Application of Modified Shuffled Frog Leaping Algorithm on Optimal Power Flow Incorporating Unified Power Flow Controller

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Abstract—**This paper proposes a robust and strong algorithm to solve Optimal Power Flow (OPF) with valve-point effect in power systems involving a Unified Power Flow Controller (UPFC). In a power system, installing the UPFC can improve power transfer capability, transient stability, and system reliability, reduce loss in the transmission network and the fuel cost of generators. In order to apply UPFC in OPF problem, a mathematical model needs to be set for it. In this paper a new model based on the Injection Power Model (IPM) is presented. Due to the nonlinearity of OPF problem, it is essential to use an exact and strong method to solve it. In recent years, evolutionary and heuristic advantages of algorithms in terms of the modeling capability and search power lead to their higher application in the complicate problem like OPF. This paper presents a modified shuffle frog-leaping algorithm (MSLFA) to solve the OPF problem. The MSFLA has a flexible and well balanced mechanism in order to enhance and adapt to global and local exploration abilities. Simulation results on the modified IEEE 30-bus and 5-bus test systems indicate that the proposed MSLFA algorithm approach can obtain better solutions than other optimization algorithms.**

Index Terms—**Evolutionary algorithm, FACTS devices, Optimal Power flow, SFLA , UPFC.**

I. Introduction

Flexible AC transmission system (FACTS) devices are integrated in power systems to control power flow, increase transmission line capability to their thermal limit, and to improve the security of the transmission systems [1,2]. Power electronics were applied to FACTS controllers for rapid response and improved controllability [3,4]. FACTS devices could also be used to minimize the total generator fuel cost when the power flow controls are not needed. Along a variety of FACTS devices, UPFC is a one of the most versatile member of FACTS. In this paper, UPFC is applied in the OPF problem by a new model based on the IPM model.

The UPFC offers a unique combination of fast shunt and series compensations and provides a flexible power system control. Therefore, it can be utilized in the power system to control line active and reactive power, achieve maximum power transfer capability, stabilize system, reduce total generation cost associated with out-of-merit order, significantly improve power system reliability, and help the system operate with more security[5,6]. A mathematical model is required for investigating the effects of UPFC on power system operation. Several models have been suggested for UPFC device in steady-state power flow analysis [7-10]. Some authors modeled this device with modifications of Jacobian matrix [1, 11]. Mihalic [12] introduces a steady-state UPFC model based on a single, ideal, and series voltage source. They used a mathematical decomposition method and a linearized network model (DC load flow). Ge and Chung [13,14] proposed a method to include the power flow control need of UPFC in the OPF, based on linear programming. Kalyan proposed a steady state model suggested in [15] which is based on one ideal series voltage source and one ideal shunt current source. Ambriz-Perez [16, 17] utilizes two ideal voltage sources, one in series and one in parallel, to develop a UPFC steady state model. In the above methods, Jacobian matrix must be calculated in each iterate and it speeds down the calculation greatly. To solve this problem, in this paper a new way of modeling UPFC is presented. In this model Jacobian matrix is constant and needs to be calculated only once in the entire optimization process which speeds up the calculation to a great extent.

OPF control is used to minimize the total generator fuel cost subject to power balance constraint, real and reactive power generation limits, voltage limits and transmission line limits. The development of evolutionary algorithms over the last decade has enabled researchers to consider these issues in a better fashion. The advantages of evolutionary algorithms in terms of the modeling capability and search power have encouraged their application to the OPF problem in power systems.

Many classical techniques have been reported in the literature [18-20] to solve the OPF problem such as nonlinear programming (NLP), quadratic programming (QP) and linear programming (LP). The gradient based methods [4,20] and Newton methods[15] suffer from the difficulty in handling inequality constraints. Moreover, these NLP and QP methods rely on convexity to obtain the global optimum solution and are forced to simplify relationships in order to ensure convexity. To apply linear programming, input output function is to be expressed as a set of linear functions, which may lead to loss of accuracy. Moreover they do not guarantee converge to the global optimum of the general non convex OPF problem. These days evolutionary algorithms have been suggested to overcome the mentioned difficulties of classical methods.

The SLFA algorithm is accurate and general to solve the complicated optimization problems. It can jump from the current searching point into the effective area directly by the

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shuffled process. Generally, SFLA is characterized as simple in concept, easy to implement, and computationally efficient. However the SLFA method could possibly be locked in the local optima points. In this paper, to solve this problem, the MSLFA method is proposed, which benefits from a mutation. This method will be described in detail in the following chapters. The performance of the MSFLA has been tested on IEEE 30 and IEEE 5 bus test system; also, the obtained results are compared with conventional approaches such as genetic algorithm (GA), Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO) and original SFLA. The comparison results show that the efficiency of the proposed approach can reach higher quality solutions than the conventional methods.

II. Description and Model of UPFC

UPFC device consists of two three phase switching converters, a shunt connected transformer, connecting the shunt converter to the transmission line in the shunt and a series connected transformer connecting the series converter to the transmission line in the series, also a dc link provided by a dc storage capacitor [21]. The schematic of UPFC is shown in Fig. 1.

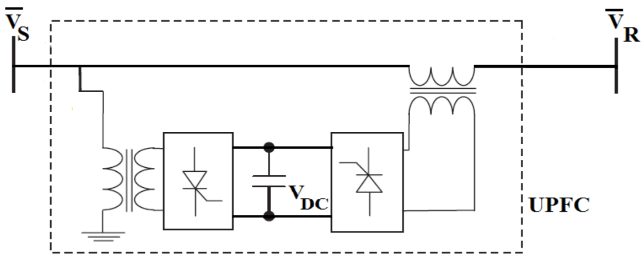


Fig 1. One line diagram of UPFC device

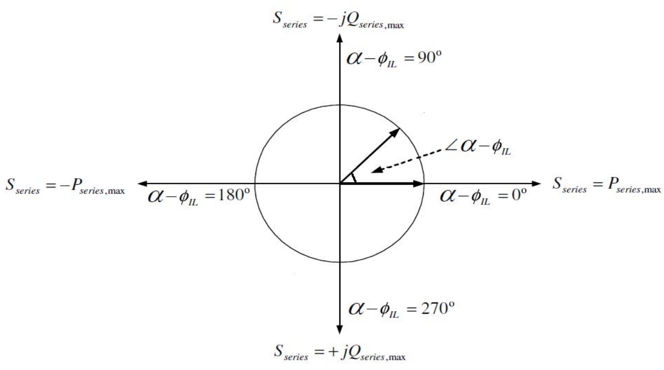


Fig. 2. Effects of real and reactive power exchange between UPFC and power system under different operating conditions.

The main function of the converters is to change a DC input voltage to a symmetrical AC output voltage of desired magnitude, frequency and phase. The functions of the coupling transformers are to isolate UPFC and the transmission line and to match the voltage levels between the line and the voltage produced by the converters. The series converter inserts a voltage of controllable magnitude and controllable phase angle in series with the transmission line via the series connected transformer, thereby provides the control of real and reactive power flow on the transmission line. The real power injected into the system by the series converter should be taken from the parallel converter and transmitted to the series branch over dc link. Over all, the series branch provides the main function by injecting an ac voltage V_{series} at system frequency with variable magnitude, ($0 \le V_{series} \le V_{series\ \max}$) and phase angle, δ_{series} ($0^0 \le \delta_{series} \le 360^0$). During the operation, V_{series} is added to the AC system terminal voltage V_R , by the series-connected coupling transformer. Transmission line current i_{series} flows through voltage source, V_{series} , resulting in real and reactive power exchange between UPFC and the power system. The phase angle of output voltage of series converter, δ_{series} can be chosen independently of the phase angle of line current (ϕ_{IL}), which means that the output voltage of the series branch, V_{series} can be independently controlled without any restriction as depicted in Fig .2. It is clear that the series converter can control active and reactive power in both directions. As shown it Fig .2, UPFC which is a versatile device between FACTS devices can control power flow in the network. This control depends on the purpose, for example in this paper UPFC control and change power flow in line is used to minimize the generation cost.

The shunt converter exchanges a current with the power system, in this manner it can generate or absorb controllable reactive power and provide shunt reactive power compensation. These formations make UPFC an ideal AC to AC power converter. The DC link capacitor is planned to supply a path for the real power exchange between converters and also provide a proper DC voltage required by both converters to control reactive power circulated internally.

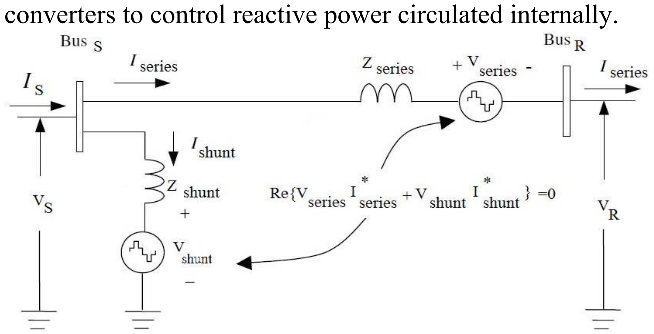


Fig. 3. Unified power flow controller equivalent circuit

The UPFC voltage sources can be presented as the following equations:

$$V_{series} = |V_{series}| \exp(j\,\delta_{series}) = |V_{series}| \times (\cos\delta_{series} + j\sin\delta_{series}) \tag{1}$$

$$V_{shunt} = |V_{shunt}| \exp(j\,\delta_{shunt}) = |V_{shunt}| \times (\cos\delta_{shunt} + j\sin\delta_{shunt}) \tag{2}$$

where V_{shunt} and δ_{shunt} are controllable magnitude ($V_{shunt\min} \le V_{shunt} \le V_{shunt\max}$) and phase angle ($0 \le \delta_{shunt} \le 2\pi$) of the voltage source representing the shunt converter. The magnitude V_{series} and phase angle

δ_{series} of the voltage source representing the series converter are controlled between limits $V_{series\min} \le V_{series} \le V_{series\max}$ and $0 \le \delta_{series} \le 2\pi$, respectively. The equivalent circuit of UPFC is shown in Fig .3.

A. An uncoupled model of UPFC and related equations

The effect of UPFC can be represented as injected power in a network as shown in Fig .4. A large number of efforts have been carried out in the modeling of UPFC for power flow analysis, in the past, but for complication and extension of these models, they are not useful and suitable for OPF analysis.

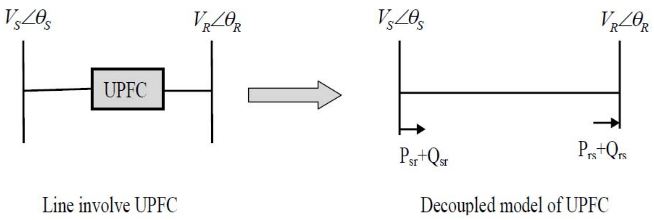


Fig.4. an injected power model of the UPFC

An injected power model of UPFC proposed in this paper is simple and very beneficial for complex problems like OPF. In this model shown in Figure.4 both ends of the UPFC were uncoupled and specified as PV bus(S bus) and PQ bus(R bus), respectively. The injected power model has the advantage of allotting the desired values of the active and reactive power in both of UPFC [22, 23]. In accordance with the basic circuit theory, the injected equivalent circuit of Fig .4 can be obtained. The injected active powers (P_{sr} and P_{rs}) and reactive powers (Q_{sr} and Q_{sr}) of a line which has a UPFC are achieved in the following section of this paper.

B. Related equations for Power flow calculation with UPFC

Based on the equivalent circuit shown in Fig .2 apparent powers at two ends of UPFC device are obtained as follows:

$$S_S = V_S\left(\frac{V_S - V_{shunt}}{Z_{shunt}} + \frac{V_S - V_{series} - V_R}{Z_{series}}\right)^* \quad (3)$$

$$S_R = V_R\left(\frac{V_S - V_{series} - V_R}{Z_{series}}\right)^* \quad (4)$$

where:

$$V_S = |V_S|\angle\delta \quad (5)$$

$$V_R = |V_R|\angle\beta \quad (6)$$

$$V_{series} = |V_{series}|\angle\alpha \quad (7)$$

$$V_{shunt} = |V_{shunt}|\angle\varphi \quad (8)$$

$$Z_{series} = |Z_{series}|\angle\theta \quad (9)$$

$$Z_{shunt} = |Z_{shunt}|\angle\lambda \quad (10)$$

By substituting the (5) to (10) into (3) and (4) we have:

$$S_S = V_S\angle\partial\Big(\frac{V_S\angle\partial - V_{shunt}\angle\varphi}{Z_{shunt}\angle\lambda} + \frac{V_S\angle\partial - V_{series}\angle\alpha - V_R\angle\beta}{Z_{series}\angle\theta}\Big)^* \quad (11)$$

$$S_R = V_R\angle\beta\left(\frac{V_S\angle\delta - V_{series}\angle\alpha - V_R\angle\beta}{Z_{series}\angle\theta}\right)^* \quad (12)$$

By expanding (11) and (12), the following equations are obtained for S_S and S_R respectively.

$$\begin{aligned} S_S = {} & |V_S|\cos(\partial) + j|V_S|\sin(\partial)\Big\{\frac{|V_s|}{|Z_{shunt}|}\cos(\delta-\lambda) \\ & -\frac{|V_{shunt}|}{|Z_{shunt}|}\cos(\varphi-\lambda) + \frac{|V_s|}{|Z_{series}|}\cos(\delta-\theta) - \frac{|V_{series}|}{|Z_{series}|}\cos(\alpha-\theta) \\ & \frac{|V_R|}{|Z_{series}|}\cos(\beta-\theta) - j\frac{|V_S|}{|Z_{shunt}|}\sin(\partial-\lambda) \\ & + j\frac{|V_{shunt}|}{|Z_{shunt}|}\sin(\varphi-\lambda) - j\frac{|V_S|}{|Z_{series}|}\sin(\partial-\theta) + \frac{|V_{series}|}{|Z_{series}|}\sin(\alpha-\theta) \\ & + j\frac{|V_R|}{|Z_{series}|}\sin(\beta-\theta)\ \Big\} \end{aligned} \quad (13)$$

$$\begin{aligned} S_R = {} & |V_R|\cos(\beta) + j|V_R|\sin(\beta)\Big\{\frac{|V_s|}{|Z_{series}|}\cos(\delta-\theta) \\ & -\frac{|V_{series}|}{|Z_{series}|}\cos(\alpha-\theta) - \frac{|V_R|}{|Z_{series}|}\cos(\beta-\theta) - j\frac{|V_S|}{|Z_{series}|}\sin(\partial-\theta) \\ & + j\frac{|V_{series}|}{|Z_{series}|}\sin(\alpha-\theta) + j\frac{|V_R|}{|Z_{series}|}\sin(\beta-\theta)\ \Big\} \end{aligned} \quad (14)$$

By considering the real part of S as active power and imaginary part of it as reactive power, P_{sr} , Q_{sr} , P_{rs} and Q_{rs} are computed as follow:

$$\begin{aligned} P_{sr} = {} & \frac{|V_s|^2}{|Z_{shunt}|}\cos(\delta)\cos(\delta-\lambda) - \frac{|V_s||V_{shunt}|}{|Z_{shunt}|}\cos(\delta)\cos(\varphi-\lambda) \\ & + \frac{|V_s|^2}{|Z_{series}|}\cos(\delta)\cos(\delta-\theta) - \frac{|V_s||V_{series}|}{|Z_{series}|}\cos(\delta)\cos(\alpha-\theta) \\ & - \frac{|V_s||V_R|}{|Z_{series}|}\cos(\delta)\cos(\beta-\theta) + \frac{|V_s|^2}{|Z_{shunt}|}\sin(\delta)\sin(\delta-\lambda) \\ & - \frac{|V_s||V_{shunt}|}{|Z_{shunt}|}\sin(\delta)\sin(\varphi-\lambda) + \frac{|V_s|^2}{|Z_{series}|}\sin(\delta)\sin(\delta-\theta) \\ & - \frac{|Vs||Vseries|}{|Zseries|}\sin(\delta)\sin(\alpha-\theta) - \frac{|Vs||VR|}{|Zseries|}\sin(\delta)\sin(\beta-\theta) \end{aligned} \quad (15)$$

$$\begin{aligned} Q_{sr} = {} & \frac{-|V_s|^2}{|Z_{shunt}|}\cos(\delta)\sin(\delta-\lambda) + \frac{|V_s||V_{shunt}|}{|Z_{shunt}|}\cos(\delta)\sin(\varphi-\lambda) \\ & - \frac{|V_s|^2}{|Z_{series}|}\cos(\delta)\sin(\delta-\theta) + \frac{|V_s||V_{series}|}{|Z_{series}|}\cos(\delta)\sin(\alpha-\theta) \\ & + \frac{|V_s||V_R|}{|Z_{series}|}\cos(\delta)\sin(\beta-\theta) + \frac{|V_s|^2}{|Z_{shunt}|}\sin(\delta)\cos(\delta-\lambda) \end{aligned}$$

$$-\frac{|V_s||V_{shunt}|}{|Z_{shunt}|}\sin(\delta)\cos(\varphi-\lambda)+\frac{|V_s|^2}{|Z_{series}|}\sin(\delta)\cos(\delta-\theta)$$
$$-\frac{|V_s||V_{series}|}{|Z_{series}|}\sin(\delta)\cos(\alpha-\theta)-\frac{|V_R||V_s|}{|Z_{series}|}\sin(\delta)\cos(\beta-\theta) \quad (16)$$

$$P_{rs}=\frac{|V_s||V_R|}{|Z_{series}|}\cos(\beta)\cos(\delta-\theta)-\frac{|V_s||V_{series}|}{|Z_{series}|}\cos(\beta)\cos(\alpha-\theta)$$
$$-\frac{|V_R|^2}{|Z_{series}|}\cos(\beta)\cos(\beta-\theta)+\frac{|V_s||V_R|}{|Z_{series}|}\sin(\beta)\sin(\delta-\theta)$$
$$-\frac{|V_R||V_{series}|}{|Z_{series}|}\sin(\beta)\sin(\alpha-\theta)-\frac{|V_R|^2}{|Z_{series}|}\sin(\beta)\sin(\beta-\theta) \quad (17)$$

$$Q_{rs}=\frac{-|V_R||V_s|}{|Z_{series}|}\cos(\beta)\sin(\delta-\theta)+\frac{|V_R||V_{series}|}{|Z_{series}|}\cos(\beta)\sin(\alpha-\theta)$$
$$+\frac{|V_R|^2}{|Z_{series}|}\cos(\beta)\sin(\beta-\theta)+\frac{|V_s||V_R|}{|Z_{series}|}\sin(\beta)\cos(\delta-\theta)$$
$$-\frac{|V_R||V_{series}|}{|Z_{series}|}\sin(\beta)\cos(\alpha-\theta)-\frac{|V_R|^2}{|Z_{series}|}\sin(\beta)\cos(\beta-\theta) \quad (18)$$

III. Description of OPF Problem and its Objective Function

OPF is a static, nonlinear optimization problem, which calculates a set of optimum variables from the network state, load data and system parameters. Optimal values are computed in order to achieve a certain goal such as generation cost minimization or line transmission power loss minimization subject to equality and inequality constraints. The OPF is, hence, the basic tool allows electric utilities to determine secure and economic operating conditions for an electric power system. Generally the problem is formulated as described in the next section. The objective function of the OPF is to reflect the cost associated with generating power in the system. The objective function for the entire power system can be written as the sum of the fuel cost model for each generator:

$$F(X)=\sum_{i=1}^{N_g} a_i P_{gi}^{\,2}+b_i P_{gi}+c_i \quad (19)$$

Since the bold line in Fig .5 gives a more pragmatic approximation for the generator cost function, it will be used instead of the quadratic function. The ripples in the bold line cost function curve depict the valve point effect. As shown in Fig .5, the curve contains higher order non linearity rather than the smooth cost function due to the valve point effects. In order to obtain a more accurate model, which takes the valve point effects into account, the cost function is modified to include the ripple curve.

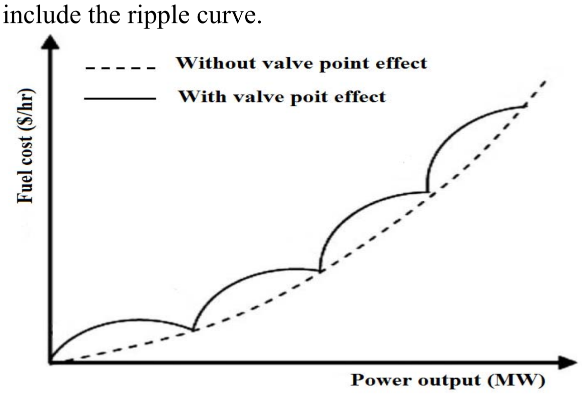


Fig. 5. Generator cost function with and without valve point effect

This can be done by adding sinusoidal functions to the quadratic function as follows [24]:

$$F(X)=\sum_{i=1}^{N_g} a_i P_{gi}^{\,2}+b_i P_{gi}+c_i+\left|d_i\times\sin(e_i\times(P_{gi}^{\min}-P_{gi}))\right| \quad (20)$$

where X is the vector of control variables consisting of real power generation of PV_{bus}, bus voltage consists of both the slack bus and PV_{bus}, the reactive power generation of the compensator capacitor and tap of transformers.

a_i, b_i, c_i, d_i and e_i are the cost function coefficients of unit, P_{gi} is the real power generation of unit i, Ng is the total number of generation units and $i=1,2,...,N_g$ Therefore, X can be expressed as:

$$X=[V_{slack\ bus}, V_{PV\ bus}, P_{PV\ bus}, Q_c, tap_{transformers}] \quad (21)$$

The OPF equality constraints reflect the physics of the power system, equality constraints are expressed in the following equations:

$$P_i=P_{gi}-P_{di}=\sum_{j=1}^{n} V_i V_j (G_{ij}\cos\theta_{ij}+B_{ij}\sin\theta_{ij}) \quad (22)$$

$$Q_i=Q_{gi}-Q_{di}=\sum_{j=1}^{n} V_i V_j (G_{ij}\sin\theta_{ij}-B_{ij}\cos\theta_{ij}) \quad (23)$$

where $i=1,2,.....,n$ and $\theta_{ij}=\theta_i-\theta_j$, that θ_i and θ_j are the voltage angle of two ending bus of an arbitrary branch, and n is expressed as the number of the buses.

The inequality constraints of the OPF reflect the limits on physical devices in the power system as well as the limits created to ensure system security that they are presented in the following inequalities:

$$P_{gi\min}\le P_{gi}\le P_{gi\max} \quad , i=1,2,....,Ng \quad (24)$$

$$Q_{gi\min}\le Q_{gi}\le Q_{gi\max} \quad (25)$$

$$|P_{ij}|\le P_{ij\max} \quad (26)$$

$$V_{i\min}\le V_i\le V_{i\max} \quad , \quad i=1,2,.....,Nl \quad (27)$$

where Ng is the number of generators, Nl load buses number and P_{ij} is the power that flows between bus i and bus j. $V_{i\max}$ and $V_{i\min}$ voltages are maximum and minimum valid voltages for each bus respectively, also $P_{ij\max}$ is the maximum power flows through the branch. $P_{gi\max}$ and $P_{gi\min}$ are the maximum and minimum active permitted generation powers generated at each PV bus. $Q_{gi\max}$ and $Q_{gi\min}$ are similar to $P_{gi\max}$ and $P_{gi\min}$, but the difference is Q which presents the reactive form.

IV. Description of the Shuffled Frog Leaping Algorithm

The OPF problem is a non linear optimization problem. The degree of nonlinearity causes difficulties in solving this problem using classical methods. Therefore, one of the precise stochastic search techniques called MSFLA which is based on SFLA [25] has been applied to solve the OPF problem in this paper. SFLA is a decrease based stochastic search method that begins with an initial population of frogs whose characteristics, known as memes, represent the decision variables. In this algorithm, individual frogs are not too important; rather they are seen as hosts for memes and described as a memetic vector [25]. The algorithm contains elements of local search and global information exchange [26]. In SFLA, the total population is partitioned into groups (memeplexes) that search independently. Partition is done as follows: the population is divided into q memeplexes which each containing p frogs. In this process, the first frog goes to the first memeplex, the second frog goes to the second memeplex, frog p goes to the q_{th} memeplex, and frog $p+1$ goes back to the first memeplex, etc. In each memeplex, the frogs with the best and the worst fitnesses are identified as X_b and X_w, respectively. Also, the frog with the most qualified fitness level among all the memeplexes is identified as X_g. Then, the following process is applied to improve only the frog with the worst fitness in each cycle. Accordingly, the position of the frog with the worst fitness is adjusted as follows:

Change in frog position

$$(C_i) = rand().(X_b - X_w) \tag{28}$$

$$X_w(new) = X_w + C_i \tag{29}$$

$$-C_{\max} \le C_i \le C_{\max}$$

where rand () is a random number between 0 and 1 and $C_{\max}$ is the maximum allowed change in a frogs position. If this process produces a better solution, it replaces the worst frog in each memeplex. If no improvement is achieved in this case, then a new population is randomly generated to replace that frog. The calculations then continue for a specific number of iterations [26]. And this procedure continues till the last iteration is accomplished. The required parameters for implementation MSFLA algorithm are p, q, $iteration_{max1}$ and $iteration_{max2}$. The best values for the aforementioned parameters are p =20, q=5, $iteration_{max1}$=50 and $iteration_{max2}$=100 which determined by 100 times MSFLA algorithm running. Nevertheless there are some privileges, mentioned for SLFA before, some problems exist for it too, such as locked in the local optima and converge to global optima in long time. This paper presented a new strategy in order to support the SLFA drawbacks. This new mode called modified shuffle leaping-frog algorithm (MSLFA) will be presented in details in following section. This goal of the overall process is to determine global optimal solutions.

A. *Modified shuffle frog leaping algorithm*

The original SFLA algorithm has good performance when dealing with some simple problems. However, it is difficult for SFLA algorithm to overcome local minima when handling some complicate functions. Therefore in this paper, a modified SFLA (MSFLA) is proposed to overcome this weak point. In this regard, all the best solutions in each memeplex (X_b) and the solution with the most qualified fitness level among all the memeplexes (X_g) are defined, then the following process is applied to generate mutation vector.

It is necessary to note that the mutation vector dimension is equal to the memeplexes number.

$$X^i_{mut} = X^i_{rand} + rand()(X^i_b - X^i_{rand}) + rand()(X^i_g - X^i_{rand}) \quad i = 1, 2, \ldots.., N_{Mem} \tag{30}$$

where X_b is the best result in each memeplex, X_g is the best solution in all memeplexes, X^i_{rand} is a randomly generated vector, $rand()$ is a random number between 0 and 1and N_{Mem} is the number of memeplexs.

If the generation cost of the trial vector $f(X^i_{mut})$ is better than that of the target vector i.e. $f(X_g)$, the target vector is replaced with the trial vector in the next generation. By this way converge of the global optima can be guaranteed and also getting stuck in a local optimum solution can be prevented.

V. Apply MSFLA in OPF Problem

In this section, the application of SFLA on the OPF problem with UPFC is presented. To apply the SFLA algorithm to solve this problem, the following steps should be taken and repeated.

Step 1: Generate the initial population.

The initial population for each iterate are randomly generated as follows:

$$population = \begin{bmatrix} X_1 \\ X_2 \\ \ldots.. \\ X_F \end{bmatrix} \tag{31}$$

$$X_i = [V_{slack}, V_{PV}, P_{PV}, UPFC_{parameters}, Q_C] \tag{32}$$

where V_{slack} and V_{PV} are voltages of the slack bus and PV buses respectively, P_{PV} is active power generation of PV buses, $UPFC_{parameters}$ involve angles of shunt converter, series converter and amplitude of series converter and Q_C is reactive power value of the compensator capacitor.

Step 2: Calculate objective function value for each individual.

Step 3: Sort the initial population based on the objective function values with decreasing manner.

Step 4: dividing sorted population in memeplexes by following process, the first population goes to the first memeplex, the second population goes to the second memeplex, population q^{th} goes to the q^{th} memeplex, and population $q+1$ goes back to the first memeplex, etc.

Step 5: Select the best and worst population in each memeplex and generate the X_b and X_w for them respectively.

Step 6: the frog with the global best fitness in all memeplexes is identified as X_g .

Step 7: a process is applied to improve only the frog with the worst fitness according to (29), if this process produces a better solution, it replaces the worst frog. Otherwise, a new population is randomly generated to replace that population. This process continues for a specific number of iterations ($itetation_{max1}$)

Step 8: in this section all memeplexes are combined and sorted again.

Step 9: apply mutation in order to compensate SFLA drawbacks mentioned in the previous section.

Step 10: If the current iteration number ($iteration_{max2}$) reaches the predetermined maximum iteration number, the search procedure is stopped, otherwise it goes to Step 4.

Step 11: The last X_g is the solution of the problem.

VI. Numerical Results

In order to illustrate the efficiency and robustness of the proposed MSLFA algorithm, two case studies were performed. In the first case study, we considered the five-bus test system described in [27], this time without any FACTS device. In the second case study, we consider the IEEE 30-bus test system given in [28] with a quadratic model of generator cost curves with UPFC device. The system data of 30-bus and 5-bus systems are given in Appendix A. In the five-bus test system shown in Figure7, there are 5 buses containing two generator buses. Bus #1 is the slack bus, bus #2 is as PV generator bus and the rest are PQ load buses and one compensator capacitor installed at bus #4. The results of the proposed approach were compared to other algorithms such as Particle Swarm Optimization(PSO), Genetic Algorithm (GA) [29], Ant Colony Optimization (ACO) [29] and original SFLA that all of these algorithms , done in MATLAB 8.1 environment. Test results show the superiority of the proposed approach over these methods. The parameters required for implementation of the MSFLA algorithm are *p*, *q*, $iteration_{max1}$ and $iteration_{max2}$. In this paper, the best values for the aforementioned parameters are p =30, q=10, $iteration_{max1}$=50 and $iteration_{max2}$=100 determined by 100 times SFLA algorithm running. The minimum and maximum of control variables are shown in Tables .I, II, III for 5-bus, 30-bus and UPFC parameters, respectively.

TABLE I Five-bus Test System Network Generators Data

Number of generator	a	B	c	P_{max}	P_{min}
G1	.042	7.5	75	125	20
G2	.042	7.5	75	125	20

The best solutions of different algorithms are shown in table 4 for 5 bus IEEE test system without UPFC. It is clear that MSFLA obtained a better result with respect to other algorithms. Also average and standard deviation for 50 trials are depicted in this table, the low standard deviation means that all results approach the average and it is a sign that the optimization algorithm could obtain a proper result in all trials.

TABLE II Fuel Coefficient, P_{MAX} and P_{MIN} of Generators for IEEE 30 Bus Network

generator	a	b	C	D	e	P_{max}	P_{min}
G1	.0375	2.00	0	18	.037	250	0
G2	.0175	1.75	0	16	.038	80	0
G3	.0625	1.00	0	14	.040	50	0
G4	.0083	3.25	0	12	.045	55	0
G5	.025	3.00	0	13	.042	30	0
G6	.025	3.00	0	13.5	.041	40	0

TABLE III Maximum and Minimum Value of UPFC Parameters

UPFC parameters	Max	Min
Angle of series converter	2π	0
Angle of shunt converter	2π	0
Amplitude of series converter	.5(pu)	0

TABLE IV Power Generation and Generation Cost for 5-bus System Without UPFC

	GA	ACO	PSO	SFLA	MSLFA
best result	2012.29	2012.25	2012.28	2012.22	2012.21
average	…………	………	2013.61	2012.65	2012.34
Standard deviation	………	………	0.32475	0.20483	0.11114

No UPFC existed in achieving 5-bus test system (case1) results and this case is put forward only to examine the presented algorithm. From Table .IV, it is obvious that the proposed algorithm is superior for solving OPF problem compared to other methods mentioned above.

The obtained results of some different number of runs are displayed in Fig .6, as it clear from this figure that the obtained results are very identical. Ofcourse some small diffrences exist between them, which indicates the convergence of the proposed algorithm in different iterations.

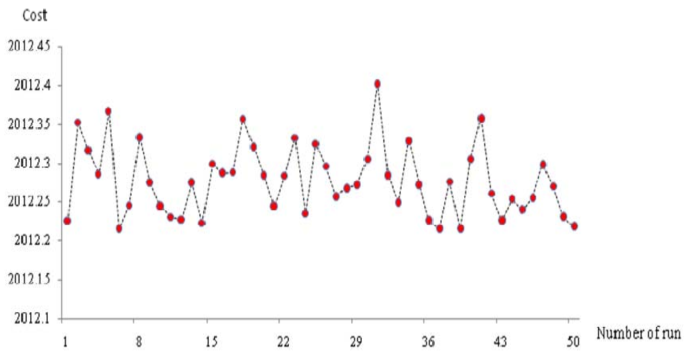


Fig .6. Variation range of best results for 5-bus test system

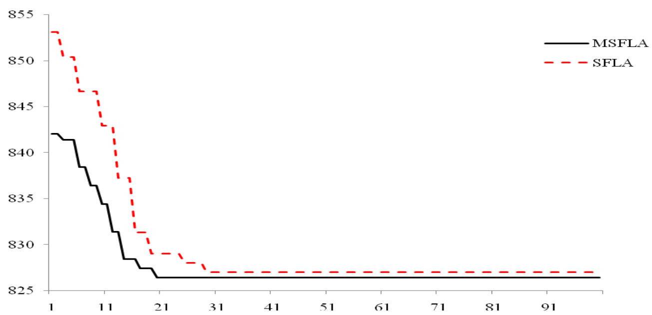


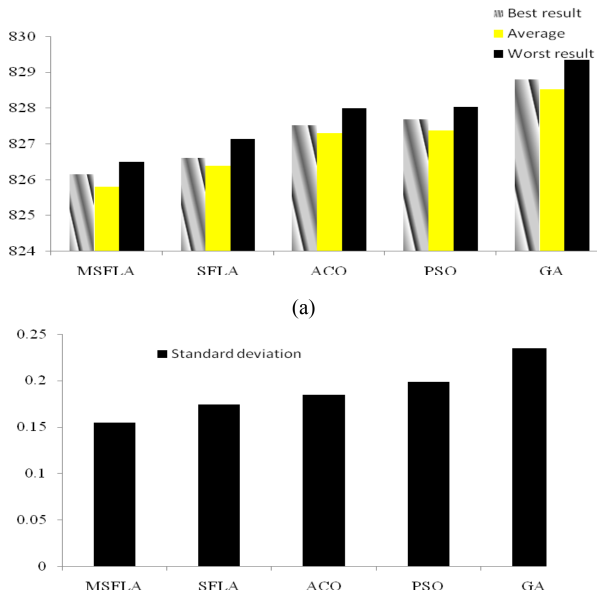
Fig.7. convergence plots for different algorithms

Fig .7 shows the variation of the total fuel cost of the best dispatch result obtained by the proposed MSFLA, SFLA, PSO, GA and ACO algorithms versus the number of generation during the evolutionary process. From Fig .7, it can be seen easily that the proposed algorithm has better convergence property compared to other algorithms when applied to solve OPF problem.

The best solutions of different algorithm are shown in Table .V for 30 bus IEEE test system without UPFC. Similar to table 4 MSFLA also obtained a better result with respect to other algorithms in this case.

TABLE V POWER GENERATION AND GENERATION COST FOR 30-BUS SYSTEM WITHOUT UPFC

	GA	PSO	ACO	SFLA	MSFLA
P_{g1}	206.258	205.250	205.249	205.254	206.365
P_{g2}	21.6903	20.6915	20.6916	22.7907	22.5811
P_{g3}	21.4191	22.2169	23.7173	21.4178	18.6180
P_{g4}	15.3434	13.5429	13.5440	14.9438	14.8427
P_{g5}	12.6077	12.4056	11.908	12.6081	10.7069
P_{g6}	19.6761	21.8758	20.8743	19.6749	22.8754
Cost	828.515	827.361	827.29	826.373	825.789



(a)

(b)

Fig. 8. Comparison of average, best result, worst result and standard deviation for 50 trails

Fig .8 shows the best and worst result, average and standard deviation for GA, PSO, ACO, SFLA and MSFLA for cost objective function. It is clear that MSFLA obtained a lower value and has a better standard deviation, best result and worst result compared to other algorithms.

From Table VI, it is clear that the proposed MSLFA algorithm can provide better results with less total fuel cost compared to the standard PSO, GA, ACO and SFLA algorithms. Also, it's clear that by setting UPFC in the power network the generation cost will reduce, which leads to a rise in peoples' welfare.

From Fig .9, it can be seen that the variation range of the total cost value of the best OPF result obtained from each independent simulation is relatively small, and all these total cost values are equally distributed between the minimum and the maximum total cost values without any bias, thus demonstrating the robustness of the proposed algorithm for solving the OPF problem.

TABLE VI POWER GENERATION AND GENERATION COST FOR 30-BUS SYSTEM WITH UPFC

	GA	PSO	ACO	SFLA	MSFLA
P_{g1}	215.528	213.524	213.019	213.613	214.020
P_{g2}	34.1508	34.4510	36.5506	34.5045	34.2039
P_{g3}	12.1472	14.1435	15.0000	15.1184	15.1179
P_{g4}	12.5418	12.5421	10.0000	10.0532	10.3650
P_{g5}	11.1372	10.1367	10.0000	10.7131	10.1429
P_{g6}	10.5630	11.5630	12.0000	12.1010	12.1003
Cost	817.515	816.534	815.786	815.160	814.796

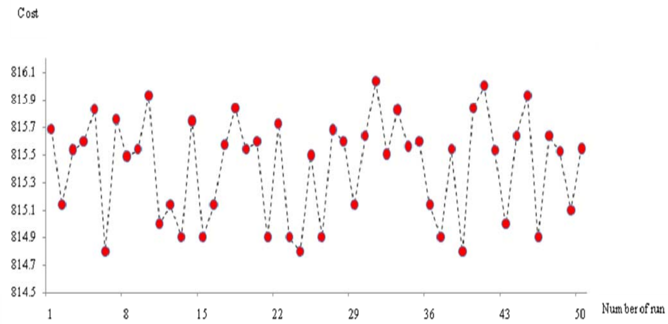


Fig. 9. Variation range of best results

As follows, the series converter amplitude of UPFC is changed and the results are shown in table .VII, it is obvious that by increasing the amplitude of the series converter the cost of generation decreases, but with increasing amplitude of the series converter the UPFC installation cost increases also, therefore we should have tradeoff among the UPFC cost and the amplitude of the series converter.

TABLE VII EFFECTIVENESS OF AMPLITUDE SERIES CONVERTER ON COST GENERATION

amplitude of series converter	.1 P.U	.2 P.U	.3 P.U	.4 P.U	.5 P.U
cost of generation	815.48	814.247	813.0149	810.621	808.955

VII. CONCLUSIONS

A new power injection model of UPFC was proposed in this paper to investigate its function. This model is incorporated in Newton Raphson algorithm for optimal power flow studies. It was found that the UPFC decreased the total fuel cost of generators as well as regulated the active and reactive power of the buses and the lines within specified limits. Putting UPFC in power network makes equations become more complicated, thus optimal OPF problem with UPFC device is solved with the help of a modified shuffled frog-leaping algorithm which is a strong optimization algorithm in this paper. It has been observed that MSLFA algorithm is a simple but powerful tool for power system optimization problem with nonlinear objectives and constraints. The results obtained are compared with those obtained from other variations of evolutionary algorithms and obvious that MSFLA approach achieves better solutions than PSO, GA, ACO, and original SFLA on the modified

IEEE 30 bus system with UPFC fixed at the given locations. From the results obtained, it is concluded that this algorithm is an efficient way of reducing the cost of generation. The experiment results show the proposed MSFLA algorithm can obtain better result and convergence property in solving OPF problem compared with other methods, so it provides a new effective approach to solve OPF problem. Over all this paper is significant from two sides: 1.The presented model for UFC that holds symmetry of network and also its simplicity. 2. Presented a solving method which is a new strong one for solving nonlinear problems like OPF problem.

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