| Without facts devices | - | 194.0901 | 727.2477 | - | 194.0901 | 890.9225 | - | 194.0901 | 967.403 |
| Fire fly | 42, 49, 69 | 200.0197 | 407.4471 | 2, 12, 117 | 206.9383 | 451.8616 | 69, 70, 75 | 201.6973 | 493.7443 |
| PSO | 23, 32, 114 | 199.6735 | 465.9265 | 11, 12, 117 | 209.7999 | 494.7168 | 42, 49, 69 | 200.8221 | 452.163 |
| YYPO | 26, 30, 38 | 199.7068 | 460.171 | 16, 17, 113 | 205.9051 | 437.8258 | 42, 49, 69 | 202.6319 | 535.2601 |
| MA | 26, 30, 38 | 200.1297 | 502.7692 | 16, 17, 113 | 212.4105 | 603.8775 | 38, 65, 68 | 201.8142 | 618.9342 |



(a)

(b)

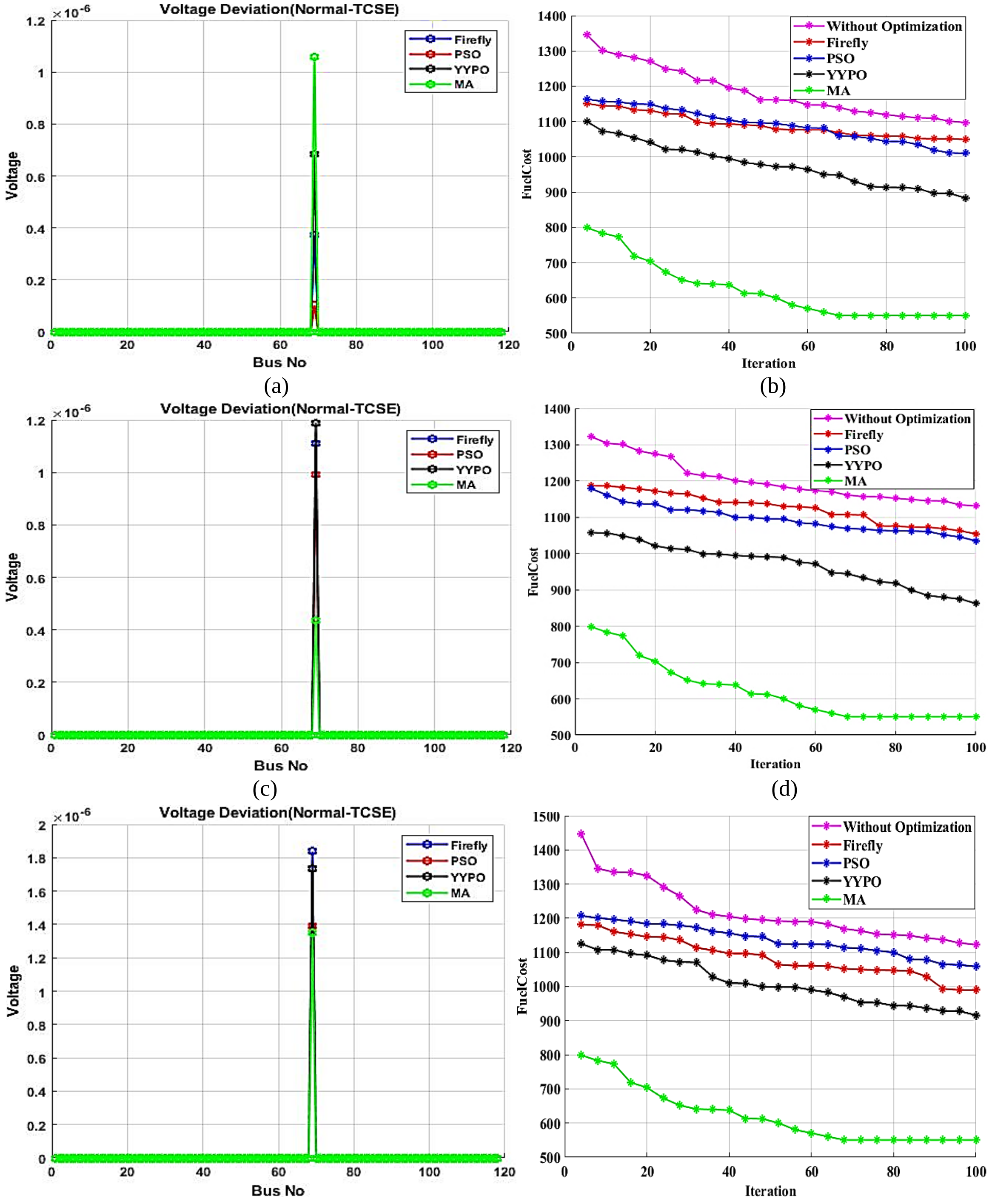
**Figure 20** Analyze various conditions of IPFC connected IEEE 118 bus system (a) Voltage deviation; (b) characteristics of system severity function; and (c) System severity function with and without device

Moreover, the severity of the system is analysed with and without the device, and voltage deviation is also analysed. In the absence of the device, the severity function is not regulated properly, but the IPFC is integrated into the system to reduce the severity function to secure the system as shown in Figure 20.

### ***Case D:*** *Applying mayfly algorithm in TCSC device*

Now, the TCSC is placed in the weakest transmission line of the IEEE 118 bus system carried out by means of the mayfly optimization algorithm. The proposed method most efficiently reduces the power loss, voltage loss and voltage deviation. MA optimizer finds the suitable location of the TCSC in IEEE 118 bus system to reduce the loss. The location of TCSC is identified by MA, which optimizes the six objective values. Figure 21 shows the voltage deviation and fuel cost of generation outages, fuel outages and both outages, respectively.

Voltage deviation reaches the highest peak value at bus no.70 under these three outage circumstances. Considering both outage systems, the proposed MA's voltage deviation reach $1.36*10^{-6}$ at the bus no. 70 and its fuel cost is reduced below 800. Table 9 shows the performance of TCSC at the period of generation outage, line outage and both outages. These outage power loss, fuel cost and TCSC best location are observed. MA-based TCSC’s best location is bus no. 38, 65, 68 at generation outage, bus no. 11, 12, 117 at line outage period, and bus no. 42, 49, 69 at both outage periods.



(a) (b)

(c) (d)

(e) (f)

**Figure 21** Analysis of after connecting TCSC device in IEEE 118 bus system (a) Voltage deviation in generation outage; (b) Fuel cost in generation outage; (c) Voltage deviation in line outage (d) Fuel cost in line outage; (e) Voltage deviation in both outage; and (f) Fuel cost in both outage

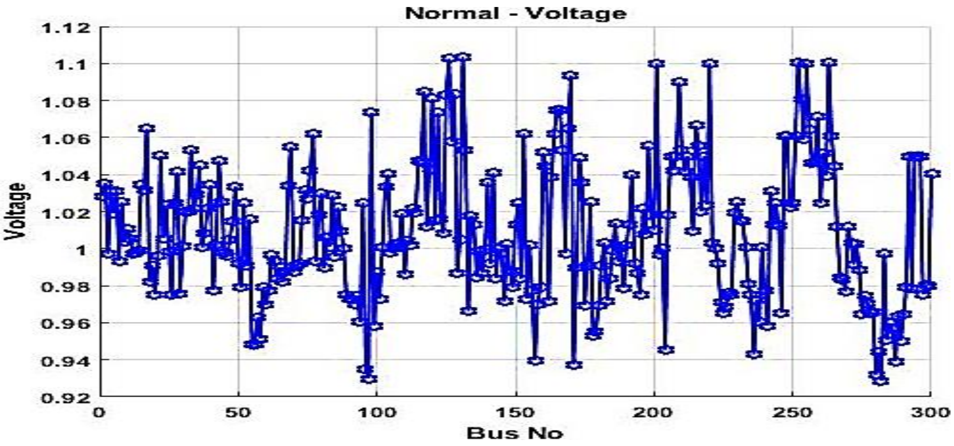
**Table 9** Analysis of TCSC performance

| Algorithm | Generation Outage | | | Line Outage | | | Both Outage | | |
|---|---|---|---|---|---|---|---|---|---|
| | Bus no | Power loss | Fuel cost | Bus no | Power loss | Fuel cost | Bus no | Power loss | Fuel cost |
| Without facts devices | - | 194.0901 | 654.6484 | - | 194.0901 | 810.845 | - | 194.0901 | 810.845 |
| Fire fly | 38, 65, 68 | 199.6928 | 440.0447 | 5, 11, 13 | 207.4563 | 450.0891 | 38, 65, 68 | 201.6664 | 481.6208 |
| PSO | 42, 49, 69 | 200.7446 | 494.634 | 16, 17, 113 | 204.4451 | 509.0525 | 38, 65, 68 | 200.9193 | 463.4462 |
| YYPO | 42, 49, 69 | 200.6721 | 474.7875 | 11, 12, 117 | 209.2939 | 479.2418 | 23, 32, 114 | 200.8816 | 505.0216 |
| MA | 38, 65, 68 | 200.521 | 558.4349 | 11, 12, 117 | 213.8078 | 575.0905 | 42, 49, 69 | 202.1191 | 507.3905 |

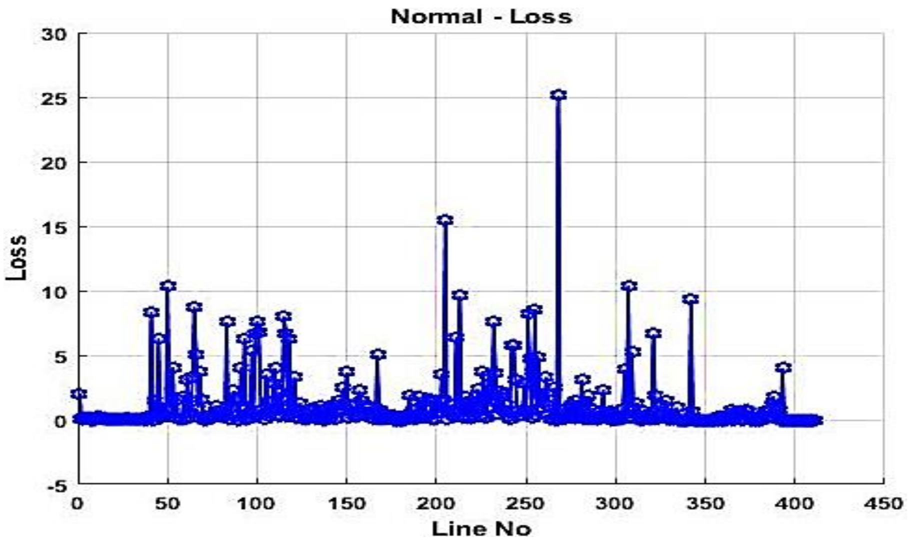
Consider the fuel cost; the proposed method is less than the existing method. The proposed method reduces the fuel cost and reduces the device cost. In Table 9, the fuel cost without the Facts device is 810.845, but after connecting the Facts devices, the fuel cost is reduced.

## 5.6 Analysis of the performance of IEEE 300 bus system

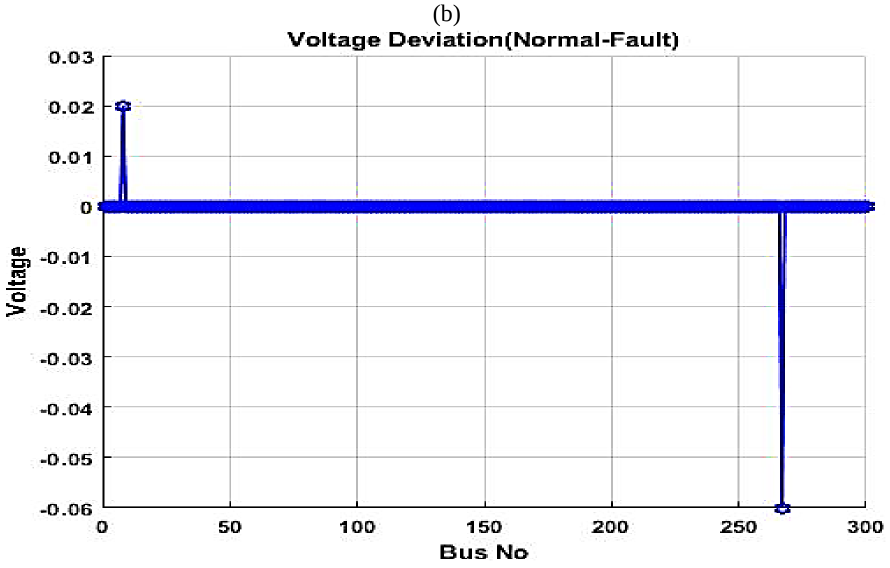
The mayfly algorithm carries out the effective analysis of the Facts devices' performance. The innovative technique aims to find a proper location of Facts devices and analyse the performance. Mayfly optimization selects the best location of Facts device integration of the IEEE 300 bus system. Based on the use of six objective functions, the suitable location of the Facts devices is found. The system performance without the Facts device is shown in Figure 22. The voltage of the normal system is observed. It does not flow constantly, varied by each other. Likewise, loss of power is also varied due to non-constant voltage flow. In addition, LCPI, voltage deviation and power flow severity function were also analysed and verified.



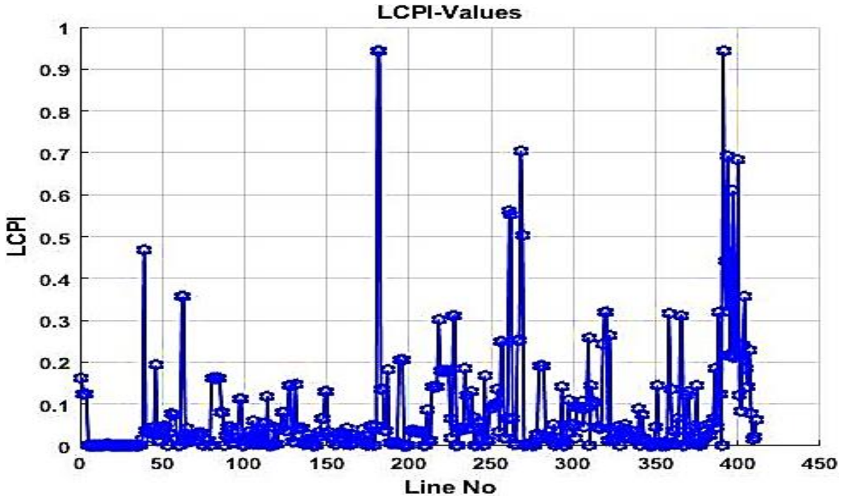
(a)


Normal - Loss
Loss
Line No
30
25
20
15
10
5
0
-5
0
50
100
150
200
250
300
350
400
450

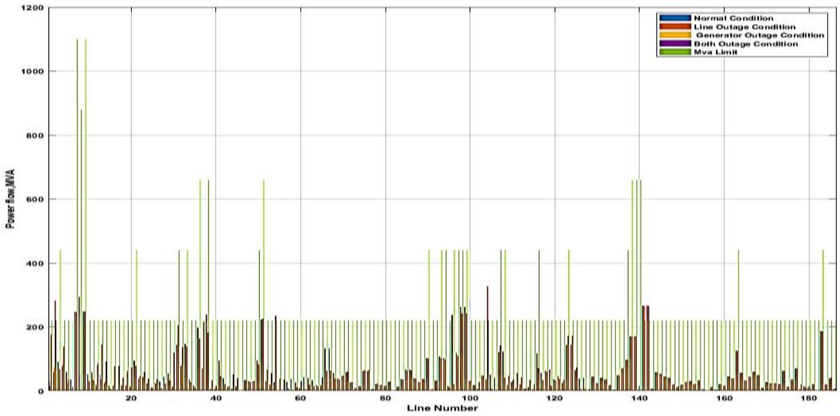
(b)


Voltage Deviation(Normal-Fault)
Voltage
Bus No
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
0
50
100
150
200
250
300

(c)


LCPI-Values
LCPI
Line No
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
50
100
150
200
250
300
350
400
450

(d)



(e)

**Figure 22** Base case result of IEEE 300 bus system under normal condition (a) Voltage loss; (b) Power loss; (c) voltage deviation; (d) Variation of LCPI values; and (e) Variation of power flows in system severity function

## 5.7 Performance analysis after connecting Facts devices*:*

The Facts gadgets extend a helping hand in enhancing the voltage profile, considerably cutting down losses, stepping up power flows, in addition to offering reactive power support. The Facts devices fit in the proper location, and analysis of the performance is present in this scenario. The main objective of the proposed method is to minimize the loss and improve the stability of the system. This scenario is divided into four different categories.

**Case 1:** Mayfly applied in STATCOM device

**Case 2:** Mayfly applied in UPFC device

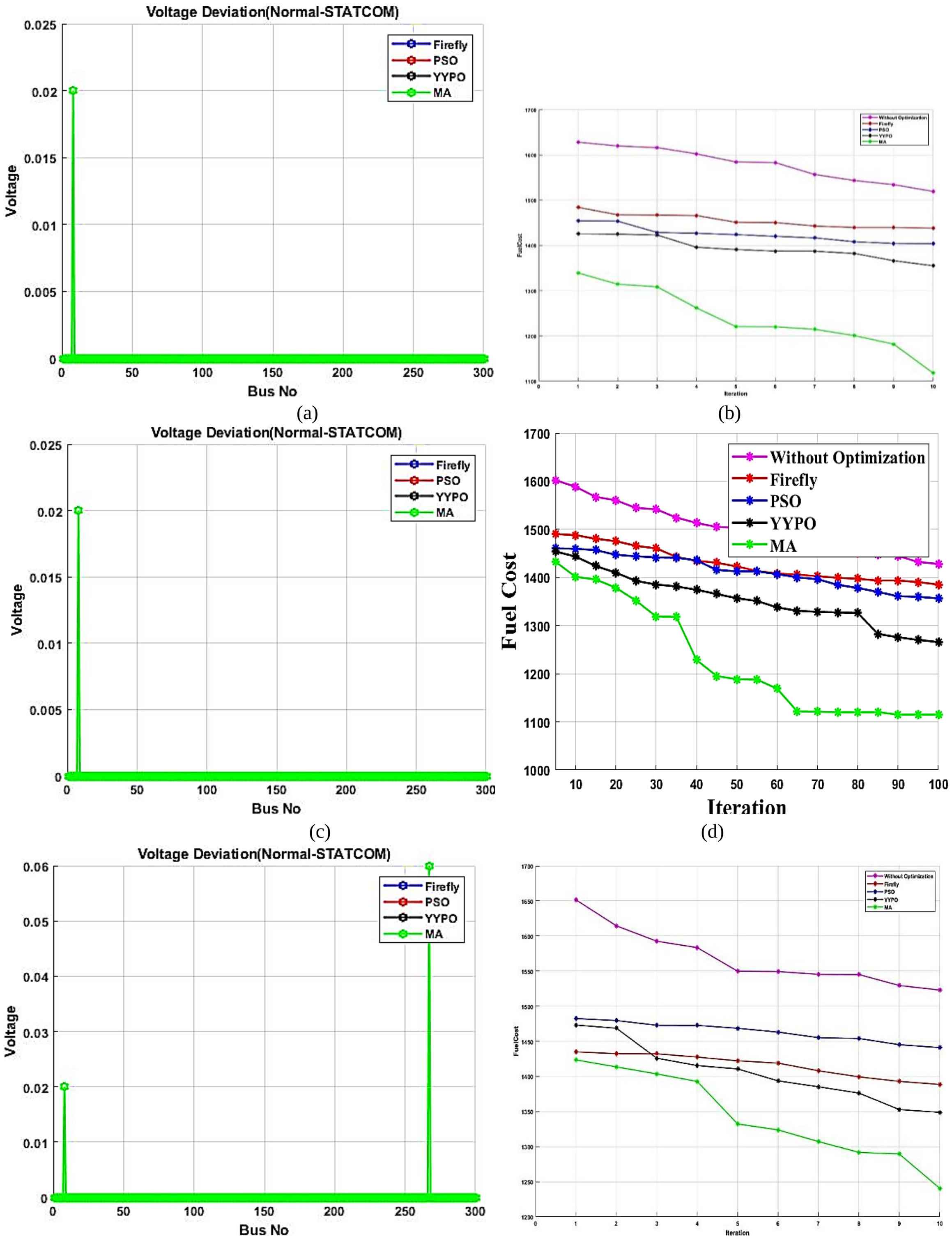
**Case 3:** Mayfly applied in IPFC device

**Case 4:** Mayfly applied in TCSC device

***Case 1:*** *Mayfly applied in STATCOM device*

The STATCOM is well-equipped with the ability to enhance the voltage profile. Mayfly optimization-based STATCOM device more efficiently reduces losses and improves system stability. The best location of the STATCOM device is found via the mayfly optimization algorithm. Objective functions are given in the MA optimizer, which analyses the best location in which bus the device is fitted to gain the best solution. Figure 23 shows the comparison of the proposed method, firefly OA, PSO and YYPO. As considered for both outage systems, the voltage is varied at 1st bus and 270th bus, and the fuel cost reduced below 1200. At generation outage, line outage and both outage periods, the voltage is varied in the 1st bus since the voltage in the 300 bus carry more power.

The graphical representation clearly explains the proposed method, which is more advantageous than the existing methods. The power loss is also reduced in the proposed method over other methods. Table 10 present the performance of STATCOM present and previous technique during generation outage, line outage and both outage circumstance. In the proposed approach system, the best location of STATCOM is observed, that is, bus no. 11, 13 in generation outage period, bus no. 4, 16 inline outage period and bus no. 4, 16 in both outage period. As well as the fuel cost of generation outage, line outage and both outages are 618.0288, 474.0826, 620.9615, respectively.



(a) (b)

(c) (d)

(e) (f)

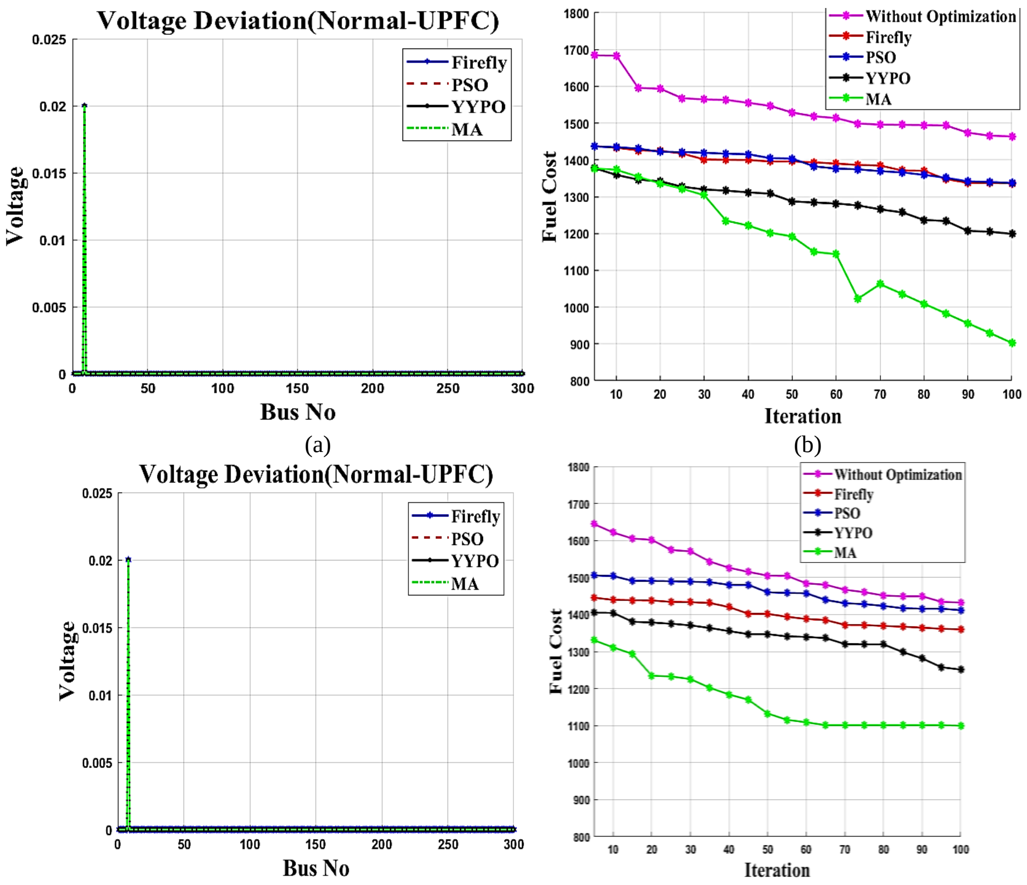
**Figure 23** Analysis of after connecting STATCOM device in IEEE 300 bus system (a) Voltage deviation in generation outage; (b) Fuel cost in generation outage; (c) Voltage deviation in line outage; (d) Fuel cost in line outage; (e) Voltage deviation in both outage; and (f) Fuel cost in both outage

**Table 10** Analysis of STATCOM performance

| Algorithm | Generation Outage | | | Line Outage | | | Both Outage | | |
|---|---|---|---|---|---|---|---|---|---|
| | Bus no | Power loss | Fuel cost | Bus no | Power loss | Fuel cost | Bus no | Power loss | Fuel cost |
| Without facts devices | - | 479.9071 | 810.845 | - | 479.9071 | 810.845 | - | 479.9071 | 810.845 |
| Fire fly | 16, 15 | 481.7037 | 464.1252 | 18, 72 | 487.6793 | 481.6641 | 4, 16 | 483.1327 | 371.446 |
| PSO | 11, 13 | 482.775 | 461.0789 | 8, 14 | 487.4904 | 460.0614 | 16, 15 | 481.544 | 510.565 |
| YYPO | 16, 15 | 482.6096 | 462.2995 | 52, 54 | 488.0604 | 495.9618 | 8, 14 | 482.6298 | 395.6386 |
| MA | 11, 13 | 482.1797 | 618.0288 | 4, 16 | 487.6176 | 474.0826 | 4, 16 | 481.2849 | 620.9615 |

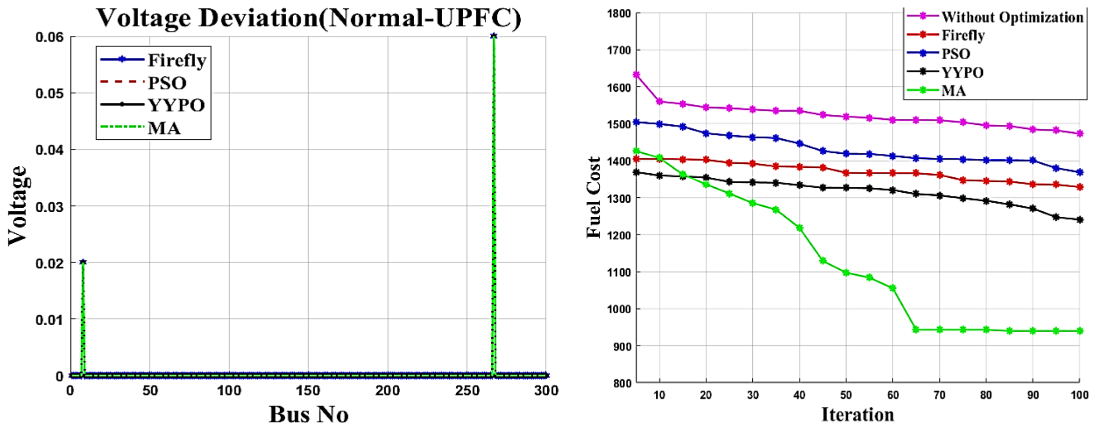
***Case 2:** Mayfly applied in UPFC device*

The fuel and device costs are under normal, and device conditions and best locations are duly estimated after connecting. In this case, the optimal location is chosen for using the UPFC to scale up the power system security and cut down the active and reactive power losses, voltage deviation, and fuel cost, respectively. Figure 24 represent the voltage deviation and fuel cost during generation outage, line outage and both outage period. For the generation and line outage period of MA, the voltage deviation reaches the peak value at bus 1. The fuel cost is reduced to 1100 in the generation outage period and reduced below 1400 at the line outage period. Considering both outages, the voltage is varied at the period of bus 1 and bus 270 due to high power transfer. The proposed approach also reduces the fuel cost at below 1200 cost.



(a) (b)

(c) (d)



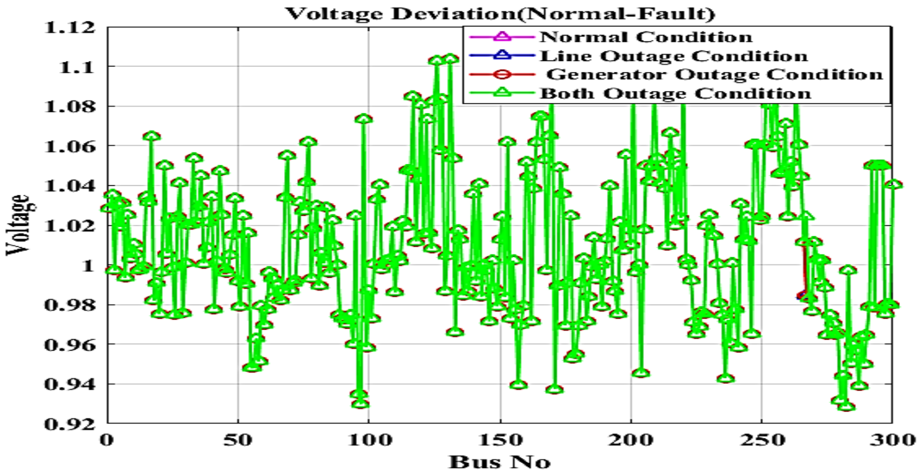
(e) (f)

**Figure 24** Analysis of after connecting UPFC device in IEEE 300 bus system (a) Voltage deviation in generation outage; (b) Fuel cost in generation outage; (c) Voltage deviation in line outage; (d) Fuel cost in line outage; (e) Voltage deviation in both outage; and (f) Fuel cost in both outage

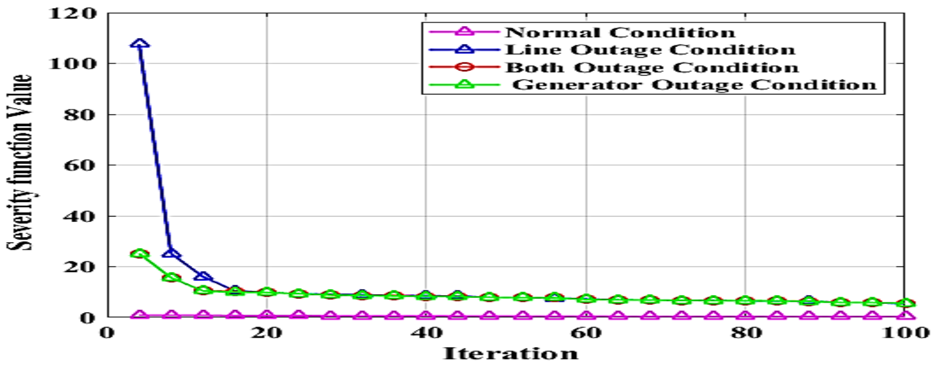
The performance of the UPFC investigation is presented in Table 11. The circumstances are present in the system like generation outage, line outage and both outage. The best location, power loss, and fuel cost are analysed in each circumstance. For the proposed MA-based UPFC, the best location of generation outage is bus no. 2, 8, and the best line outage is bus no. 4, 16, and the best location of both outage periods is bus no. 4, 16.

**Table 11** Analysis of UPFC performance

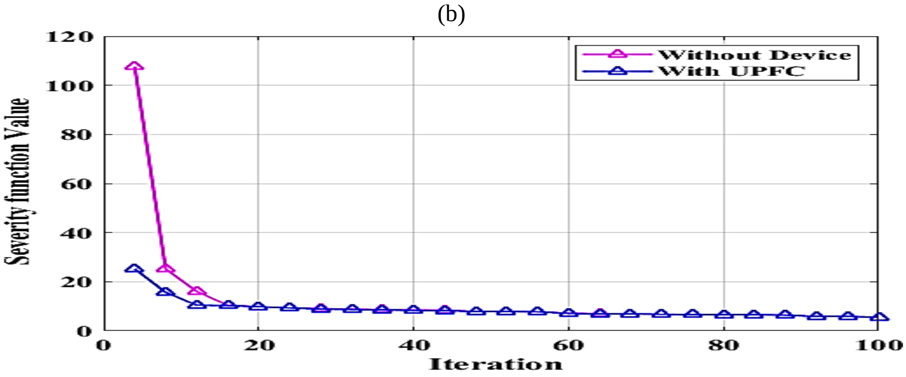
| Algorithm | Generation Outage | | | Line Outage | | | Both Outage | | |
|---|---|---|---|---|---|---|---|---|---|
| | Bus no | Power loss | Fuel cost | Bus no | Power loss | Fuel cost | Bus no | Power loss | Fuel cost |
| Without facts devices | - | 479.9071 | 810.845 | - | 479.9071 | 810.845 | - | 479.9071 | 810.845 |
| Fire fly | 52, 54 | 482.4836 | 487.5952 | 8, 14 | 654.5216 | 467.7318 | 8, 14 | 484.4901 | 428.406 |
| PSO | 52, 54 | 483.0172 | 446.4375 | 52, 54 | 653.9375 | 493.6575 | 18, 72 | 484.433 | 424.3379 |
| YYPO | 52, 54 | 482.7993 | 414.3492 | 52, 54 | 655.1099 | 464.2463 | 16, 15 | 483.4085 | 499.962 |
| MA | 2, 8 | 482.9655 | 511.0878 | 4, 16 | 653.4854 | 598.8625 | 4, 16 | 484.1744 | 498.0453 |



(a)



(b)



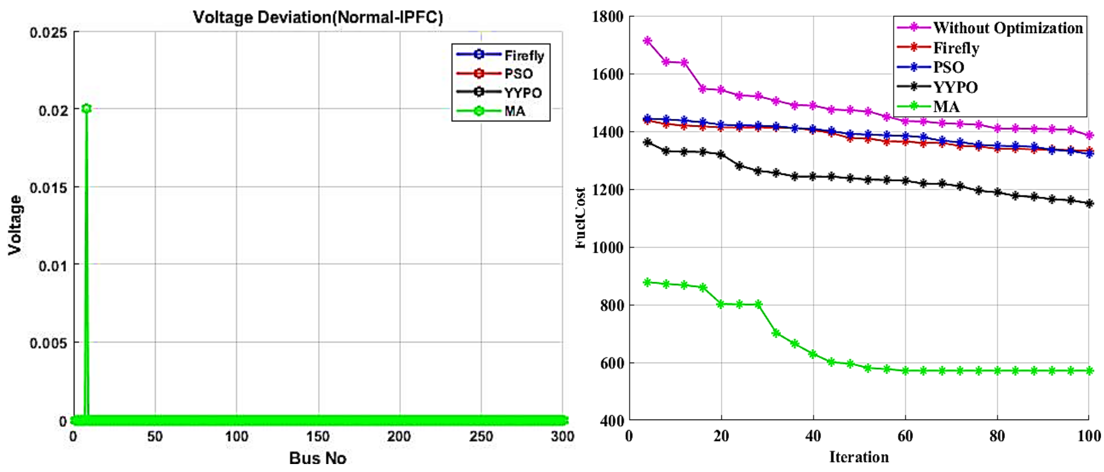
(c)

**Figure 25** Analyze various conditions of UPFC connected IEEE 300 bus system (a) Voltage deviation; (b) characteristics of system severity function; and (c) System severity function with and without device

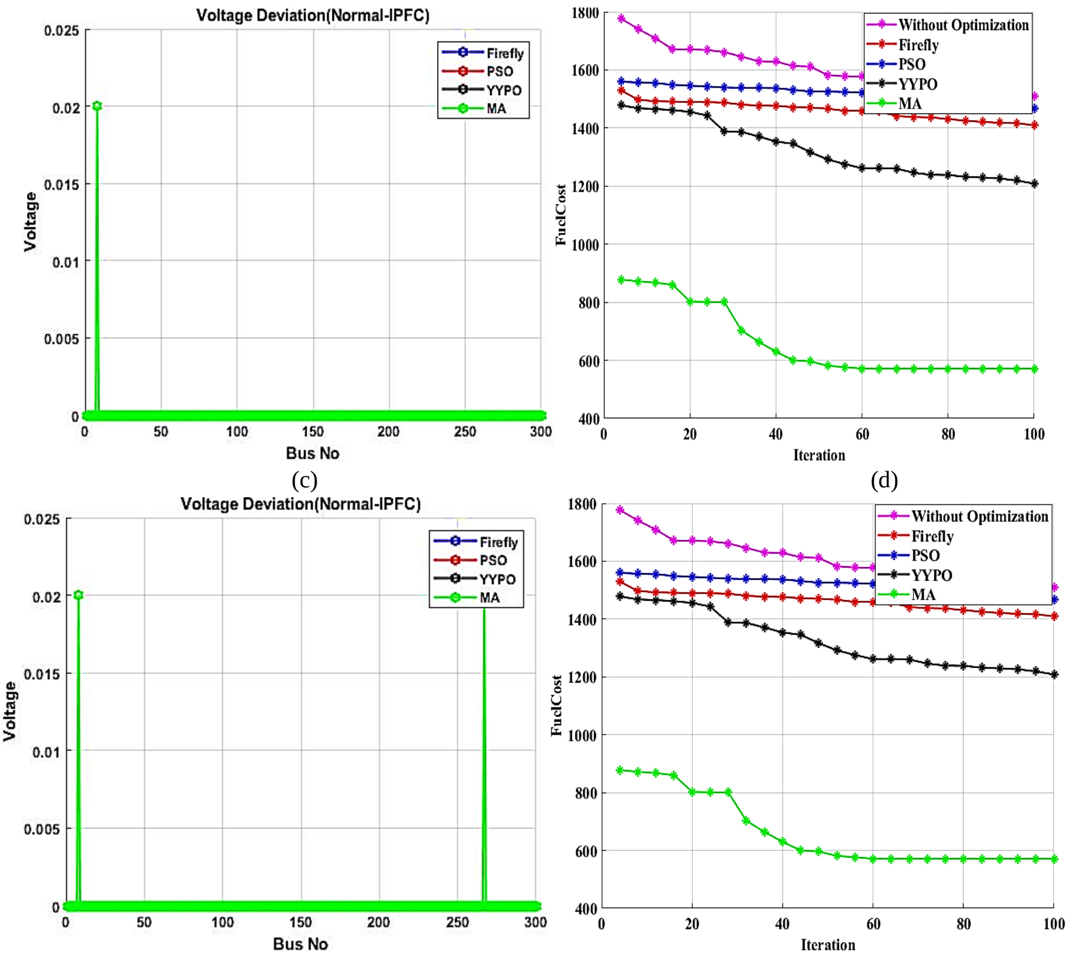
In addition, the severity function of the system is analysed in two conditions such as with and without the device. In the absence of a device in the system, the severity function is initiation from a value of 33. For the presence of UPFC in the system, the severity function starts from the value of 20. UPFC reduce the severity function to secure the system to avoid damage.

***Case 3:*** *Mayfly applied in IPFC device*

Here, the Facts device of IPFC is duly chosen and positioned in the optimal location to reduce the voltage loss, power loss and voltage deviation. The proposed method IPFC reduces the fuel cost compared to the normal operation condition, shown in Table 12 and Figure 26.



(a) (b)



(c) (d)

**(e)** (f)

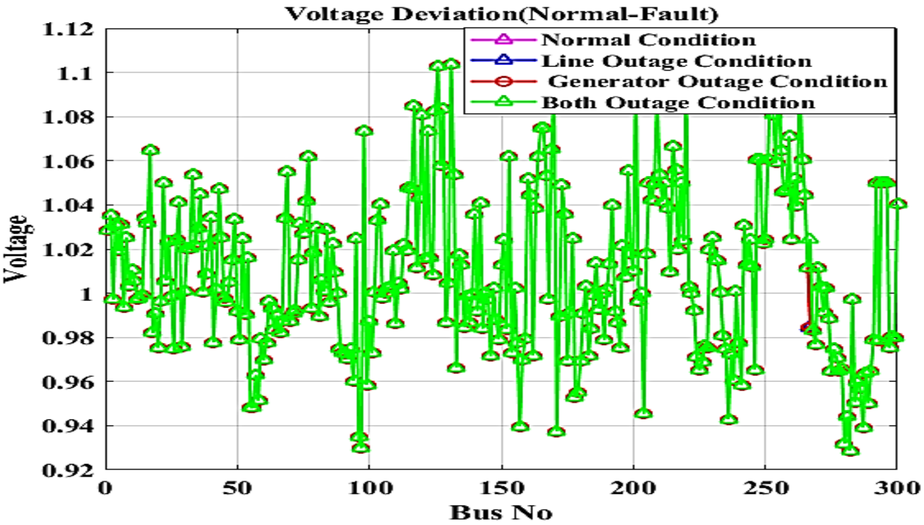
**Figure 26** Analysis of after connecting IPFC device in IEEE 300 bus system (a) Voltage deviation in generation outage; (b) Fuel cost in generation outage; (c) Voltage deviation in line outage, (d) Fuel cost in line outage; (e) Voltage deviation in both outage; and (f) Fuel cost in both outage

Fuel cost and voltage deviation of the proposed and existing approach is analysed and validated as shown in Figure 26. In both outage condition, the MA-based IPFC contain the voltage variation in bus no. 1 and 270, as well the cost of fuel is reduced to 1150. The performance of IPFC's proposed and previous techniques are presented in Table 12. The performance is analysed for generation outage, line outage and both outage circumstances. And in each circumstance, power loss, fuel cost and best locations are analysed. The best location of MA-based IPFC is bus no. 8, 14, 15 at generation outage period, bus no. 52, 54, 53 at line outage period, and bus no. 52, 54, 53 at both outage periods.

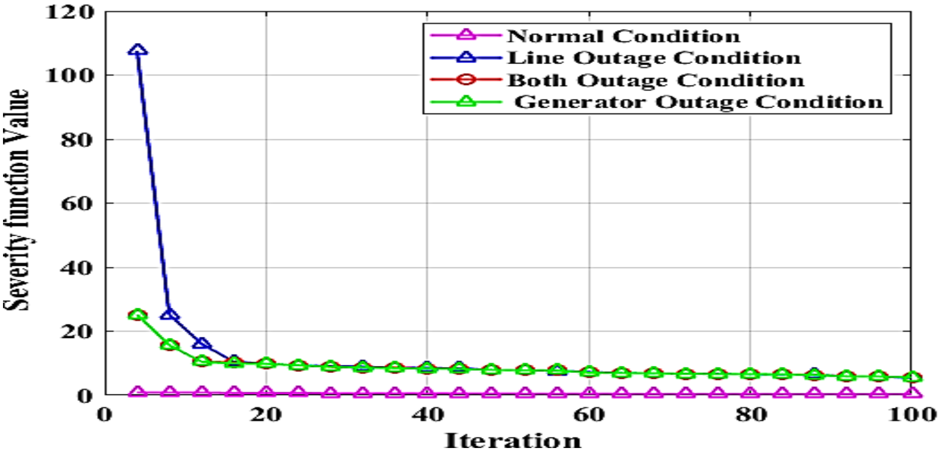
**Table 12** Analysis of IPFC performance

| **Algorithm** | **Generation Outage** | | | **Line Outage** | | | **Both Outage** | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Bus no** | **Power loss** | **Fuel cost** | **Bus no** | **Power loss** | **Fuel cost** | **Bus no** | **Power loss** | **Fuel cost** |
| Without facts devices | - | 479.9071 | 810.845 | - | 479.9071 | 810.845 | - | 479.9071 | 810.845 |
| Fire fly | 8, 14, 15 | 482.6269 | 444.8493 | 52, 54, 53 | 525.6213 | 428.3779 | 18, 72, 78 | 482.8246 | 534.572 |

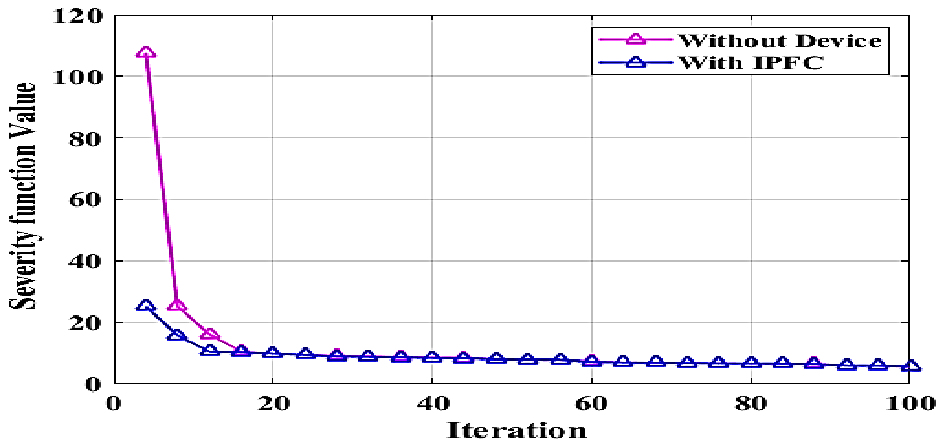
| **Algorithm** | **Generation Outage** | | | **Line Outage** | | | **Both Outage** | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Bus no** | **Power loss** | **Fuel cost** | **Bus no** | **Power loss** | **Fuel cost** | **Bus no** | **Power loss** | **Fuel cost** |
| PSO | 39, 52, 54 | 482.1821 | 435.8031 | 31, 43, 44 | 525.851 | 401.546 | 52, 54, 53 | 483.2428 | 471.2211 |
| YYPO | 52, 54, 53 | 482.1655 | 483.6355 | 18, 72, 78 | 525.6602 | 449.1523 | 16, 15, 17 | 483.2685 | 467.1146 |
| MA | 8, 14, 15 | 482.7225 | 472.7255 | 52, 54, 53 | 524.932 | 545.5248 | 52, 54, 53 | 483.4379 | 451.823 |



(a)



(b)



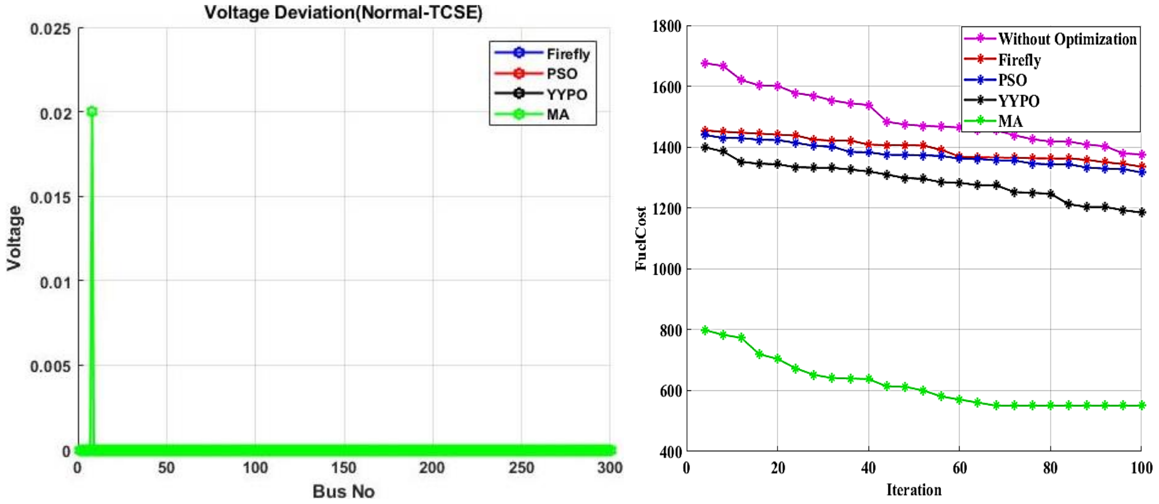
(c)

**Figure 27** Analyze various conditions of IPFC connected IEEE 118 bus system (a) Voltage deviation; (b) characteristics of system severity function; and (c) System severity function with and without device

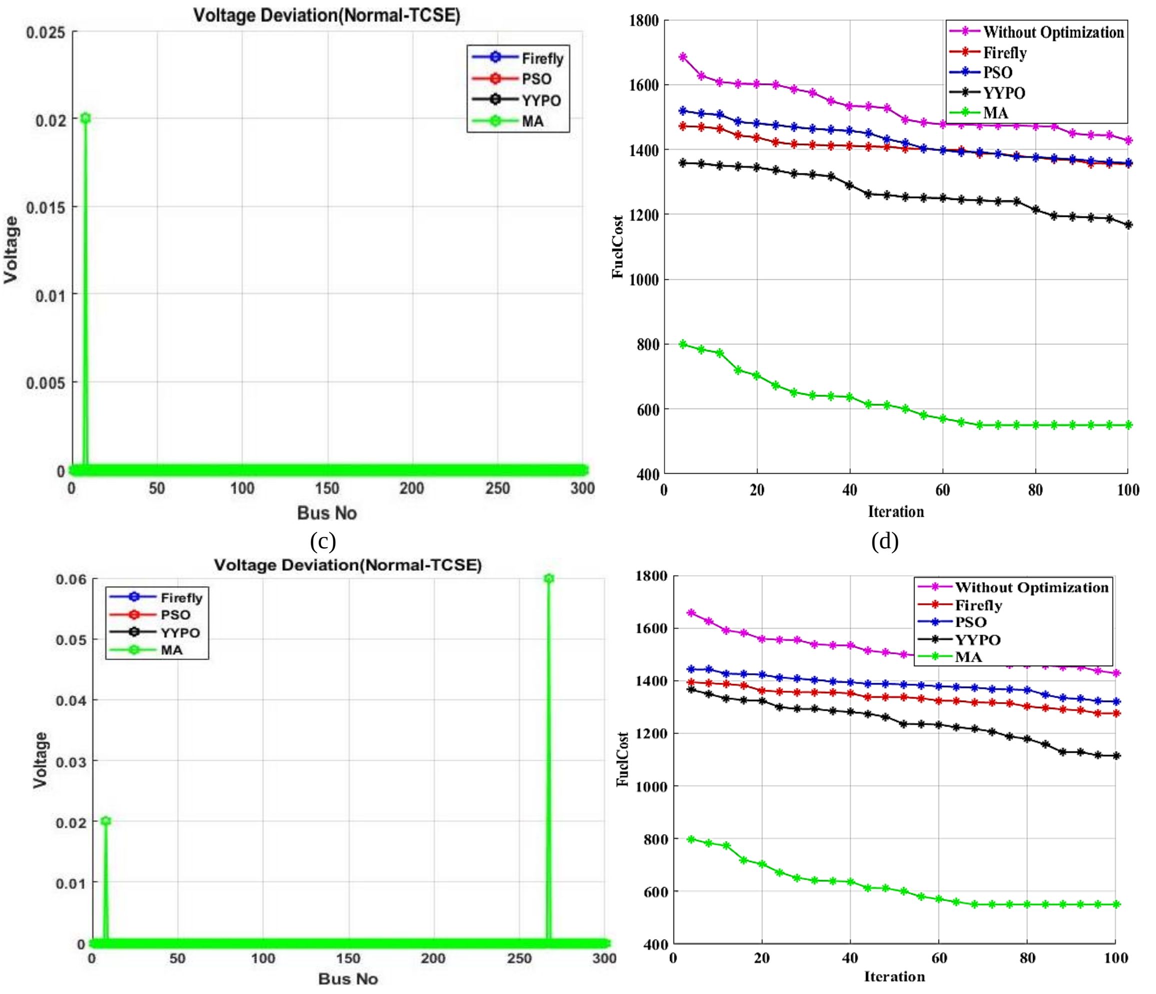
Moreover, the severity function is analysed with and without the device as shown in Figure 27. Severity function is high in value without device circumstance, and the value is 110 in 1st iteration. On the other hand, MA-based IPFC is linked in the system. The value of the severity function is 28 in 1st iteration, and this variation proves that the advanced system is more effectively reducing the severity function value.

***Case 4:** Mayfly applied in TCSC device*

Now, the allocation of TCSC utilization is efficiently carried out by means of the innovative mayfly optimization algorithm technique. According to the objective functions, mayfly identifies the best location of TCSC integration in the IEEE 300 bus system. Comparison analysis of the proposed method and existing method is shown in Figure 28. In generation outage, voltage deviation is varied at bus no. 1, and the cost of the fuel is reduced below 1200. Similarly, the line outage is also analysed here. The deviation of voltage is varied at bus no. 1, and the cost of fuel is reduced to below 1200. And the condition of both outages is analysed, in this period the deviation of voltage arises in bus no. 1 and 270, as well as the cost of fuel is below 1200.



(a) (b)



(c) (d)

(e) (f)

**Figure 28** Analysis of after connecting TCSC device in IEEE 300 bus system (a) Voltage deviation in generation outage; (b) Fuel cost in generation outage; (c) Voltage deviation in line outage; (d) Fuel cost in line outage; (e) Voltage deviation in both outage; and (f) Fuel cost in both outage

Table 13 present the performance of TCSC at the various condition of generation outage, line outage and both outage. Power loss, best location, and fuel cost are analysed in each condition. The best location is observed in the proposed approach, i.e. bus no 8, 14, 15 in generation outage condition, bus no. 8, 14, 15 inline outage condition, and bus no. 2, 8, 248 in both outage conditions.

**Table 13** Analysis of TCSC performance

| Algorithm | Generation Outage | | | Line Outage | | | Both Outage | | |
|---|---|---|---|---|---|---|---|---|---|
| | Bus no | Power loss | Fuel cost | Bus no | Power loss | Fuel cost | Bus no | Power loss | Fuel cost |
| Without facts devices | - | 479.9071 | 810.845 | - | 479.9071 | 810.845 | - | 479.9071 | 810.845 |
| Fire fly | 8, 14, 15 | 482.4318 | 457.7296 | 18, 72, 78 | 540.3197 | 430.8405 | 52, 54, 53 | 483.1086 | 431.2251 |
| PSO | 8, 14, 15 | 482.7802 | 458.3062 | 4, 16, 15 | 540.7392 | 534.8157 | 39, 52, 54 | 483.1215 | 447.3585 |
| YYPO | 14, 15, 17 | 482.8346 | 422.8741 | 31, 43, 44 | 540.1524 | 497.8705 | 18, 72, 78 | 483.0954 | 525.0525 |
| MA | 8, 14, 15 | 481.3693 | 549.6367 | 8, 14, 15 | 540.1958 | 498.3502 | 2, 8, 248 | 482.724 | 503.2541 |

The fuel cost of the proposed method TCSC is 503.2541$/h which is low compared to the existing methods. The reduction of fuel cost is achieved by the proposed method compared to existing methods. For both outage systems, the fuel cost before connecting Facts devices is 810.845 $/h, but after fitting Facts devices like STATCOM, UPFC, IPFC and TCSC, fuel cost is reduced to 498.0453$/h, 498.0453$/h, 451.823$/h and 503.2541$/h respectively. The mayfly optimization-based Facts devices are very well to minimise the losses and improve the system performance. Singh and David, 2001, place the Facts device of TCSC and TCPAR in a proper location to secure the system via congestion management. Here, the optimal problem is solved by setting optimal parameters and location. The device's location is not rapidly analysed, and power losses are not less than the proposed approach. Reddy and Momoh, 2015, used a heuristic optimization to identify the best location of SVC and TCSC (Reddy & Momoh, 2015). More power loss and not accurately identifying the suitable location as compared to the proposed approach. The proposed work additionally observed the value of fuel cost and various conditions of outages.

### 5.8 Discussion of proposed outcome

Four various Facts devices are placed in the proper location to effectively secure the system. MA analyse the objective functions to identify the best location of Facts devices. The parameter of the Mayfly Optimization Algorithm and existing optimization is presented in Table 1. The proposed method is analysed for three busses. In those three busses, various cases are provided. Initially, IEEE 30 bus outcome is analysed. Figure 6 contain the base case result of the IEEE 30 bus system under normal condition voltage loss, power loss, voltage deviation, variation of LCPI values and variation of power flows in system severity function are provided. Again the system analysed for fitting STATCOM device, and Figure 7 contain after connecting STATCOM device in IEEE 30 bus system voltage deviation in generation outage fuel cost in generation outage, voltage deviation in line outage, fuel cost in line outage, voltage deviation in both outage and fuel cost in both outage. And its performance values are provided in Table 2. Moreover, various conditions of STATCOM connected IEEE 30 bus system like voltage deviation, characteristics of system severity function and system severity function with and without the device is analysed and sketched in Figure 8. Then, analysed the UPFC fitted system's voltage deviation and fuel cost in generation outage, in line outage, in both outages. The analysis is illustrated in Figure 9 and its performance is presented in Table 3. Then analyse various conditions of UPFC connected IEEE 30 bus system's voltage deviation, characteristics of system severity function and system severity function with and without the device, shown in Figure 10. Again, the IPFC device connected in the IEEE 30 bus system is analysed for voltage deviation and fuel cost in generation outage, line outage, and both outages. The analysis is shown in Figure 11 and its performance is presented in Table 4. Then various conditions of IPFC connected the IEEE 30 bus system's voltage deviation, characteristics of system severity function and system severity function with and without the device is analysed, sketched in Figure 12. After that, the TCSC device connected to the IEEE 30 bus system is analysed for Voltage deviation and Fuel cost in generation outage, line outage, and both outages. The analysis is shown in Figure 13 and its performance is presented in Table 5. Then various conditions of TCSC connected the IEEE 30 bus system's voltage deviation, characteristics of system severity function and system severity function with and without device are analysed in Figure 14.

Second, the IEEE 118 bus outcome is analysed. Figure 15 presents the base case result of IEEE 118 bus system under normal condition voltage loss, power loss, voltage deviation, variation of lcpi values and variation of power flows in system severity function are provided. The system is then analysed for fitting STATCOM device. Figure 16 shows after connecting STATCOM device in IEEE 118 bus system voltage deviation in generation outage fuel cost in generation outage, voltage deviation in line outage, fuel cost in line outage, voltage deviation in both outage and fuel cost in both outages. And its performance values are provided in Table 6. Then, the UPFC fitted system is then analysed for voltage deviation and fuel cost in generation outage, in line outage, and both outages. That is illustrated in Figure 17 and its performance is presented in Table 7. Then analyse various conditions of UPFC connected IEEE 118 bus system's voltage deviation, characteristics of system severity function and system severity function with and without the device, which is shown in Figure 18. The IPFC device connected in the IEEE 118 bus system is analysed for voltage deviation and fuel cost in generation outage, line outage, and both outages. That is shown in figure 19 and its performance is presented in Table 8. Then various conditions of IPFC connected the IEEE 118 bus system's voltage deviation, characteristics of system severity function and system severity function with and without the device are analysed, sketched in figure 20. TThen, the TCSC device connected to IEEE 118 bus system and analysed for voltage deviation and fuel cost in generation outage, line outage, and both outages. That is shown in Figure 21 and its performance is presented in Table 9.

Similarly, the performance of the IEEE 300 bus system is analysed. Initially, voltage loss, power loss, voltage deviation, LCPI values, and power flows in system severity function under normal conditions are analysed, and its graphical model is shown in Figure 22. The system is then analysed after fitting STATCOM device in IEEE 300 bus system, and Figure 23 shows device voltage deviation and fuel cost in the three outages. And its performance values are provided in Table 10. Then the UPFC is fitted in the system to analyse voltage deviation and fuel cost in the three outages and is illustrated in Figure 24. Its performance is presented in Table 11. Then analyse various conditions of UPFC connected IEEE 300 bus system's voltage deviation, characteristics of system severity function and system severity function with and without the device, which is shown in Figure 25. The IPFC device connected to IEEE 300 bus system to analyse voltage deviation and fuel cost in the three outages. That is shown in Figure 26 and its performance is presented in Table 12. Then various conditions of IPFC connected the IEEE 300 bus system's voltage deviation, characteristics of system severity function and system severity function with and without the device are analysed, sketched in Figure 27. After that TCSC device is connected to IEEE 118 bus system to analyse voltage deviation and fuel cost in the three outages. That is shown in Figure 28 and its performance is presented in Table 13. The above result proves that the proposed approach is most accurately finds the best location and provide a rapid operation. Compared to existing methods, the proposed approach proves a good performance to secure the power system from power loss and reduce fuel costs.

## 5. Conclusion

The main objectives of the proposed method are to reduce the losses and improve the stability of the system. Facts devices like STATCOM, TCSC, IPFC and UPFC are used to reduce the losses very excellently. These Facts devices carry a mayfly optimization algorithm to reduce the losses very well. The benefits of using Facts devices are reduced fuel cost and more flexibility to operate in critical conditions as well as to reduce losses. The validation of the novel method contains three buses, namely IEEE 30 bus, IEEE 118 bus and IEEE 300 bus system. The Facts devices fit in the weakest bus of these busses individually to observe the performance. The suitable busses are identified by mayfly optimization with six objective functions. The value of objective functions is reduced the main scope of the proposed work. The objective value is high that is the best location of fitting Facts devices because the weakest bus contains the highest losses, fuel cost, and voltage variation. It leads to improving the security of the power system and providing more power to the consumer without loss. After finding the suitable place for Facts devices, the devices are fitted in that location to analyse and observe the performance.

The performance of the novel method is validated based on comparison with the existing methods like PSO, firefly and YYPO techniques. The proper location of fitting Facts devices with mayfly optimization to reduce the losses proficiently. The simulation studies are performed on IEEE 30, 118 and 300 bus systems for four different weather conditions. Finally, the results illustrate that via Facts devices in the optimal location with the optimal parameter settings know how to reduce loss and then drastically improve the security of the power system under critical conditions. In a real-time application, the facts devices are placed in the suitable location of transmission line at IEEE bus system to improve the power transferring capacity and secure the system to avoid economic losses. In the future scope, working methods are enhanced at hybrid MA optimization or other meta-heuristic algorithms. For the fast-growing RES diffusion in the electricity market, specifically in wind turbines, the outcome of wind generation and fitting cost of Facts devices are studied in an advanced manner.

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