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Controller Design of STATCOM Using Modified Shuffled Frog Leaping Algorithm for Damping of Power System Low Frequency Oscillations

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Abstract

In this paper, a new modified shuffled frog leaping algorithm (MSFLA)-based approach is proposed for optimal selection of the static synchronous compensator (STATCOM) damping controller parameters, in order to shift the closed loop eigenvalues toward the desired stability region. The optimal selection of the parameters for the STATCOM controller is converted to an optimization problem. To solve this complicated problem by MSFLA, a new frog leaping rule, associated with a new strategy for frog distribution into memeplexes, is proposed to improve the local exploration and performance of the basic shuffled frog leaping algorithm. A single machine infinite bus (SMIB) system has been considered to examine the operation of proposed controllers. Sudden change in the input power of generator is considered as a disturbance. The effectiveness of the proposed controller for damping low frequency oscillations is tested in different loading conditions and results are compared to particle swarm optimization (PSO) and SFLA methods. For the sake of methodology validation, an ordinary SFLA as well as a particle swarm optimization (PSO) are both applied to solve the same problem in different loading conditions. Simulation results show the potential and superiority of the proposed MSFLA over the SFLA and PSO.

Keywords: *Modified Shuffled Frog Leaping Algorithm, Low Frequency Oscillations Damping, Particle Swarm Optimization, Static Synchronous Compensator.*

1. Introduction

As power systems became interconnected, areas of generation were found to be prone to electro-mechanical oscillations. These oscillations have been observed in many power systems worldwide [1]. Typical range of these oscillations is in the range of 0.2 to 3 Hz. If these low frequency oscillations are not well damped, these may keep growing in magnitude until loss of synchronism results [1–3]. Power system stabilizer (PSS) is possibly the first measure that has been used to improve damping of oscillations. PSSs have proven to be efficient in performing their assigned tasks, which operate on the excitation system of generators. However, PSSs may unfavorably have an effect on the voltage profile, may result in a leading power factor, and may be unable to control oscillations caused by large disturbances such as three phase faults which may occur at the generator terminals [2–3]. Some of these were due to the limited capability of PSS, in damping only local and not inter-area modes of electro-mechanical oscillations [4]. Recently, the fast progress in the field of power electronics has opened new opportunities for the application of the flexible AC transmission systems (FACTS) as one of the most useful ways to improve power system operation controllability and solving various power system steady state control problems, such as voltage regulation, transfer capability enhancement, power flow control and damping of power system oscillations [3], [5–6]. Static synchronous

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compensator (STATCOM) is one of the important FACTS devices and can be used for dynamic compensation of power systems to provide voltage support and stability improvement [7]. The application of STATCOM based controllers for power oscillations damping and dynamical stability improvement can be found in several references [8–14]. In this field, optimization methods such as genetic algorithm [10], particle swarm optimization (PSO) [11–12], chaotic optimization algorithm [13] and Honey Bee Mating Optimization [14] for obtaining parameters of STATCOM controller are used.

The shuffled frog leaping algorithm (SFLA) is a new and very strong method for optimization and has emerged as a useful tool for engineering optimization. So it is used in multiple applications, such as static synchronous compensator for transient stability improvement of a grid-connected wind farm [15], solving unit commitment problem [16] or optimal placement and sizing of distributed generation units in distribution networks [17].

In this study, STATCOM damping controller designing using modified shuffled frog leaping algorithm (MSFLA), is presented. To show effectiveness of the proposed method, it is compared to ordinary SFLA and PSO techniques. STATCOM based damping controller is considered as an optimization problem and all three, MSLFA, SFLA and PSO techniques are used for searching optimized parameters. The effectiveness and robustness of the proposed controller are demonstrated through time-domain simulation and some performance indices studying the damping of low frequency oscillations under various loading conditions and large disturbances.

2. Description of the Proposed Optimization Method

2.1. Overview of Shuffled Frog Leaping Algorithm

The SFLA is a meta-heuristic algorithm inspired by the memetic evaluation of a group of frogs, seeking for food [18]. It was originally introduced by Eusuff and Lansey in 2003 [19]. The algorithm starts with an initial randomly generated population of 'P' hypothetical frogs. The position of the *i*th frog in a S-dimensional problems (S variables) is determined with $X_i = [x_{i1}, x_{i2}, \ldots, x_{is}]^T$. The fitness of each frog evaluates based on its position in the solution space, using a defined fitness function. Then, the frogs are sorted in descending order, according to their fitness values. In the next stage, the population is divided into *m* subsets called memeplexes. Each memeplex consist of *n* frogs such that $P=m\times n$. In the division stage, the first frog goes to the first memeplex, the second one goes to the second memeplex, the *m*th frog goes to the *m*th memeplex, and the (*m*+1)th frog backs to the first memeplex, and so on. The dividing procedure continues until all frogs are divided in the memeplexes. In the next stage, called local search, the frog with the worst fitness (X_w) and the frog with the best fitness (X_b) are first determined in each memeplex. Then, worst frog position is adjusted by using the frog leaping rule during the memeplex evolution as follows:

$$Position\ Change\ (D_i) = rand() \times (X_b - X_w) \tag{1}$$

$$X_w(new) = X_w + D,\ \ (\|D\| \langle D_{\max}) \tag{2}$$

where rand () is a random number in [0, 1] and D_{max} is the maximum permitted change in a frog's position in one jump. If this process results in a frog with better fitness, it replaces the worst frog; otherwise, the calculations in (1) and (2) are repeated but with respect to the global best frog (X_g), (i.e. X_g replaces X_b). If no improvement becomes possible in this case, the worst frog replace by a new random generated frog. The memeplex evolution process is continued for a specific number of iterations. After this, the frogs are shuffled and sorted again. The local search and the shuffling procedure continue until the termination criterion is met. More details can be found in [18-19].

2.2. Modified Shuffled Frog Leaping Algorithm

Besides the advantages of the SFLA, it has some problems such as slow convergence speed and getting trapped into local optimum. The above problems have common reasons explained as follows:

- As mentioned before, in the SFLA population dividing stage, the frogs with highest fitness values go to the first memeplexes in each step of frog assignment into memeplexes. This strategy is non-homogeneous and causes the first memeplexes performance to be better than the last ones. Hence, because of attending the frogs with lower fitness value in last memeplexes, learning process cannot perform well.

- According to the original frog leaping rule demonstrated in Fig. 1(a), the worst frog cannot jump over the best one. The reason is that, the possible new position of the worst frog is restricted in the line segment between its current position and the best frog's position. As a result, the space around the best frog, where the existence probability of the near optimum solutions is high, cannot be searched well.

The above mentioned problems cause an insufficient learning mechanism in the algorithm and lead to premature convergence and trapping in the local optimum. In this paper, a new strategy for partitioning frogs into memeplexes and a new frog leaping rule is proposed to overcome the problems and to give the algorithm, in search space exploration, a better performance. The improvements are explained in the follows.

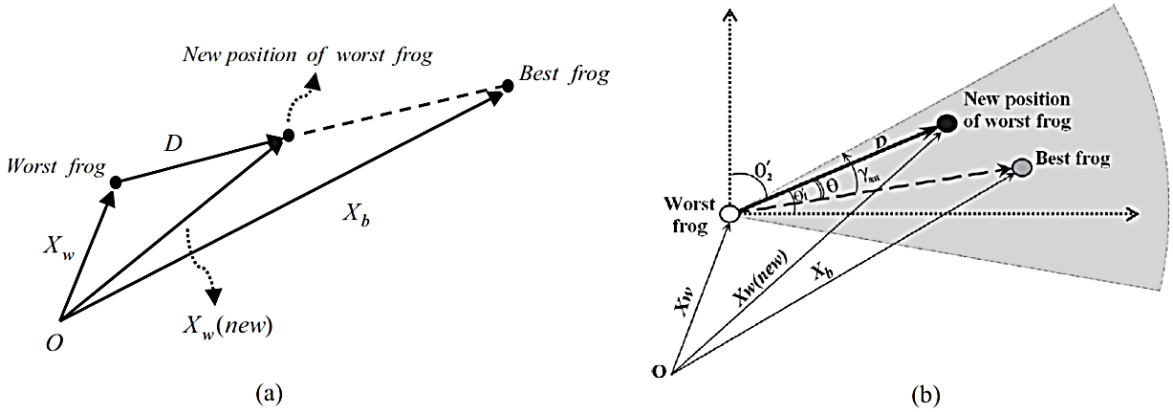


Figure 1. The ordinary frog leaping rule (a), and the new frog leaping rule (b).

2.2.1. New strategy for partitioning frogs into memeplexes

The proposed partitioning method combines the ordinary SFLA memeplex partitioning and the geometric partitioning method, which is addressed in [20]. The main idea in geometric partitioning method is grouping of vicinity frogs in a same memeplex. Similar to center based clustering algorithms, in this method, center position of each memeplex is selected randomly. Then, the frogs are partitioned based on their geometric distance to the center frog. Note that it is possible there are no frogs with a high fitness value in some memeplexes. As a result, the learning process cannot perform well in the memeplexes. To obviate the problem in the proposed partitioning method, the *m* best frogs, in terms of fitness value, go to *m* memeplexes and considered as the center position of the corresponding memeplexes. Then, for the first memeplex, the distance between the center position 1 and all other frogs is calculated and a frog which has less distance to the center position 1 is selected and goes to the memeplex 1. For the second memeplex, the distance between the center position 2 and all other remaining frogs is calculated and the frog which has less distance to center position 2 is selected and goes to the memeplex 2. This process continues until all the frogs are assigned to all memeplexes. It should be noted that all distances are calculated in the Euclidian space. Fig. 2 illustrates the proposed strategy for partitioning a population to memeplexes in a sample 2D Euclidian space. Therefore, using the proposed method, each memeplex have vicinity filled by frogs with a close distance to each other. It also ensures that there is at least one frog with high fitness value. Finally, the proposed method leads to improve the learning process performance.

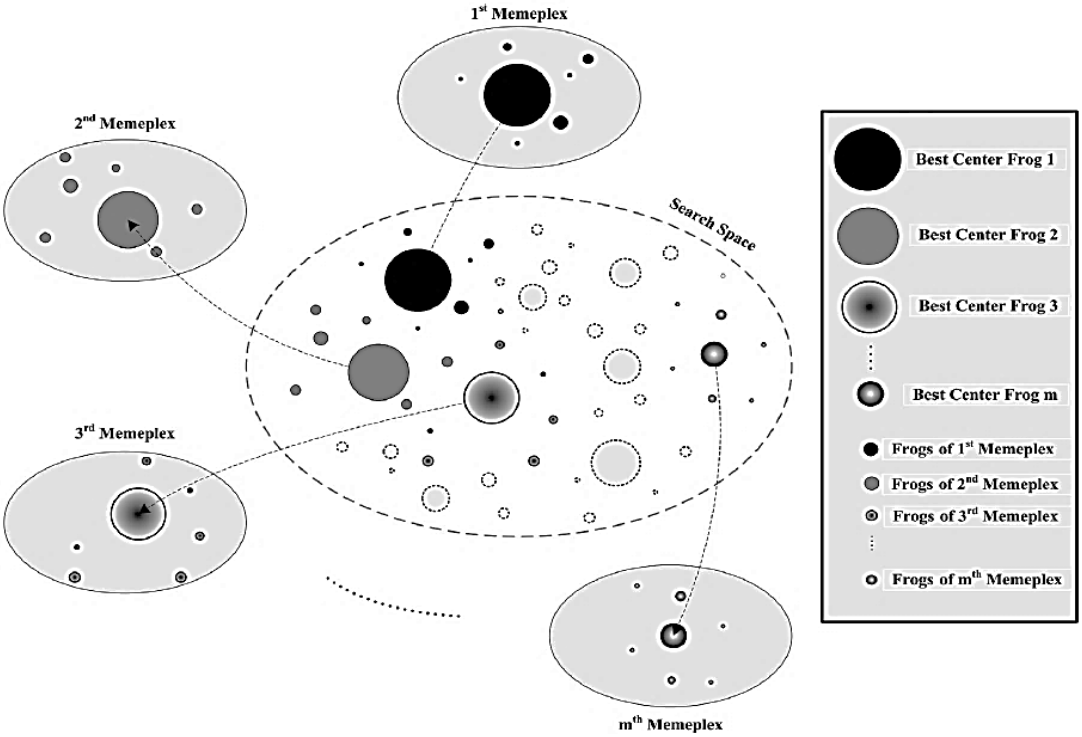


Figure 2. New strategy for population partitioning.

2.2.2. Frog leaping rule modification

The proposed frog leaping rule extends the local search space in each memeplex evolution step by adding a deviation angle ϑ, to the right movement of the worst frog toward the best frog position. The new leaping rule is illustrated in Fig. 1(b) graphically. The figure is depicted for a 2-dimensional problem in which the new position of the worst frog is shown by a bold tick line.

As shown in the figure, the direction of movement is a vector from the worst frog to the best frog. X_w and X_b are vectors that show the position of the worst and the best frogs, respectively. Deviation angle ϑ is added to the direction of movement to search different solutions around the best. X_w (*new*) is a vector of the worst frog's new position after leaping process that is calculated by (3).

$$X_w(new) = X_w + D \tag{3}$$

where D is a vector calculated by the following equations:

$$D = r.\ \|X_b - X_w\|\ .V \tag{4}$$

$$V = [\cos\theta_1' \quad \cos\theta_2' \quad \cos\theta_S']^T \tag{5}$$

where r is a uniformly distributed random number in the interval of $[0, C_{max}]$. C_{max} is a constant that determines the maximum allowed distance in one jump and must be greater than one. Value $C_{max} >> 1$ gradually results in divergence of the worst frog from the best frog. For value C_{max} very close to 1, the search ability is reduced. Moreover, ϑ'_i is deviation angle from direct movement of the worst frog toward the best frog in the ith dimension of the search space, that is calculated by (6) and (7).

$$\theta_i' = \cos^{-1}\left(\frac{X_b(i) - X_w(i)}{\|X_b - X_w\|}\right) + \Delta\theta \quad , \quad i = 1,2,\ \ldots\ ,S \tag{6}$$

$$\Delta\theta \approx U(-\gamma_{\max}\gamma_{\max}) \tag{7}$$

In Eq. (7), $\Delta\vartheta$ is a parameter that adjusts the deviation from the original direction, and γ_{max} is decay parameter that modify the area that worst frog randomly searched around the best frog through the local search process.

$$\gamma_{\max} = \frac{\gamma_{\max}^{0}}{I} \tag{8}$$

where I is the algorithm iteration count and γ^{0}_{max} is the initial maximum deviation angle from the original direction that chosen between 0 and π/2. Therefore, γ_{max} has their maximum value in the beginning of the algorithm and steadily decreased as better solutions are found. It should be noted that, since the parameter $\Delta\vartheta$ in Eq. (6) is an angle between γ_{max} and $-\gamma_{max}$ the variation of the deviation angle, ϑ will be in the interval of $[-\gamma_{max}, \gamma_{max}]$. If the repositioning process by Eq. (3) produces a frog with better fitness, it replaces the worst frog; otherwise, the process is repeated with respect to the global best frog (X_g), (i.e. X_g replaces X_b in (4)). In case of no improvement, a new frog within the feasible space is randomly generated to replace the worst frog. The principle of the MSFLA is depicted in Fig. 3.

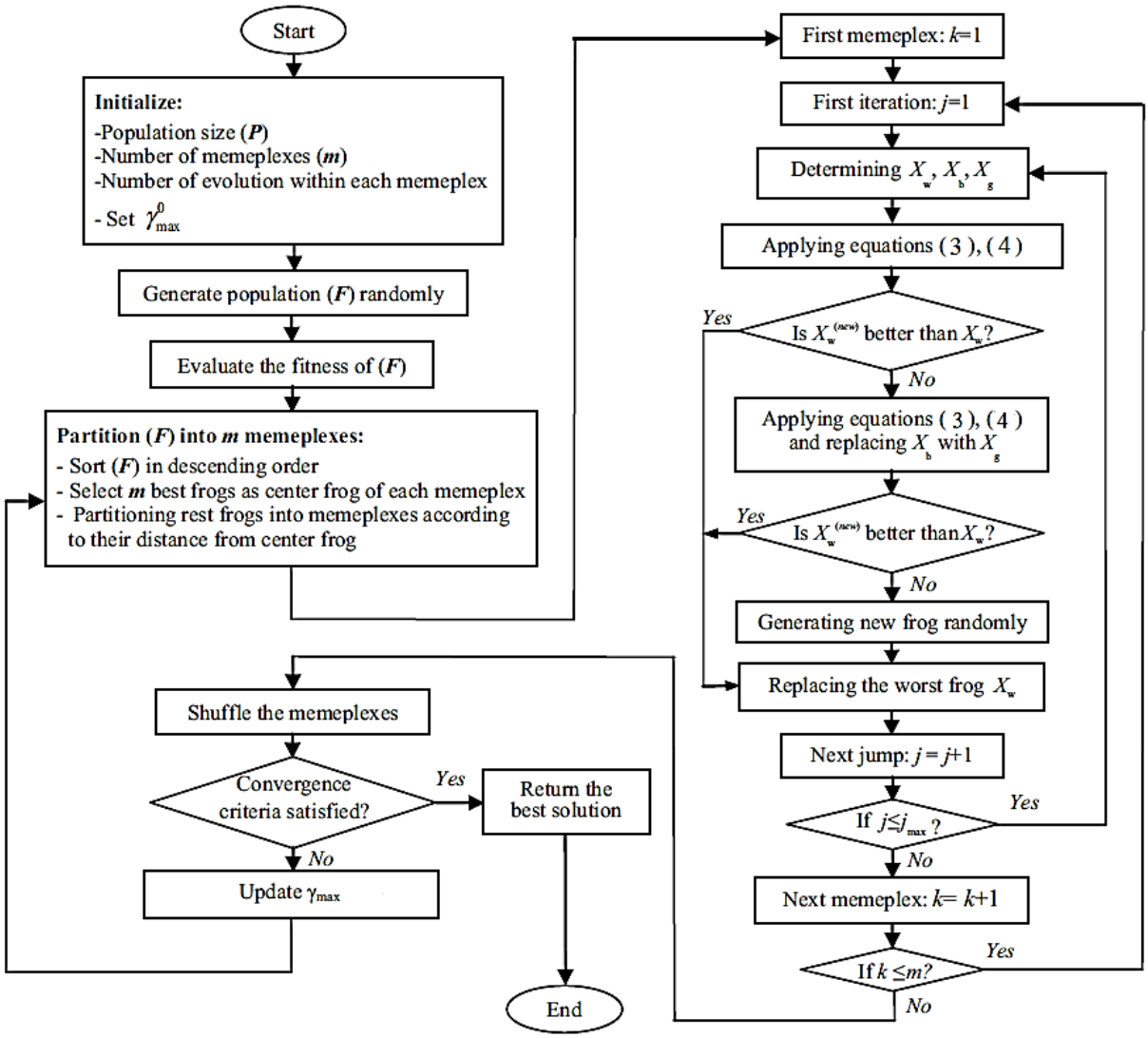


Figure 3. The principle of the MSFLA.

2.3. Overview of Particle Swarm Optimization

Particle swarm optimization was developed by Dr. Kennedy and Dr. Eberhart in 1995 [21]. PSO is one of the most popular optimization algorithms, which was inspired by the swarm behavior to find the global optimal solution. Defining the principle of PSO is out of this paper's scope and the complete review is given in several papers for instance in [21], [11–12].

3. Power System Model with the STATCOM

A Single machine infinite bus (SMIB) power system installed with a STATCOM shown in Fig. 4 is widely used for studies of power system oscillations. It is adopted in this paper to demonstrate the proposed method. The system consists of a step down transformer with a leakage reactance X_{SDT}, a gate turn off based voltage source converter, and a DC capacitor [8].

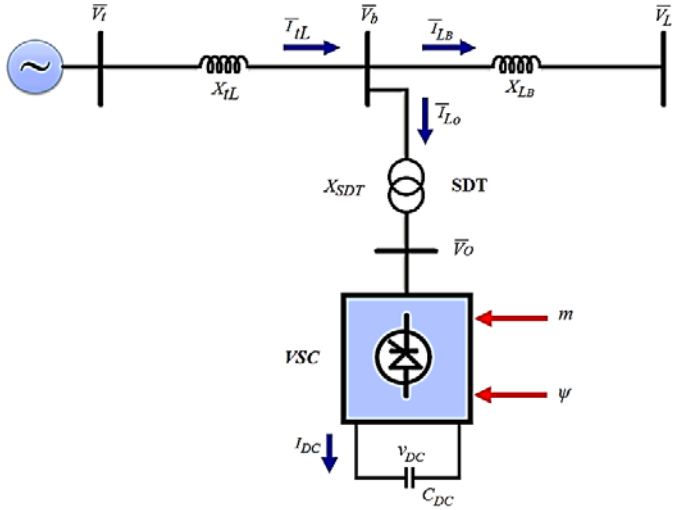


Figure 4. STATCOM installed on a SMIB system.

The STATCOM has 2 input control signals, modulation index *m* and phase ψ. In order to investigate the effects of the STATCOM on increasing the damping of power system low frequency oscillations, its dynamic model is required. Park's transformation is applied and the resistance and transients of the transformer are neglected, and so, the dynamic relation between the capacitor voltage and current in the STATCOM circuit are expressed as [8]:

$$\bar{I}_{LO} = I_{LO}^{d} + jI_{LO}^{q} \tag{9}$$

$$\overline{V_o} = mkV_{DC}(\cos\psi + j\sin\psi) \tag{10}$$

$$\dot{V}_{DC} = \frac{dV_{DC}}{dt} = \frac{I_{DC}}{C_{DC}} \tag{11}$$

$$\dot{V}_{DC} = \frac{mk}{C_{DC}}(I_{LO}^{d}\cos\psi + I_{LO}^{q}\sin\psi) \tag{12}$$

Where *k* is the voltage ratio between the AC and DC sides and is dependent on the inverter structure. The nonlinear dynamic model of the presented power system with STATCOM in Fig. 4 is:

$$\dot{\delta} = \omega_b(\omega - 1) \tag{13}$$

$$\dot{\omega} = \frac{(P_m - P_e - D)(\omega - 1)}{M} \tag{14}$$

$$\dot{E}'_q = \frac{(E_{fd} - E_q)}{T'_{d0}} \tag{15}$$

$$\dot{E}_{fd} = \frac{K_A(V_{to} - V_t) - E_{fd}}{T_A} \tag{16}$$

Where:

$$P_e = E'_q I_{tLq} + (x_q - x'_d)I_{tLd}$$

$$E_q = E'_q + (x_d - x'_d)I_{tLd}$$

$$V_t = \sqrt{(E'_q - X_d I_{tLd})^2 + (X_q I_{tLq})^2}$$

A linear dynamic model is obtained by linearizing the nonlinear model round an operating condition. By linearization using Eq. (9)–(16), the linearized model of power system is given as follows:

$$\Delta\dot{\delta} = \omega_b.\Delta\omega \tag{17}$$

$$\Delta\dot{\omega} = \frac{1}{M}(\Delta P_m - \Delta P_e - D\Delta\omega) \tag{18}$$

$$\Delta\dot{E}'_q = \frac{1}{T'_{d0}}(-\Delta E_q + \Delta E_{fd}) \tag{19}$$

$$\Delta\dot{E}'_{fd} = \frac{1}{T_A}(-\Delta E_{fd} + K_A \Delta V_t) \tag{20}$$

$$\Delta\dot{V}_{DC} = K_7\Delta\delta + K_8\Delta E'_q + K_9\Delta V_{DC} + K_{dm}\Delta m + K_{d\psi}\Delta\psi \tag{21}$$

Where,

$$\Delta P_e = K_1\Delta\delta + K_2\Delta E'_q + K_{pDC}\Delta V_{DC} + K_{pm}\Delta m + K_{p\psi}\Delta\psi$$

$$\Delta E_q = K_4\Delta\delta + K_3\Delta E'_q + K_{qDC}\Delta V_{DC} + K_{qm}\Delta m + K_{q\psi}\Delta\psi$$

$$\Delta V_t = K_5\Delta\delta + K_6\Delta E'_q + K_{vDC}\Delta V_{DC} + K_{vm}\Delta m + K_{v\psi}\Delta\psi$$

In the above equations, K_1, K_2,… K_9, K_{pu}, K_{qu} and K_{vu} are linearization constants and are dependent on system parameters and the operating condition. The state space model of power system is given by:

$$\dot{x} = Ax + Bu \tag{22}$$

where the state vector *x*, control vector *u*, *A* and *B* are:

$$A = \begin{bmatrix} 0 & \omega_b & 0 & 0 & 0 \\ -\frac{K_1}{M} & -\frac{D}{M} & -\frac{K_1}{M} & 0 & -\frac{K_{pDC}}{M} \\ -\frac{K_1}{T'_{d0}} & 0 & -\frac{K_3}{T'_{d0}} & -\frac{1}{T'_{d0}} & -\frac{K_{qDC}}{T'_{d0}} \\ -\frac{K_A K_5}{T_A} & 0 & -\frac{K_A K_6}{T_A} & -\frac{1}{T_A} & -\frac{K_A K_{vDC}}{T_A} \\ K_7 & 0 & K_8 & 0 & K_9 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 & 0 \\ -\frac{K_{pm}}{M} & -\frac{K_{p\psi}}{M} & \frac{1}{M} \\ -\frac{K_{qm}}{T'_{d0}} & -\frac{K_{q\psi}}{T'_{d0}} & 0 \\ -\frac{K_A K_{vm}}{T_A} & -\frac{K_A K_{v\psi}}{T_A} & 0 \\ K_{dm} & K_{d\psi} & 0 \end{bmatrix}$$

$$x = [\Delta\delta \quad \Delta\omega \quad \Delta E'_q \quad \Delta E_{fd} \quad \Delta v_{DC}]^T$$

$$u = [\Delta m \quad \Delta\psi \quad \Delta P_m]^T$$

Fig. 5 shows the block diagram of the linearized dynamic model of the test system with STATCOM.

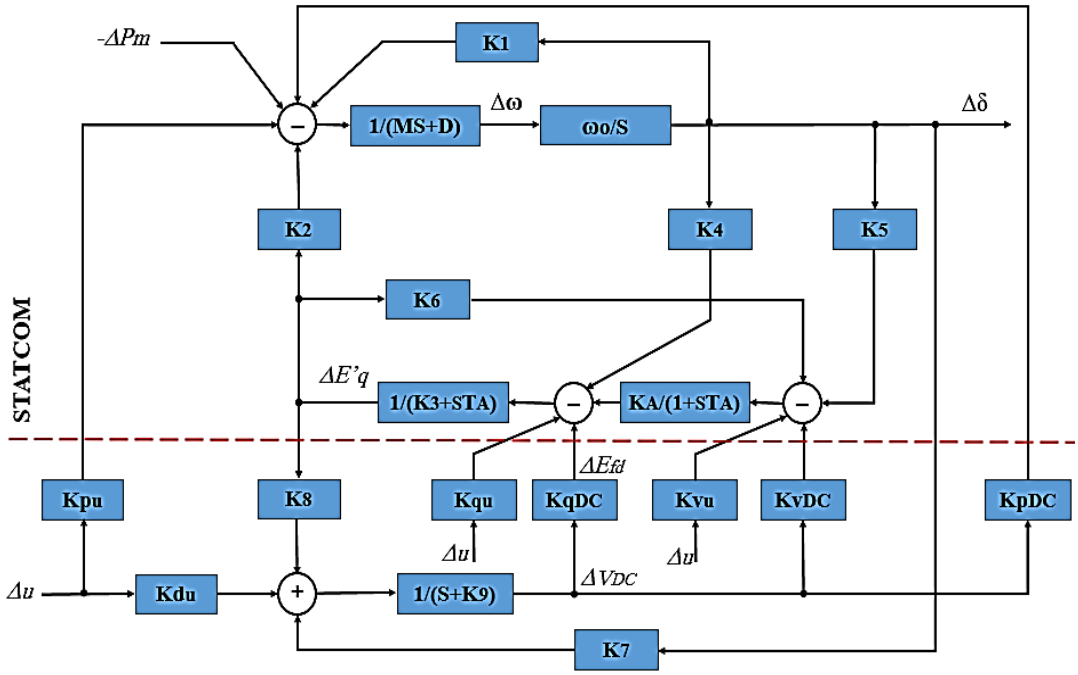


Figure 5. Modified Heffron-Phillips model of a SMIB system with STATCOM.

4. MSFLA-Based STATCOM Damping Controller Designing

4.1. STATCOM Based Proposed Controller Structure

The STATCOM damping controller's structure is shown in Fig. 5, where u can be m or ψ. It comprises gain block, signal washout block and lead-lag compensators [5]. Based on singular value decomposition (SVD) analysis in [22] modulating ψ has an excellent capability in damping low frequency oscillations in comparison to other inputs of STATCOM, thus in this paper, ψ is modulated in order to damping controller design.

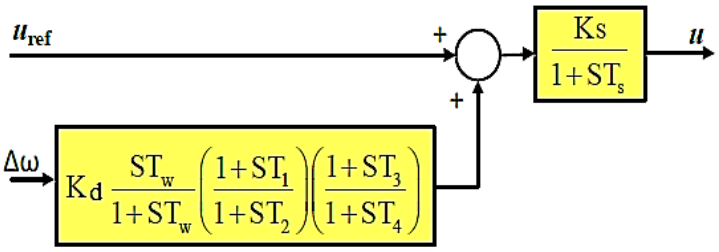


Figure 6. Lead-lag damping controller structure.

4.2. Objective Function

In the proposed algorithm, we must tune the STATCOM controller parameters optimally to improve overall system dynamic stability in a robust way under different operating conditions. For this reason, an eigenvalue based multi-objective function reflecting the combination of damping factor and damping ratio is considered as follows:

$$J_1 = \sum_{i=1}^{N_P} (\sigma_0 - \sigma_i)^2$$
$$J_2 = \sum_{i=1}^{N_P} (\xi_0 - \xi_i)^2 \qquad (23)$$
$$J = J_1 + a\ J_2$$

where σ_i and ξ_i are real part and damping ratio of ith eigenvalue, respectively. The value of weighting factor α is equal to 10 and NP is equal to the number of operating points in optimization problem. The value of σ_0 determines the relative stability in terms of damping factor margin provided for constraining the placement of eigenvalues during the process of optimization and ξ_0 is the desired minimum damping ratio which is to be achieved. By considering J_1, the dominant eigenvalues are transferred to the left side of the line $S=\sigma_0$ in the S-plane according to Fig. 7(a). This provides relative stability in the system. Similarly, if we consider objective function J_2, the maximum overshoot of eigenvalues becomes limited and eigenvalues are transmitted to the specified area which is shown in Fig. 7(b). Multi-purpose objective function J transmits the eigenvalues of the system to the specified area shown in Fig. 7(c).

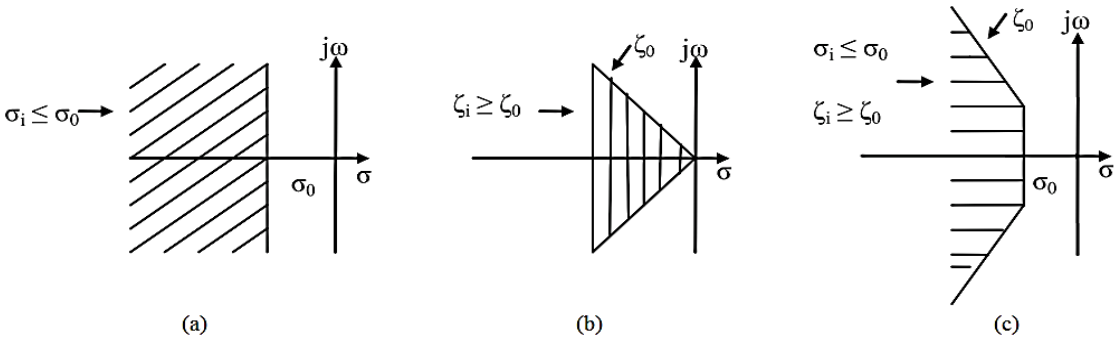


Figure 7. Region of eigenvalue location for multi-objective function.

4.3. Optimization Problem

In this study, it is aimed to minimize the proposed objective function J. The problem constraints are the stabilizer optimized parameter bounds. Therefore, the design problem can be formulated as the following optimization problem.

$$\text{Minimize } J$$
$$Subject\ to: \begin{cases} K_d^{\min} \le K_d \le K_d^{\max} \\ T_1^{\min} \le T_1 \le T_1^{\max} \\ T_2^{\min} \le T_2 \le T_2^{\max} \\ T_3^{\min} \le T_3 \le T_3^{\max} \\ T_4^{\min} \le T_4 \le T_4^{\max} \end{cases} \qquad (24)$$

Typical ranges of the five parameters of lead-lag controller are [-100, 100] for K_d and [0.01, 1.5] for T_1, T_2, T_3 and T_4.

5. Simulation Results

5.1. Application of MSFLA to the Design Process

Fig. 3 shows flowchart of the proposed optimization method. Based on the linearized power system model with STATCOM, the suggested approach employs MSFLA to solve optimization problem and search for an optimal or near optimal set of controller parameters. The optimization of STATCOM

controller parameters is carried out by evaluating the multi objective cost function as given in (23), for the lead-lag controller.

In this paper, the values of σ_0 and ξ_0 are taken as -2 and 0.5, respectively. In order to acquire better performance of MSFLA, proper parameters are given in Table 1. Notice that the optimization process for optimization method has been carried out with the system operating at nominal loading conditions given in Table 2. Table 3 shows the optimal controller parameters. Eigenvalues and damping ratios of the electromechanical modes with MSFLA method at three different loading conditions are given in Table 4. The convergence characteristics of different methods are shown in Fig. 8. The results show that the proposed MSFLA-based STATCOM controller acts faster to a better than the SFLA and PSO-based controller and greatly improves the dynamic stability of the power system.

Table 1. Best parameters for MSFLA implementation.

Population Size	Number of iterations	Local search iterations	Number of memeplexes	C_{max}	γ^0_{max}	D_{max}
300	150	10	10	1.5	π/4	*Inf.*

Table 2. System loading conditions.

Loading Condition	Case 1 (Nominal)	Case 2 (Light)	Case 3 (Heavy)
Active Power (P.U.)	1.000	0.600	1.100
Reactive Power (P.U.)	0.150	0.015	0.040

Table 3. The optimal parameter settings of MSFLA, SFLA and PSO based controllers.

Controller Parameters	K_d	T_1	T_2	T_3	T_4	Cost
MSFLA	87.1137	0.0598	0.1520	0.5419	0.02240	1.8578
SFLA	49.3152	0.1014	0.1981	0.5712	0.04008	2.4069
PSO	-62.0000	1.0513	0.2132	1.4817	0.16380	6.3619

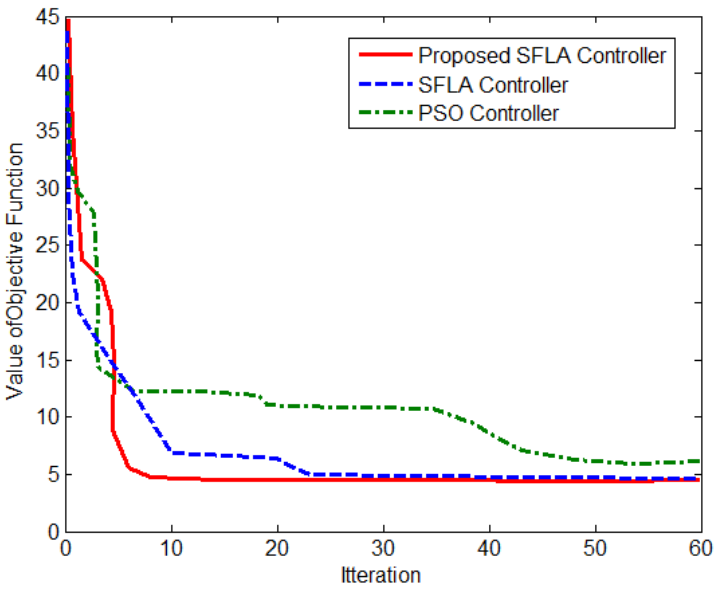


Figure 8. Convergence characteristics of MSFLA, SFLA and PSO.

Table 4. Eigenvalues of the electromechanical modes with controllers.

Loading Condition	Case 1 (Nominal)	Case 2 (Light)	Case 3 (Heavy)
Without Controller	-9.7188 ±j14.5590 1.2231 ± j4.8569 -0.6756	-10.1261±j 16.4602 1.2592±j 5.0855 -0.0197	-9.2385±j 13.2122 1.1200 ±j 4.6027 -1.8010
PSO	-100.13 -97.23 -20.59 -9.35±j14.75 -1.46 -0.56±j4.99 -0.66	-110.23 -98.97 -56.00 -17.72 -10.99±j17.49 -0.59±j5. 14 -0.05	-108.91 -93.91 -76.22 -11.20±j20.86 -9.37 -1.86 -0.15±j4.69
SFLA	-98.34 -97.17 -21.59 -10.43±j12.58 -2.61±j7.22 -1.22 -0.84	-101.12 -96.88 -54.694 -23.1903 -17.54±j 9.6335 -8.216±j 10.527 -0.0417	-110.2054 -88.093 -40.66 -21.108 -8.3109±j11.24 -2.37±j9.735 -1.77
Proposed MSFLA	-95.16 -94.52 -43.30 -25.74 -8.1179±j 9.5389 -2.3522±j 4.7617 -0.6914	-95.48 -71.22 -41.48 -21.0971 -10.0165±j 13.6335 -2.0818±j 4.9632 -0.0461	-102.39 -79.36 -31.49 -18.88 -5.00±j7.14 -1.93±j5.23 -1.79

5.2. Time Domain Simulation

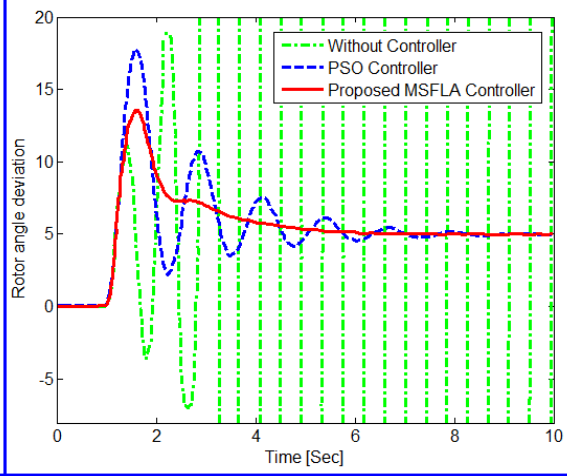
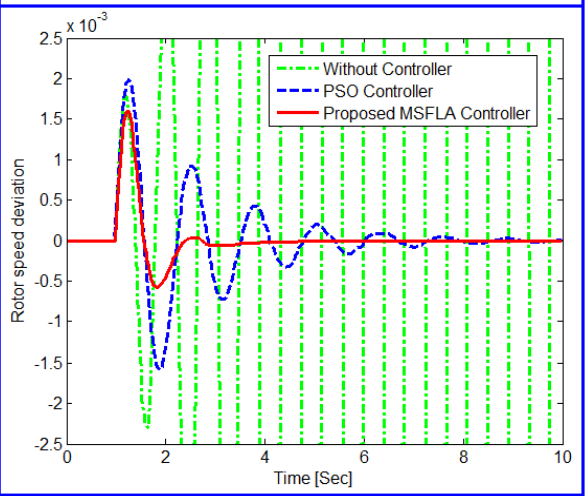
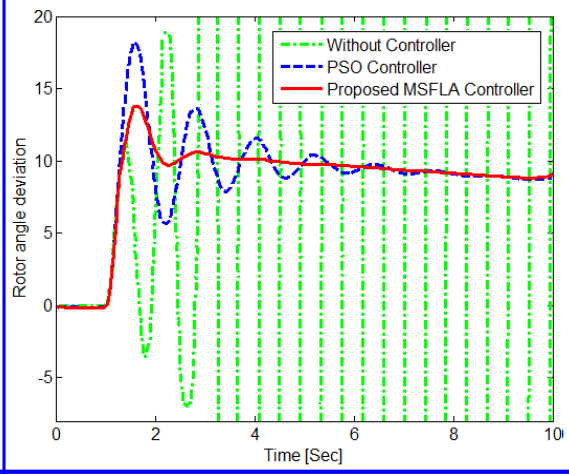
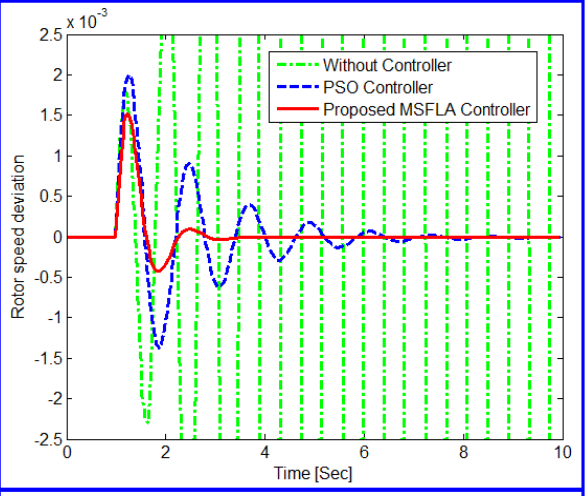
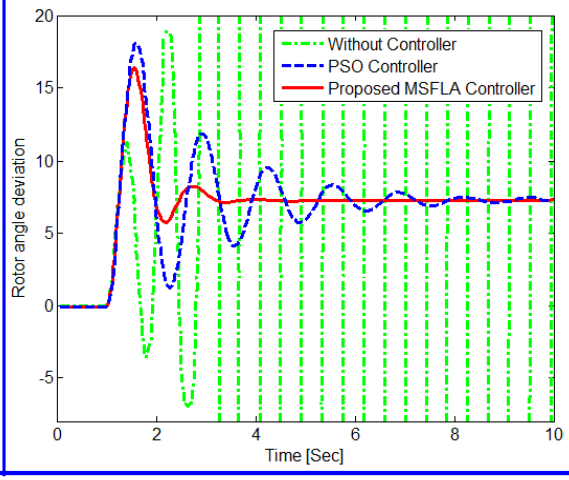
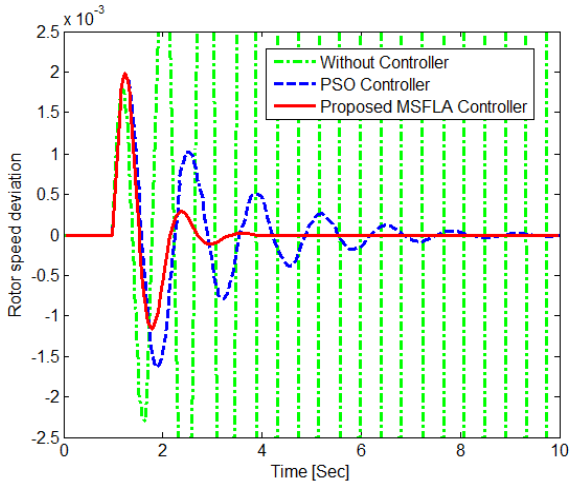
The performance of the suggested MSFLA method for the STATCOM during transient conditions is verified by applying %10 step increase in mechanical power input at t=1s. The system responses with proposed MSFLA and PSO based STATCOM controllers to this disturbance under three different loading conditions for speed deviation and rotor angle deviation with ψ based controller are shown in Table 5. Simulation results clearly illustrate abilities of the MSFLA and PSO in low-frequency oscillation damping, while show that MSFLA has good performance in damping low-frequency oscillations and stabilizes the system quickly in comparison to the SFLA and PSO methods.

6. Conclusion

This paper presented a MSFLA-based power oscillation damping controller in which the controller was installed on a STATCOM. The stabilizer design problem was formulated as an objective optimization problem, which was solved by MSFLA as a new and strong optimization method. The effectiveness of the proposed STATCOM controller for damping of low frequency oscillations was demonstrated by a weakly connected example power system subjected to a disturbance; an increase in mechanical input power. The designed MSFLA, SFLA and PSO controllers are applied to the system and their responses are compared to each other. Results from time domain simulations show that the low frequency oscillations can be easily damped with the designed MSFLA-based STATCOM controller.

The comparison of results between three methods, showed the effectiveness of the proposed MSFLA-based controller in damping of power system low frequency oscillations.

Table 5. Dynamic responses for Δδ and Δω with Ψ-based controller under different loading conditions.

	Dynamic responses for $\Delta\delta$ with Ψ-based controller	Dynamic responses for $\Delta\omega$ with Ψ-based controller
Case 1 (Nominal Load)		
Case 2 (Light Load)		
Case 3 (Heavy Load)		

Appendix

The nominal parameters and operating condition of the system are listed in the follows.

Generator: $\begin{cases} M = 8.0MJ/MVA & f = 60Hz & x_d = 1.0pu & x'_d = 0.3pu \\ D = 0.0 & V = 1.0pu & x_q = 0.6pu & T'_{do} = 5.044s \end{cases}$

STATCOM: $\begin{cases} C_{DC} = 1 & T_w = 0.01s & X_{SCT} = 0.15pu \\ V_{DC} = 2pu & T_s = 0.05s & K_s = 1.2 \end{cases}$

Excitation System: $K_A = 120$ $T_A = 0.05s$

Transmission Line: $X_{tL} = 0.15pu$ $X_{LB} = 0.6pu$

References

[1]. P. Kundur, "Power System Stability and Control", New York: McGraw-Hill, (1994).

[2]. P.M. Anderson and A.A. Fouad, "Power System Control and Stability", Ames, IA: Iowa State University Press, (1977).

[3]. A.T. Al-Awami, Y.L. Abdel-Magid and M.A. Abido, "A Particle Swarm Based Approach of Power System Stability Enhancement with Unified Power Flow Controller", International Journal of Electrical Power and Energy Systems, Vol. 29, 3 (2007), pp. 251-259.

[4]. A.J.F. Keri, A.S. Mehraban, X. Lombard, A. Eiriachy and A.A. Edris, "Unified Power Flow Controller (UPFC): Modeling and Analysis", IEEE Transactions on Power Delivery, Vol. 14, 2 (1999), pp. 648-654.

[5]. H. Shayeghi, H.A. Shayanfar, S. Jalilzadeh and A. Safari, "A PSO Based Unified Power Flow Controller for Damping of Power System Oscillations", International Journal of Energy Conversion and Management, Vol. 50, 10 (2009), pp. 2583-2592.

[6]. N.G. Hingorani and L. Gyugyi, Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems, New Jersey: Wiley-IEEE Press, (1999).

[7]. L. Gyugyi, "Dynamic Compensation of AC Transmission Line by Solid State Synchronous Voltage Sources", IEEE Transactions on Power Delivery, Vol. 9, 22 (1994), pp. 904-911.

[8]. H.F. Wang, "Phillips-Heffron Model of Power Systems Installed with STATCOM and Applications", IEE Proceedings on Generation, Transmission and Distribution, Vol. 146. 5 (1999), pp. 521-527.

[9]. K.R. Padiyar and N. Prabhu, "Design and Performance Evaluation of Sub Synchronous Damping Controller with STATCOM", IEEE Transactions on Power Delivery, Vol. 21, 3 (2006), pp. 1398-1405.

[10]. M. A. A. Golkar and M. Zarringhalami, ''Coordinated Design of PSS and STATCOM Parameters for Power System Stability Improvement Using Genetic Algorithm'', Iranian Journal of Electrical and Computer Engineering, Vol. 8, 2 (2009), pp. 80-88.

[11]. A. Ajami and M. Armaghan, ''A comparative study in power oscillation damping by STATCOM and SSSC based on the multi objective PSO algorithm'', Turkish Journal of Electrical Engineering and Computer Sciences, vol. 1, 21 (2013), pp. 213-224.

[12]. A. Safari, H. Shayeghi, H.A. Shayanfar, ''Optimization based control coordination of STATCOM and PSS output feedback damping controller using PSO technique'', International Journal on Technical and Physical Problems of Engineering (IJTPE), Vol. 2, 4 (2010), pp. 6-12.

[13]. A. Safari, H. Shayeghi, H.A. Shayanfar, ''A chaotic optimization algorithm to output feedback damping controller design for a STATCOM '', International Journal on Technical and Physical Problems of Engineering (IJTPE), Vol. 2, 3 (2010), pp. 44-50.

[14]. A. Safari, A. Ahmadian, M. A. A. Golkar, ''Controller Design of STATCOM for Power System Stability Improvement Using Honey Bee Mating Optimization'', Journal of Applied Research and Technology, vol. 11, 1 (2013), pp. 144-155.

[15]. H. M. Hasanien, ''Shuffled frog leaping algorithm-based static synchronous compensator for transient stability'', IET Renewable and Power Generation, vol. 8, 6 (2014), pp. 722-730.

[16]. M. Barati, M. M. Farsangi, ''Solving unit commitment problem by a binary shuffled frog leaping algorithm'', IET Generation, Transmission & Distribution, vol. 8, 6 (2014), pp. 1050-1060.

[17]. E. Afzalan, M.A. Taghikhani, M. Sedighizadeh, ''Optimal placement and sizing of DG in radial distribution networks using SFLA'', International Journal of Energy Engineering, Vol. 2, 3 (2012), pp. 73-77.

[18]. M. M. Eusuff, K. Lansey, F. Pasha, ''Shuffled frog leaping algorithm: a memetic meta-heuristic for discrete optimization'', Journal of Engineering Optimization, Vol. 38, 2 (2006), pp.129–54.

[19]. M. M. Eusuff, K. Lansey, ''Optimization of water distribution network design using the frog leaping algorithm'', Journal of Water Resources Planning and Management, Vol. 129, 3 (2003), pp.5–21.

[20]. A. M. Kashtiban, M. A. Ahandani, ''Various strategies for partitioning of memeplexes in shuffled frog leaping algorithm'', 14th international CSI computer conference, Tehran-Iran, (2009), pp. 576–581.

[21]. J. Kennedy and R. Eberhart, ''Particle Swarm Optimization'', Proceeding of IEEE International Conference on Neural Networks'', (1995), pp.1942–1948.
[22]. M.A. Abido, "Analysis and assessment of STATCOM-based damping stabilizers for power system stability enhancement," Electric Power System Research, Vol. 73, 1(2005), pp.177-185.

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