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Optimal Power Flow Using Firefly Algorithm with Unified Power Flow Controller

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Abstract

Firefly algorithm is the new intelligent algorithm used for all complex engineering optimization problems. Power system has many complex optimization problems one of which is the optimal power flow (OPF). Basically, it is minimizing optimization problem and subjected to many complex objective functions and constraints. Hence, firefly algorithm is used to solve OPF in this paper. The aim of the firefly is to optimize the control variables, namely generated real power, voltage magnitude and tap setting of transformers. Flexible AC Transmission system (FACTS) devices may used in the power system to improve the quality of the power supply and to reduce the cost of the generation. FACTS devices are classified into series, shunt, shunt-series and series-series connected devices. Unified power flow controller (UPFC) is shunt-series type device that posses all capabilities to control real, reactive powers, voltage and reactance of the connected line in the power system. Hence, UPFC is included in the considered IEEE 30 bus for the OPF solution.

Keywords

Real Power Loss, Fuel Cost, Optimal Power Flow, Unified Power Flow Controller, Firefly Algorithm

1. Introduction

In power engineering bus voltage, real, reactive power flow needs to calculate for proper operation and planning. This information may derive from power flow analysis, and that does not include economic operation. "Optimal Power Flow" (OPF) was introduced in 1968 [1], including economic operation along with information of real, reactive power. The prime objective of OPF is to minimize the fuel cost by optimizing the real power generation.

OPF problem may have multi-objectives and become non-linear and constrained optimization problem. Tra-

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ditionally, OPF problem has been solved for various types of objectives are converted into one objective problem [2]-[4]. But the result of a solution gives importance to any one objective. OPF problem finds an optimal generating pattern for multi-objectives, and has equality and inequality constraints. Differential evolution (DE), an intelligent algorithm used to find OPF solution that aimed to reduce transmission line loss [5]. The same set of control variables in addition to UPFC control variables is considered for firefly algorithm. P and Q decomposition method was used to find optimal reactive power dispatch. It has the same of an objective of OPF that is to minimization of the generating cost [6]. OPF that was solved by conventional gradient method was inferior in the solution and struck to local minima [7]. From the Recent research, the intelligent algorithms have been found superior to solve many of power systems problems, particularly optimal power flow [8] [9]. The problem of tuning control variables using LP (linear programming) [10], nonlinear programming [11] and mixed-integer programming [12] is not efficient to find global minima and may strike local minima. FACTS devices are power electronics converters used to process voltage and current waveforms to control power, voltage and impedance. These devices may connect in parallel or series to the power system and hybrid devices have both parallel and series connection as like UPFC [13]. It is a hybrid of STATCOM (Static Compensator)—parallel device and SSSC (static synchronous series compensator)—series device. These two devices are back to back connected to the common DC voltage source. Hence, UPFC has two converters: one connected in parallel and another one in series. Shunt connected converters' prime objective is to maintain rated DC link voltage and independently control power flow in the connected bus. The main work of UPFC is done by series converter uses DC link voltage and control power, voltage, phase angle and impedance of the series-connected transmission line. UPFC connection reduces the losses, which is equivalent of power generation and hence the power generation cost is reduced [14]. UPFC increases voltage level and further reduces the losses and controls the power flow to aid the objective of OPF. The effective connection of UPFC is decided by an intelligent algorithm to find location and amount of power injection by the UPFC. In genetic algorithm and Differential Evolutionary Algorithms, it is very difficult to find crossover rate and mutation rate for UPFC control variables [15]. UPFC inclusion power flow used NR method [16] was considered for this analysis of power flow. Bacterial Forging algorithm (BFA) is one of the latest intelligent optimization algorithms. This BFA is used for economic load dispatch for generating cost minimization [17]. This algorithm is enhanced and used to solve OPF with FACTS devices [18]. BFA has an inferior selection process that is enhanced with Nelder-Mead method for good optimization. In this paper, multi-objective Optimization for Optimal Power Flow (OPF) along with UPFC is considered, and Firefly Algorithm is used to optimize the multi-objective OPF problem. It is one of the innovative optimization algorithms that will be used for optimizing the objective function. The paper is organized as follows. Problem formulation of the OPF is discussed in Section 2. Section 3 presents about UPFC in the power system, and Section 4 represents a detailed coverage of solving the OPF with UPFC using Firefly algorithm. Section 5 focuses on the test system results. Section 6 gives the conclusion of the work done.

2. Problem Formulations for OPF

OPF is the minimization problem to find the optimal fuel cost and subjected to equality constraints, and inequality constraints. The Objective function is given by the Equations (1) and (2). Generating cost is the fuel cost for the thermal power plant obeys quadratic function given in \$/Hr [19]. The generating cost of all generators in the power system is summed and need to be minimized. The reactive and real power generation should be equal to corresponding power demand and their loss in the system form the equality constraint as given in Equations (3) and (4). Limits on control and dependent variables form the inequality constraints as given in Equations (5) to (9).

$$\text{Minimize} \quad C_t = \sum_{i=1}^{NG} f_i(P_G) \ \ \$/\text{hr} \tag{1}$$

$$\sum_{i=1}^{NG} f_i(P_G) = F_i(x) = \sum_{i=1}^{NG} \left(\alpha_i P_{gi}{}^2 + \beta_i P_{gi} + \gamma_i\right) \tag{2}$$

Subject to

Equality Constraints (3) and (4)

$$\sum_{i=1}^{NG} P_{Gi} = P_D + P_L \quad (3)$$

$$\sum_{i=1}^{NG} Q_{Gi} = Q_D + Q_L \quad (4)$$

Inequality Constraints (5)-(9)

$$P_{gi}^{\min} \le P_{gi} \le P_{gi}^{\max} \quad \text{for } i = 1 \text{ to } N_G \quad (5)$$

$$Q_{gi}^{\min} \le Q_{gi} \le Q_{gi}^{\max} \quad \text{for } i = 1 \text{ to } N_G \quad (6)$$

$$V_i^{\min} \le V_i \le V_i^{\max} \quad \text{for } i = 1 \text{ to } N_B \quad (7)$$

$$T_i^{\min} \le T_i \le T_i^{\max} \quad \text{for } i = 1 \text{ to } N_T \quad (8)$$

$$MVA_i \le MVA_i^{\max} \quad \text{for } i = 1 \text{ to } N_{br} \quad (9)$$

where,

C_t = Total generation cost; α, β, γ = Cost coefficients of the generator;
P_{Gi}, Q_{Gi} = Active and Reactive power generation ith generator;
P_D, Q_D = Active and Reactive power Demand; P_L, Q_L = Active and Reactive power Loss;
V_i = Voltage at *i*th bus; t_i = Transformer tap position; MVA_i = MVA flow in *i*th branch;
NB = Number of buses; NG = Number of generators; NT = Number of transformers;
Nbr =Number of branches;

This constraint minimization of generating cost is achieved by tuning the set of control variables. The set of control variables are generator real power, voltage, transformer tap position and UPFC location and power injection. Considered Firefly algorithm explores the solution space bounded by equality and inequality constraint and find better values for all these control variables. Loss minimization and generating cost minimization combined and the objective problem become multi- objective optimization problem.

3. Flexible AC Transmission Systems (FACTS)

The existing transmission system is laid for AC transmission and has a limitation of power transfer due to thermal constraint and its impedance. To increase the power transfer capability of the transmission system requires the new installation and huge money and time. To solve this bottleneck problem, FACTS devices are introduced which are power electronic devices. By connecting this FACTS device, an impedance of the transmission line may alter and loss thereby temperature of the transmission line. This gives new way for using the existing transmission infrastructure but with enhanced power transfer capability. Based on the connection of these FACTS devices, they are classified as series, parallel, and hybrid FACTS devices. UPFC is one hybrid FACTS device having parallel and series connection [20] as explained in the following section.

Unified Power Flow Controller (UPFC)

It consists of two power electronic converters. These converters are connected back to back to the common DC link. This power electronic converter has three arm bridge thyristors controlled by the control unit. DC link is the capacitor used to store the DC voltage needed for the converter. The first converter is connected in parallel to the transmission line at the sending end. The second converter is connected in series with the transmission line and the injection effect the receiving end bus. UPFC converters are designed to work in medium voltage hence insertion transformers are required to connect high voltage transmission line as shown in **Figure 1**. At sending end first converter takes power that is used to charge the DC link capacitor. Between converters, only real power may exchange since it is a DC link. The second converter takes real power stored in the DC capacitor, and it converted into 3 phase voltage that is injected at receiving end bus. This Vpq injected voltage is added with line voltage V0 the vector sum of these become V01 at receiving end. By changing injected voltage Vpq magnitude and phase angle it is possible to control real, reactive power, voltage regulation and phase angle. To

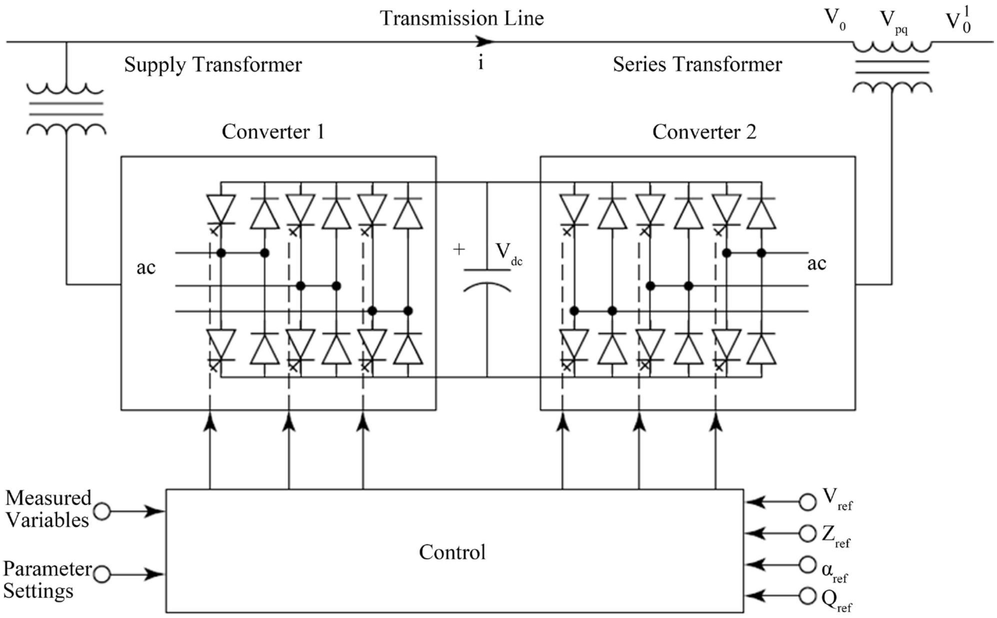

Figure 1. Unified power flow controller block diagram.

control the converter one (shunt converter) control signals VVR and ΘVR are used and for converter two (series converter) control signals VCR and ΘCR are used. These control signals are derived from the control unit that which takes the feedback signals of transmission line voltage, current and reference values of control variables.

4. OPF with UPFC Using Firefly Algorithm

The Firefly optimization technique is used by Yang. X. S in 2008 [21] then it become popular. It mimics flashing characteristic of fireflies to find it mating partner or prey. This paper uses firefly algorithm to solve non-linear constraint OPF problem. This technique used to reduce generating cost, power losses and improve the magnitude of voltage. By controlling transformer turns ratio and VAR outputs UPFC are the control parameters. Firefly algorithm finds global minima in the solution space and gives a best multi-objective solution.

4.1. OPF with UPFC Using Firefly Algorithm

Step 1: Read bus data and line data
Step 2: Select the control variables
Step 3: Create the initial population
Step 4: Find the light intensity or objective of each firefly
Step 5: For the all firefly find the attractive with other firefly based on the light intensity
Step 6: Find distance between the fireflies to move towards brighter one
Step 7: Move the less intensity firefly towards the brighter firefly
Step 8: Repeat the steps 4 to 7 until convergence criterion satisfied
Step 9: Maximum iteration is considered as the convergence and iteration stopped after maximum iteration
Step10: After the convergence print the results
Step11: Stop

4.2. Implementation of Firefly Algorithm

The following are the steps used in the implementation of Firefly Algorithm for Optimal Power Flow is explained as follows. Flowchart for Firefly Algorithm is shown in **Figure 2**.

The fireflies characteristics are the following three rules are given below [22].

1) Fireflies are assumed to be unisex which attracts another one without considering its sex.
2) Less light intensity Firefly move towards brighter Firefly, this attractiveness is inversely proportional to the

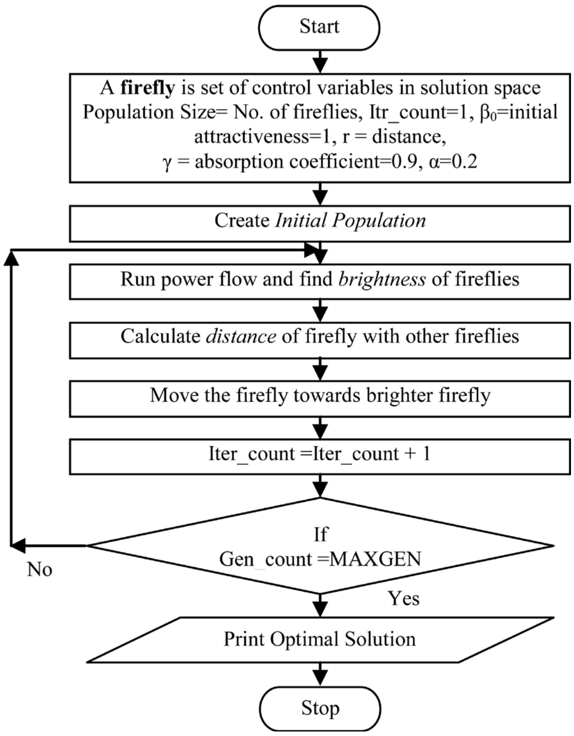

Figure 2. Flowchart of firefly algorithm.

distance between them. If the brighter Firefly could not found, then the firefly moves in the random direction.

3) Brightness of Firefly also subjected to the nature environment, based on this environment the brightness is affected.

5. Results and Discussion

Test case IEEE 30 bus considered to validates the developed algorithm; the parameters considered to evaluate the performance are reactive power, voltage and losses. MATLAB environment is used to develop and implement the program. The IEEE 30 bus system has six generator bus, 24 load bus and 41 transmission lines [23]. For UPFC, three control variables are included in the control variables for the position, shunt and series injection. The optimal real power loss has been identified using the Firefly algorithm. Firefly algorithm finds the minimized power loss of the bus system and corresponding reactive power limits of the generators. The proposed system also analyzes the voltage stability of the system, which is given in the following. The proposed IEEE 30 system structure is given in the following **Figure 3**.

Minimization of Generating Cost and Power Loss

For the economical operation, generating cost has to be minimized as far as possible. This obeys the quadratic cost function. The coefficient of the cost function is given in **Table 1**. Real power generation limits of generators also given in **Table 1**. Transmission line real power loss minimization is the major component of reactive power optimization and it needs more attention [22]. This case takes only the real power loss minimization, voltage improvement and loss minimization lead to minimum generating cost. The problem is solved in the baseline scenario and then it is optimized using firefly algorithm then UPFC is included in the system to get a better optimized result.

The optimal allocation of UPFC in buses and Lines are represented in **Table 2**. In this case, the FFA algorithm better optimizes both real power loss and fuel cost as given in **Table 3**. It shows the comparison results between existing methods and proposed method results. From the results it is clear that UPFC placement given best optimal power flow. The reduction in loss indicated by FFA algorithm is highly encouraging and it is only 4.65 MW. And another important objective of proposed method is fuel cost and it is also reduced to 803.15 $/Hr.

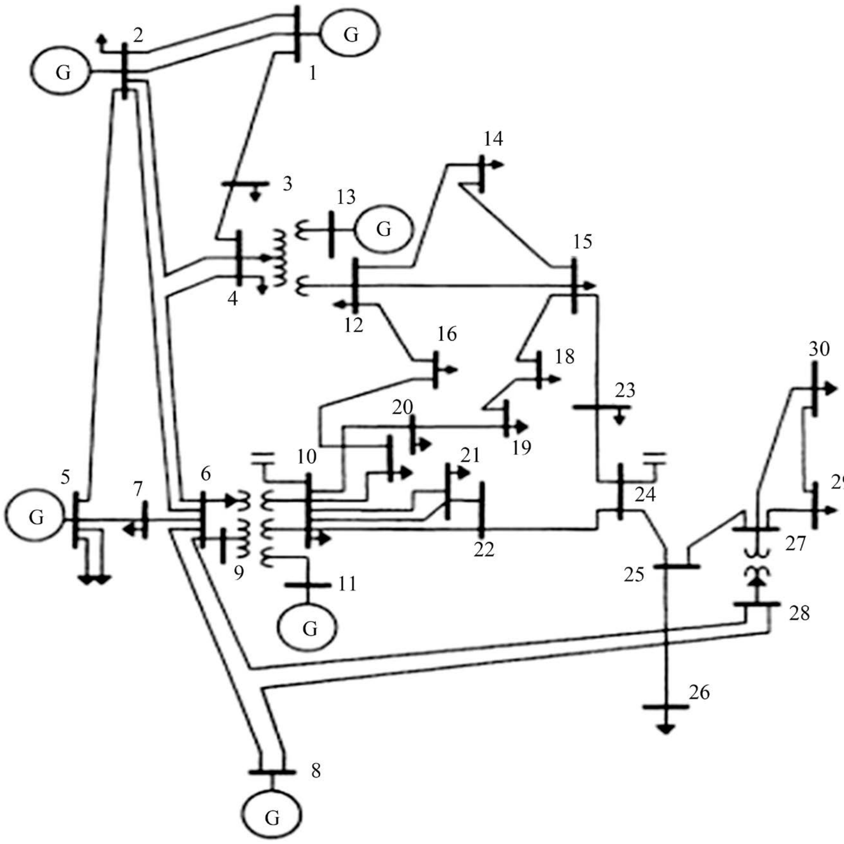

Figure 3. IEEE 30 bus system.

Table 1. Cost coefficients of generator.

S. No	Bus No	Min Real Power (MW)	Max Real Power (MW)	Alpha ($/hr)	Beta ($/Mwhr)	Gamma ($/Mw2hr)
1	1	50	200	0.0038	2	0
2	2	20	80	0.0175	1.75	0
3	5	15	50	0.0625	1	0
4	8	10	35	0.0083	3.25	0
5	11	10	30	0.025	3	0
6	13	12	40	0.025	3	0

Table 2. Optimal location and of power injection of UPFC.

S. No.	Sending end Bus	Receiving end Bus	Shunt MVAr	Series MVAr
1	6	7	4.0736	25.2553

UPFC has shunt and series power injection; Firefly algorithm optimizes the location and value of reactive power injection. STATCOM has shunt power injection and support voltage control there by losses in the transmission line. UPFC has shunt and series power injection and superior to STATCOM. The best location of UPFC is given in the table that is connected between the buses 6 and 7. The corresponding reactive power injection is also given in **Table 2**. To prove the superiority of UPFC the same firefly algorithm and same control variables are used. For the same number of iteration, UPFC provides the better result as compared to STATCOM.

Table 3 gives the comparison of the result, the generating cost and real power losses are less as compared to STATCOM as given in the reference [22]. Voltages in all buses are within its minimum and maximum limit and satisfy the inequality constraint as shown in **Figure 6**. The total power Generation and real power loss of firefly algorithm is compared with other algorithms as shown in **Figure 4** and **Figure 5** respectively. The convergence characteristics of Firefly Algorithm for the multi-objectives of real power loss minimization and cost minimization are plotted in **Figure 6** and **Figure 7**. **Figure 6** gives convergence curve of real power optimization and **Figure 7** gives convergence curve for generating cost optimization.

Table 3. Comparison of objective terms.

S.No	Parameter	Pmin (MW)	Pmax (MW)	Base Case without FACTS device [22]	FFA with STATCOM [22]	FFA with UPFC
1	PG1 (MW)	50	200	229.687	151.314	150.289
2	PG2 (MW)	20	80	20	42.5989	41.857
3	PG5 (MW)	15	50	15	24.0831	23.471
4	PG8 (MW)	10	35	10	31.9497	30.543
5	PG11 (MW)	10	30	10	24.9827	23.481
6	PG13 (MW)	12	40	12	19.5219	18.402
7	Total Generation, MW	---	---	296.687	294.45	288.05
8	Total Demand, MW	---	---		283.4	
9	Real Power Loss, MW	---	---	13.29	11.05	4.65
10	Generating Cost ($/Hr)	---	---	833.70	826.120	803.15

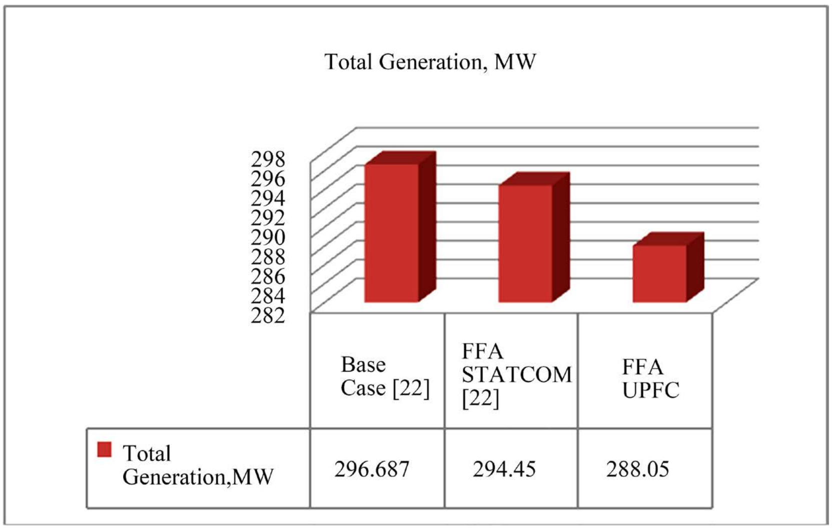

Figure 4. Total power generation.

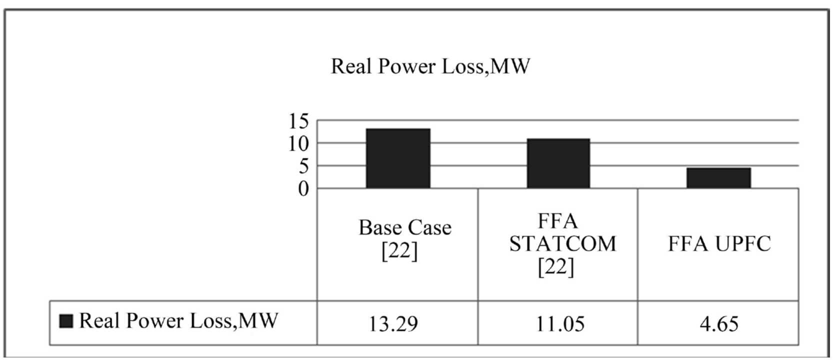

Figure 5. Real power loss, MW.

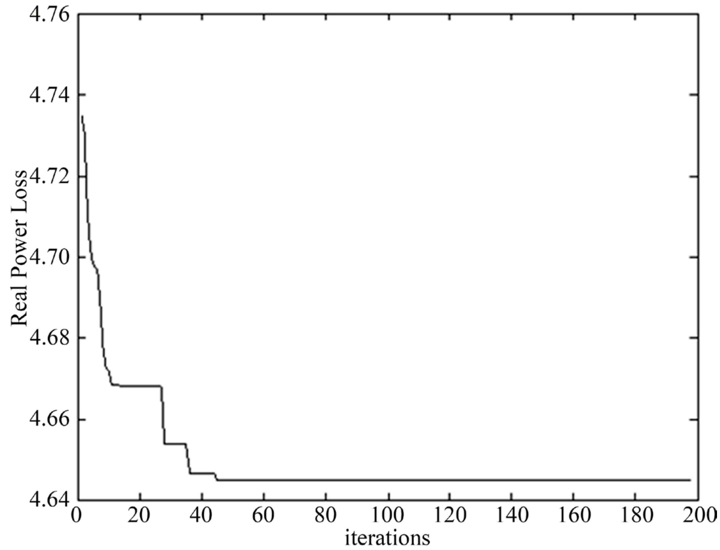

Figure 6. Real power loss.

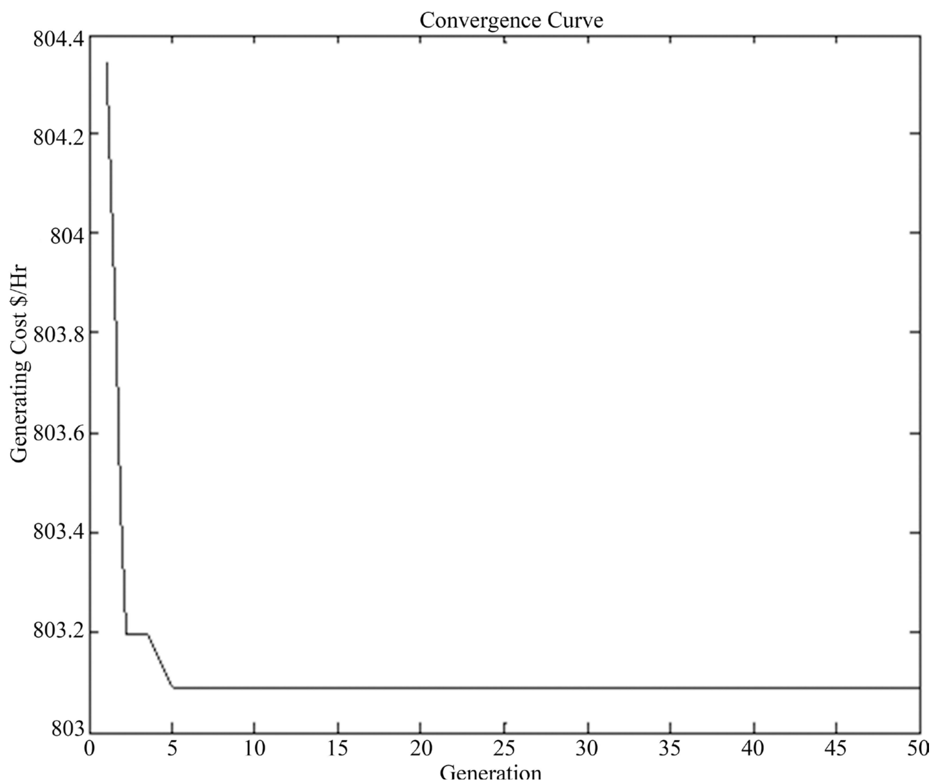

Figure 7. Fuel cost.

6. Conclusion

Firefly Algorithm is implemented to solve OPF with UPFC. The implemented FACTS devices UPFC results are compared to STATCOM, and it is clear that the UPFC outperforms well. Firefly algorithm is used for the both FACTS device to prove the performance of the UPFC. The losses and prime objective of cost minimization of OPF problem are minimized very well when UPFC is included in the system. Voltage profile of all the generator and load buses is within the limit and satisfies constraints that are required for the practical implementation of the developed algorithm.

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