Journal of Engineering Science and Technology
Vol. 10, No.10 (2015) 1239 - 1260

OPTIMUM STEADY STATE LOAD SHEDDING USING SHUFFLED FROG LEAPING ALGORITHM TO AVERT BLACKOUT IN POWER SYSTEMS DURING OVERLOAD AND GENERATION CONTINGENCIES

R. MAGESHVARAN*, T. JAYABARATHI, VAIBHAV SHAH, SHIVAM SOOD

School of Electrical Engineering, VIT University,
Vellore-632014, Tamil Nadu, India
*Corresponding Author: rmageshvaran@vit.ac.in

Abstract

During generation and overload contingencies in a power system, the system voltage and frequency will decline due to the deficiency of real and reactive powers. Consequently cascaded failures may occur which will lead to complete blackout of certain parts of the power system. Load shedding is considered as the ultimate step of emergency control action that is necessary to prevent a blackout in the power system. This paper proposes a memetic meta-heuristic algorithm known as shuffled frog leaping algorithm (SFLA) to find a solution for the steady state load shedding problem presented here. The optimum steady state load shedding problem uses squares of the difference between the connected active and the reactive load and the supplied active and reactive power. The supplied active and reactive powers are treated as dependent variables modeled as functions of bus voltages only. The proposed algorithm is tested on IEEE 14 and 30 bus test systems. The viability of the proposed method is established by comparison with the other conventional methods presented earlier in terms of solution quality and convergence properties.

Keywords: Optimal load shedding, Shuffled frog leaping algorithm, Overload contingency, Generation contingency, Voltage dependent load model.

1. Introduction

The main objective of the power utility is to operate the power system without violating the system constraints and operational limits. However under certain situations like unexpected outages or sudden increase in system demand, the system constraints and operational limits are violated. Load shedding is considered

Nomenclatures

NB	Total number of buses
NG	Total number of generator buses
P_{di}	Active power supplied to the load
$\overline{P}_{di}$	Connected active load
P_{Gi}	Active power generation at bus 'i'
P_i	Active power injections at bus 'i'
$P_{Gi}^{\max}$	Maximum limit of real power generations
$P_{Gi}^{\min}$	Minimum limit of real power generations
Q_{di}	Reactive power supplied to the load
$\overline{Q}_{di}$	Connected reactive load
Q_i	Reactive power injections at bus 'i'
Q_{Gi}	Reactive power generation at bus 'i'
$Q_{Gi}^{\max}$	Maximum limit of reactive power generations
$Q_{Gi}^{\min}$	Minimum limit of reactive power generations
V_i, V_j	The bus voltage magnitude
$V_i^{\max}$	Maximum limit of bus voltages of the system
$V_i^{\min}$	Minimum limit of bus voltages of the system

Greek Symbols

α_i , β_i	Parameters related to priority assigned to the demand at each bus
δ_i , δ_j	Voltage angles at bus i and bus j
θ_{ij}	Angle of admittance of the transmission line between bus i and bus j

Abbreviations

SFLA	Shuffled frog leaping algorithm
VDLM	Voltage dependent load model

as a last resort to avoid cascaded tripping and blackout. Load shedding is defined as coordinated sets of controls that decrease the electric load in the system to restore the system back to its normal operating condition.

After load shedding the disturbed system state can settle to a new equilibrium state. An optimal load shedding program finds a best steady-state stable operating point for a post fault system with a minimum amount of load shed.

Reference [1] has formulated the optimal steady state load shedding problem that uses the sum of the squares of the difference between the connected active and the reactive load and the supplied active and reactive power. The optimization package MINOS [11], developed to solve large scale dense or sparse linearly or nonlinearly constrained or unconstrained optimization problems is used to simulate the algorithm.

An algorithm to minimize the amount of load curtailment which is based on Newton-Raphson (NR) method for solving the power flow equations, and Kuhn-

Tucker theorem for the optimization has been described in [2]. Here, the load shedding policy, defining the priority schedules is obtained first, and then the minimum load to be shed at each bus is calculated. System reactive power and losses are not included in the problem formulation and the active and reactive power of loads is assumed to be independent of bus voltages.

A method for optimal load curtailment, that considers generator control effects, voltage and frequency characteristics of the load, has been proposed in [3]. The resulting nonlinear optimization problem is solved using Second-order gradient technique. Inability to curtail system loads during an emergency is the major drawback of the formulation in [3]. Another drawback is the algorithm's inability to converge during emergency condition due to over definition of system generation through the governor action and the poor reconciliation of the frequency variations applied to the load model equations.

Ref. [4] has presented a reformulated optimal load shedding policy that takes into account generator control effects and voltage and frequency characteristics of loads. Ref. [5] has presented another work of optimal load shedding problem that uses the sum of squares of the difference between the connected active and reactive load and the supplied active and reactive power. In the formulation, the supplied active and reactive power is considered as dependent variables modeled as a function of bus voltages only.

A sensitivity based approach to solve the load shedding problems and to minimize the loss of loads has been proposed in [6]. In order to limit the size of the load being dropped, different priorities to loads are assigned using a weighted error criterion. Ref. [7] and [8] has formulated a non-linear optimization problem for the optimal load shedding and rescheduling of generators during an emergency state. The non-linear problem has been approximated by an accurate sensitivity model which takes into account the real and reactive nodal injections, voltage magnitudes and angles and loads' sensitivity to voltage magnitudes. The accuracy of the solution in both these papers is affected by the linearization approach.

In [9] and [10] two different methods for generation rescheduling and load shedding to alleviate line overloads, based on the sensitivity of line overloads to bus power increments have been developed. In [11], a mesh approach has been developed for the formulation of the network equations in the load flow analysis. A hybrid approach using a combination of an impedance matrix method and a nodal-admittance matrix method which exploits the salient characteristics of the impedance and admittance method is developed. A new power flow model for the steady state behavior of large complex power system that allows the study of power flow under normal and abnormal operating conditions has been developed in [12].

In [13], differential evolution algorithm has been implemented for optimal allocation of repair times and failure rates in meshed distribution system. An optimal under-voltage load shedding scheme to provide long term voltage stability using a new hybrid particle swarm based simulated annealing optimization technique has been presented in [14]. The technical and economic aspects of each load are considered by including the sensitivities of voltage stability margin into the cost function. In [15], a new voltage stability margin index considering load characteristics has been introduced in under-voltage centralized load shedding scheme. Quantum inspired evolutionary programming has been implemented in [16] for the optimal location and sizing of distributed generations (DGs) in radial distribution system. In [17], an optimal load shedding scheme have been proposed to monitor the load-generation unbalance in the plants with internal co-generation and to quickly initiate shedding of an optimal amount of load during a contingency.

DC optimal load shed recoveries with transmission switching model have been presented in [18]. This model reduces the amount of load shed required during generation and/or transmission line contingencies, by modifying the bulk power system topology. An approach based on parallel-differential evolution has been proposed in [19] for the optimal load shedding against voltage collapse. The non-linearity of the problem is fully considered in this approach and thereby able to escape from local optima and not limited to system modeling.

Basically, the optimal load shedding strategies are classified into two types, namely, centralized load shedding and de-centralized or distributed load shedding. Centralized load shedding strategies are solved based on stability margin sensitivities. These methods are based on the assumptions of linearity and constancy of the sensitivities [21], and depend on linear programming techniques to solve the comprehensive optimization problem. In actual practice, these assumptions are not realistic [22], particularly when the non-linear characteristics of the system components, such as, reactive power generation limits, actions of switched shunt devices load-tap changers and so on are considered. A multi-stage method to solve the non-linear optimal load shedding problem stage by stage has been presented in [22]. Here, each stage corresponds to a linearized sub-problem based on sensitivity analysis. Usually these methods do not consider priorities for the loads to be shed, whereas, in distributed load shedding schemes priorities for the loads are being considered. Moreover, in the mathematical formulation of optimal load shedding schemes, reactive power of loads to be shed are not considered [13-23]. Also, the loads are considered to be independent of the system voltage, but in actual practice, the real and reactive power of the loads depends on the system voltage [1].

In the present paper the optimal load shedding problem to minimize the sum of squares of the difference between the connected loads and the supplied power has been formulated. The Shuffled frog leaping (SFL) algorithm is implemented to solve the formulated optimization problem. The performance of the proposed algorithm for generation deficiency and overload contingencies are analyzed. Testing is done using IEEE 14 and 30, representing small power system. The optimal solutions are compared with those reported in [1, 3, 5].

2. Problem Formulation

During emergency conditions an operational objective is to minimize the difference between the connected load and the supplied power [1]. System frequency deviation must be included in the problem formulation if the system considered is under transient state. In this paper, system under steady state condition is considered for the problem formulation and thus the frequency is treated as constant. The objective function can be expressed as

$$F = \sum_{i=1}^{NB} \left[\alpha_i \left(P_{di} - \overline{P}_{di} \right)^2 + \beta_i \left(Q_{di} - \overline{Q}_{di} \right)^2 \right] \quad (1)$$

where NB is the number of buses in a system, P_{di}, and Q_{di} are the active and reactive powers supplied to the load. $\overline{P}_{di}$, and $\overline{Q}_{di}$ are the connected active and reactive load. The weighting factors α_i and β_i are the parameters related to priority assigned to the demand at each bus. Flat values are assigned to the priorities of the loads. The objective function given in Eq. (1) is subjected to both network and system limits constraints resulting in a non-linear optimization problem. The equality constraints are the power flow equations of the networks and inequality constraints are characterized by the limits on the system variables.

2.1. Equality constraints

The transmission network is represented by a steady-state AC power flow model. In this model every node is characterized by two nonlinear algebraic equations. In these network equations the active and reactive power injected at a node is related to the power imported through the branches incident at that node. These network equations are equality constraints which are to be satisfied in order to obtain the balance of active and reactive power at each node. For a network with NB number of nodes, a total of 2 NB equations can be written as

$$P(V) = P_{Gi} - P_{di}(V) - P_i(V, \delta) = 0 \quad (2)$$

$$Q(V) = Q_{Gi} - Q_{di}(V) - Q_i(V, \delta) = 0 \quad (3)$$

where P_{Gi} and Q_{Gi} represents the respective active and reactive power generations at bus i. P_i and Q_i represents the active and reactive power injections at bus i. The active and reactive power injections at bus i in terms of bus voltage magnitude and phase angle is expressed as

$$P_i(V, \delta) = V_i \sum_{i=1}^{NB} V_j Y_{ij} \cos\left(\delta_i - \delta_j - \theta_{ij}\right) \quad (4)$$

$$Q_i(V, \delta) = V_i \sum_{i=1}^{NB} V_j Y_{ij} \sin\left(\delta_i - \delta_j - \theta_{ij}\right) \quad (5)$$

2.2. Inequality constraints

The inequality constraints considered are the limits of real and reactive power generations, bus voltage magnitudes and angles, and line flows.

The limits of real and reactive power generations of the system are

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \qquad i = 1, \ldots\ NG \quad (6)$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \qquad i = 1, \ldots\ NB \quad (7)$$

where $P_{Gi}^{\min}$ and $Q_{Gi}^{\min}$ are the minimum real and reactive power generations and $P_{Gi}^{\max}$ and $Q_{Gi}^{\max}$ are the maximum available real and reactive power generations . The limits of bus voltages of the system are

$$V_i^{\min} \le V_i \le V_i^{\max} \qquad i = 1,\dots\ NB \tag{8}$$

where $V_i^{\min}$ and $V_i^{\max}$ are the minimum and maximum limits of bus voltages of the system.

Either current magnitude constraint due to thermal considerations or electrical angle (difference in voltage angle across a line) constraint due to stability considerations can be considered for transmission line loading limits.

In the present formulation the electrical angle inequality constraint is used, which can be expressed as

$$LF = \left|\delta_i - \delta_j\right| \le \in_{ij} \qquad i = 1,\dots\ NB-1;\ \ j = i+1,\dots\dots NB \tag{9}$$

where δ_i and δ_j are the voltage angles at bus *i* and bus *j*, and $\in_{ij}$ is the maximum voltage phase angle difference between *i* and *j*.

2.3. Load model

The system active and reactive power demands can be expressed using different load models in terms of bus voltage and system frequency. A polynomial function of the bus voltage is used in this formulation to express the active and reactive power demands at any given bus as

$$P_{di} = \overline{P}_{di}\left[P_p + P_c\left(\frac{V_i}{\overline{V_i}}\right)^{N1} + P_z\left(\frac{V_i}{\overline{V_i}}\right)^{N2}\right] \tag{10}$$

$$Q_{di} = \overline{Q}_{di}\left[Q_q + Q_c\left(\frac{V_i}{\overline{V_i}}\right)^{N3} + Q_z\left(\frac{V_i}{\overline{V_i}}\right)^{N4}\right] \tag{11}$$

where P_p, P_c, P_z , Q_q, Q_c and Q_z are constants associated with this voltage dependent load model and *N1*, *N2*, *N3* and *N4* are the powers of polynomial.

3. Implementation of Shuffled Frog Leaping Algorithm for the Optimal Load Shedding Problem

The SFL algorithm is a meta-heuristic optimization method based on observing, imitating and modeling the behavior of groups of frogs when searching for the location that has maximum amount of available food [23] is implemented in following steps.

The implementation of SFL algorithm for the optimal load shedding problem is shown in Figs. 1(a) and (b).

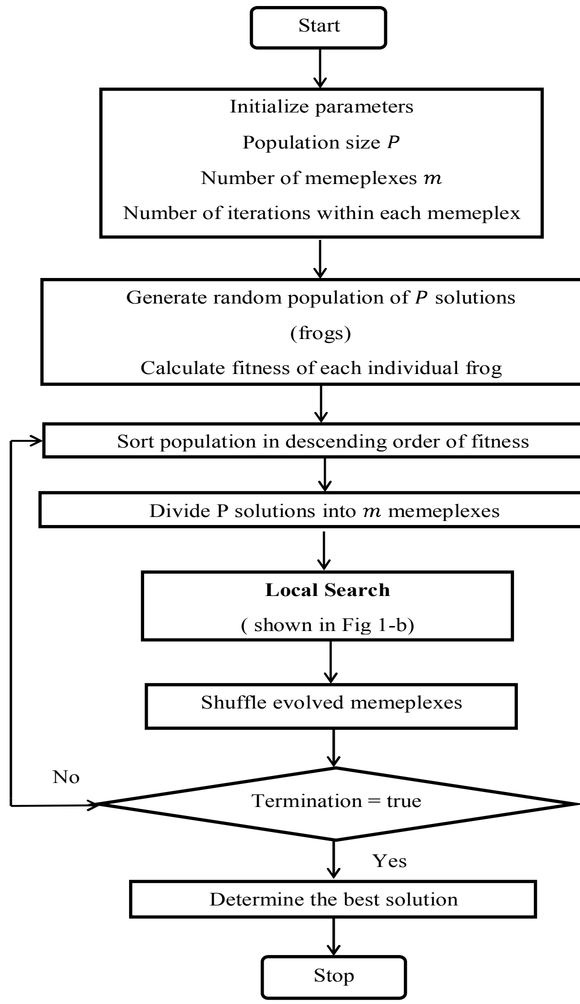

Fig. 1. (a) Flowchart of SFLA.

Step-1: Initialize the population size (P), number of memeplexes (m) and number of iteration within each memeplex. Generate random population of $'P'$ feasible solutions by generating random values of the 'n' variables (amount of load to be shed in each bus) with in their search space, i.e.,

$$X_i(0) = [x_{i1}, x_{i2}, x_{i3}, \ldots . x_{i1}]^T,\ i = 1,2, \ldots . P \tag{12}$$

These $'P'$ solutions are known as frogs.

Step-2: Using these generated solutions obtain the value of objective function given in Eq. (1) and calculate the fitness of each individual solution, i.e., frogs.

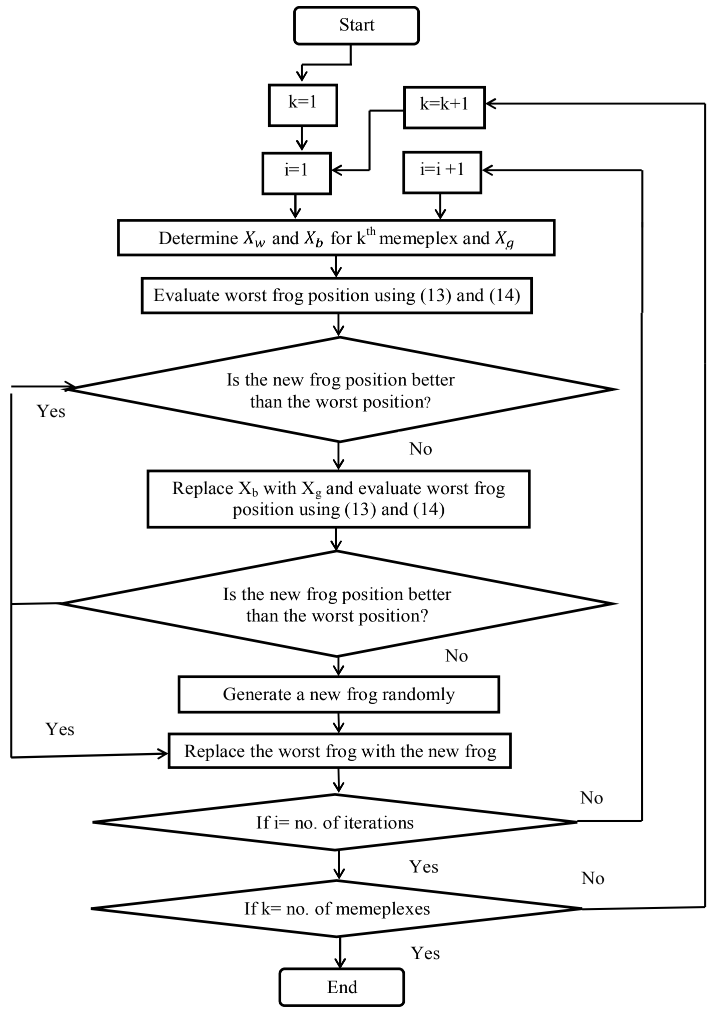

Fig. 1. (b) Local search of SFLA.

Step-3: The frogs are sorted in descending order according to their fitness. Then the entire population is partitioned into m subsets referred to as memeplexes, each containing n frogs (i.e., $P = m \times n$). The strategy of the partitioning is as follows: the first frog goes to the first memeplex, the second frog goes to the second memeplex, the m^{th} frog goes to the m^{th} memeplex, the $(m+1)^{th}$ frog goes back to the first memeplex, and so forth.

Step-4: A local search for the best solution from each memeplexes should be carried out. Select each memeplex and set the iteration count $i = 1$. Determine,

X_w, X_b & X_g for each memeplexes, where X_w, X_b & X_g were the positions of frogs with worst, best and global best fitness respectively.

Step-5: Evaluate the new frog position to replace the worst frog using the following equations

$$D_i = Rand * (X_b - X_w) \tag{13}$$

$$X_w^{new} = X_w^{current} + D_i$$
$$D_{i\min} < D_i < D_{i\max} \tag{14}$$

where $D_{i\max}$ and $D_{i\min}$ are the maximum and minimum step sizes allowed for a frog's position respectively.

Step-6: If the new frog position is better compared to the worst frog position then replace the worst frog with new frog else replace X_b by X_g and evaluate the new frog position using Eq. (13) and Eq. (14). In this case also if the new frog is not better than the worst frog then generate new frog and replace the worst frog with this new generated frog. The evaluations will continue for a specific number of iterations. Therefore, SFLA simultaneously performs an independent local search in each memeplex using a process similar to the PSO algorithm. After a predetermined number of memetic evolutionary steps within each memeplexes, the solutions of evolved memeplexes $(X_1, ..., X_P)$ are shuffled for the global information exchange among the frogs.

Step-7: If the constraints are satisfied, obtain the best solution, if not go to step3 and continue.

4. Simulation Results and Analysis

The prediction of the aerodynamic coefficients of the investigated projectiles The proposed SFL algorithm has been verified on two small systems – IEEE 14-bus and 30-bus. The results obtained by the proposed approach are compared with those obtained by using conventional methods reported earlier, such as projected augmented Lagrangian method implemented using MINOS – an optimization package [1], gradient technique based on Kuhn-Tucker theorem [2] and second order gradient technique [3]. The single line diagram and the detailed data of IEEE-14 and 30 bus systems are given in [11]. The software was written in Matlab and executed on 2.4 GHz, Intel i3 processor with 2 GB RAM PC.

The constants and the powers of the polynomial associated with the load model given in Eq. (10) and (11) were assumed as follows:

P_p =0.2, P_c =0.3, P_z =0.5, Q_q =0.2, Q_c =0.3 and Q_z =0.5. $N1$ =1, $N2$ =2, $N3$ =1 and $N4$ =2.

4.1. Application to small size systems

IEEE 14, 30-bus test systems [11] are considered here. The two cases of contingencies analyzed are loss of generation and overload. The population size used for the proposed SFL algorithm for these test systems is 50.

4.1.1. IEEE 14-bus system

This system consists of 20 lines, two generators, three synchronous condensers, three transformers and one static capacitor.

The generated reactive power limits are:

$-150 \le Q_{G1} \le 150$

$0 \le Q_{G2} \le 140$, $0 \le Q_{G3} \le 140$

$0 \le Q_{G6} \le 140$, $0 \le Q_{G8} \le 140$

The generated active power limits are:

$0 \le P_{G1} \le 200$, $0 \le P_{G2} \le 200$

The connected load for this test system is 259 MW. Under normal operating conditions the supplied power to the connected load using NR method with VDLM is 257.8 MW. The reactive power supplied by the method used here is 72.92 MVAR. The supplied powers in Refs. [2], [3] and [5] are 259.0 MW, 258.81 MW and 258.59 MW respectively for a connected load of 259 MW. For the same connected load the supplied power In Ref [1] is 258.59 MW. The reactive power supplied by the methods reported in Refs [2], [3] and [5] are 54.59 MVAR, 73.42 MVAR and 73.51 MVAR respectively.

The deficit in the supplied power obtained in this paper and in Refs. [1],[3] and [5] represents the effect of using a voltage dependent load model (VDLM) to express the active power. The total active and reactive power generation obtained under normal operating condition by the NR method with VDLM used in this paper is 272.00 MW and 82.50 MVAR respectively. The total real power loss obtained here is 9.250 MW. The total active power generation obtained by the method reported in Refs [2], [3] and [5] for the normal operating conditions were 271.85 MW, 270 MW and 269.250 MW respectively. The corresponding reactive power generation reported in these Refs [2], [3] and [5] were 8.56 MVAR, 80.220 MVAR and 79.1700 MVAR respectively. The total active power loss presented in the Refs [2], [3] and [5] were 12.8454 MW, 11.3274 MW and 10.6685 MW respectively. The bus voltages vary between 1.01 pu and 1.08 pu in the NR method with VDLM, whereas the voltages vary from 0.98 pu to 1.07 pu in Ref. [1,5], 0.93 pu to 1.035 pu in Ref. [2] and 0.9765 pu to 1.016 pu in Ref. [3].

The aim of optimal load shedding is to restore normal operating conditions following loss of generation and overload contingencies by shedding minimum load.

a) Loss of Generation Contingencies

An abnormal operating condition representing the loss of generating unit #2 generating 72.0 MW or 26% of normal generation is considered here.

The amount of load shed using the proposed SFLA for this contingency is 67.556 MW and the supplied active power demand is 191.444 MW.Whereas the load shed and the supplied active power demand reported by Mostafa in Refs [1] and [5] are 71.11 MW and 187.89 MW respectively. It can be observed that the proposed approach has yielded lower amount of load shed and higher supplied active power demand when compared with other methods. The total active power demand presented in Refs [2] and [3] for these contingencies were 192 MW and 231.57 MW respectively. Reactive powers supplied by the proposed method and by the methods used in the Refs [2], [3] and [5] are 55.245 MVAR, 54.59 MVAR, 65.2 MVAR and 53.39 MVAR respectively.

The total active and reactive power generation obtained by the proposed SFL approach for this abnormal condition is 200 MW and 82.5 MVAR respectively. The corresponding loss obtained by this approach is 5.279 MW.

Whereas the total active power generation obtained by the method reported in Refs [2], [3] and [5] for this loss of generation contingency were 200 MW, 260.690 MW and 200.250 MW respectively. The corresponding reactive power generation reported in these Refs [2], [3] and [5] were 135.6880 MVAR, 67.950 MVAR and 82.50 MVAR respectively. The corresponding active power losses reported in the Refs [2], [3] and [5] are 7.9952 MW, -31.581 MW and 12.111 MW respectively. The bus voltages vary between 1.01 pu and 1.09 pu in the proposed SFL algorithm. Whereas the voltages vary from 0.8065 pu to 0.917 pu in Refs. [1,5] and 1.04883 pu to 1.1pu in Ref. [2] . The proposed approach yields better bus voltage profile as compared with other approaches.

Figure 2 shows the convergence characteristics of the proposed SFL algorithm for the test system operated under the generation contingency considered here. The maximum number of iterations to converge for the proposed approach is 15.

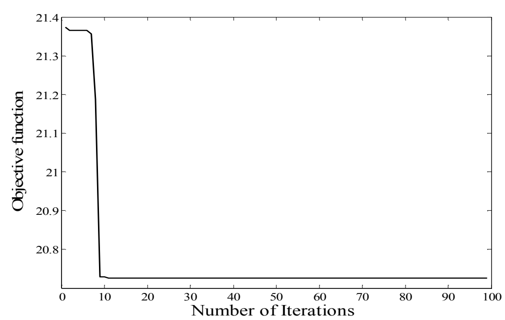

Fig. 2. Convergence Characteristics of SFL Algorithm for IEEE 14-Bus System Under Loss of Generating Unit Contingency.

b) Range of generation deficits contingency

The test system is also subjected to contingencies characterized by generation deficits. The range of generation is varied from 260 MW to 160 MW, with a connected load of 259 MW, which means, the resulting generation deficit varies from 0 to 99 MW.

Figure 3 shows that the minimum iteration to converge for the proposed SFL algorithm is 19 corresponding to 160 MW generation. Figure 4(a) shows the total supplied power obtained by the proposed SFL approach decreases from 248.531 MW at 260 MW generations to 155.823 MW at 160 MW generations. Figure 4(b) shows the corresponding active power loss decrease from 11.469 MW to 4.118 MW.

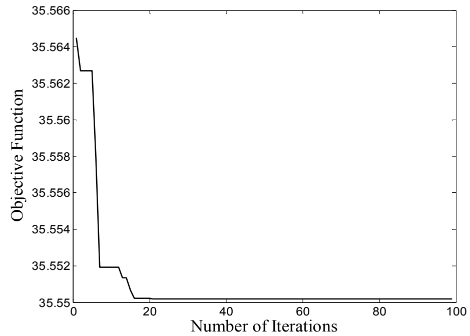

Fig. 3. Convergence Characteristics of SFL Algorithm for IEEE 14-Bus System Under Generation Deficit Contingency

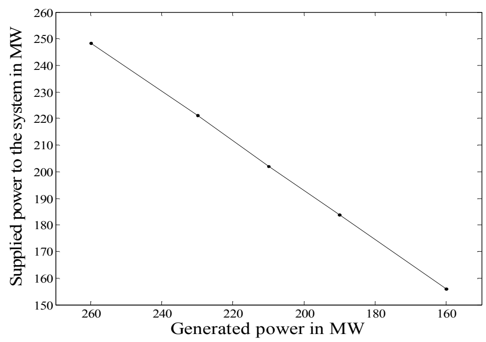

Fig. 4 (a). Optimal Supplied Load for IEEE 14-Bus System under Generation Deficit Contingency using SFL Algorithm.

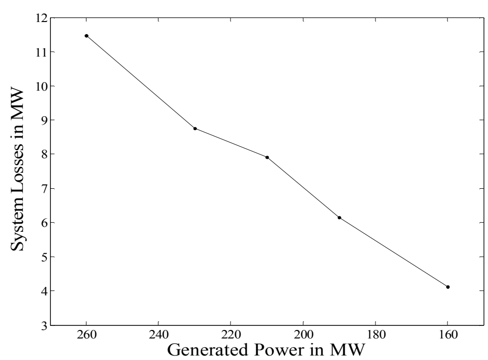

Fig. 4 (b). System Losses of IEEE 14-Bus System under Generation Deficit Contingency using SFL Algorithm.

Whereas the total supplied power in Refs. [1] and [5] decreases from 249.30 MW at 260 MW generation to 153.78 MW at 160 MW generation with corresponding active power loss decrease from 10.70 MW to 6.22 MW and in Ref

[2] the supplied load decreases from 252.92 MW to 157.22 MW with the corresponding active power loss decrease from 7.08 MW to 2.78 MW for the same range of generation deficits.

For this loss of generation contingency the maximum voltage obtained by the proposed shuffled frog leaping approach remains constant at 1.025pu and the minimum voltage varies between 1.01 pu and 1.03 pu. Whereas in Refs. [1] and [5] the maximum voltage decreases from 1.062 pu to 0.5838 pu and the minimum voltage magnitude decreases from 0.9507 pu to 0.77 pu.

For IEEE 14 bus system, bus 3 is the bus with heaviest load and bus 4 is the bus with second heaviest load. The supplied powers at bus 3 and bus 4 by the proposed SFLA are 89.547 MW and 46.247 MW respectively. In Refs [1] and [5] the supplied powers at bus 3 and bus 4 are 85.52 MW and 39.70 MW respectively. The supplied powers at bus 3 in Ref [2] is 78.02 MW and at bus 4 it is 36.69 MW. The proposed approach supplies more power at the heaviest loaded buses - bus 3 and bus 4- as compared to [1, 2, 5].

c) Overload contingency:

In this contingency it is considered overloading up to 55.4% above the maximum available generation of 400 MW. This corresponds to a connected load between 388.5 MW (150% of the nominal connected load) to 621.6 MW (240% of the original connected load) . Figure 5 shows the minimum iterations to converge for the proposed SFL algorithm is 22 iterations corresponding to connected load of 621.6 MW. For this contingency the supplied load obtained using the proposed method decreases from 366.172 MW at 150% overload to 365.483 MW at 240 % overload. Whereas for the same range of overload contingencies, in refs [1,5] and ref [2] the supplied power decreases from 376.121 MW to 363.785 MW and from 383.3MW to 383.45 MW respectively. Figure 6(a) shows the decrease in supplied power from 366.172 MW at 150% overload to 365.483 MW at 240% overload for the proposed SFL algorithm. The corresponding increase in the system losses is shown in Fig. 6(b) for the corresponding connected load. For this range of overload contingencies the system losses obtained by the proposed method increases from 33.828 MW to 34.51 MW. Whereas the system losses for this condition reported in Refs[1,5] and Ref[2] increases from 23.879 MW to 36.215 MW and from 16.7 MW to 16.55 MW respectively.

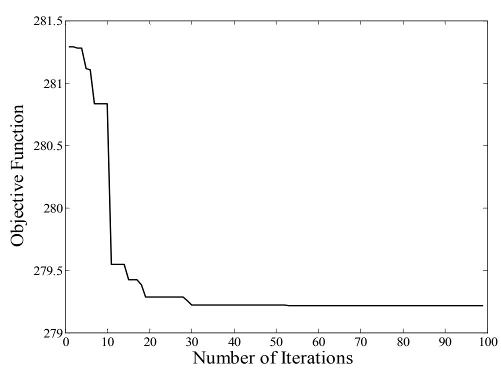

Fig. 5. Convergence Characteristics of SFL Algorithm for IEEE 14-Bus System under Overload Conditions.

The proposed approach supplies 135.814MW to bus 3 and 68.037 MW to bus 4. Whereas Ref [1,5] supplies 155.33 to bus 3 MW and 70.63 MW to bus 4 .Ref [2] supplies 139.38 MW and 71.01 MW to buses 3 and 4 respectively. A better voltage profile is obtained by the proposed method during this contingency. Maximum voltage obtained using the proposed approach is constant at 1.061 pu and the minimum voltage increases from 0.998 to 1.03444 pu.

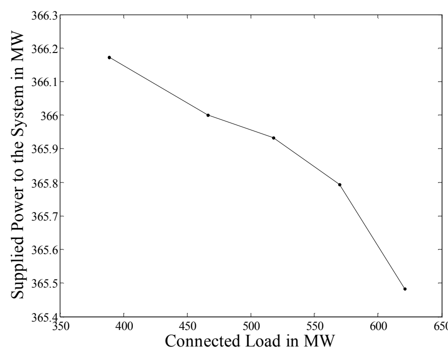

Fig. 6 (a). Optimal Supplied Power for IEEE14-Bus System under Overload Conditions using SFL Algorithm

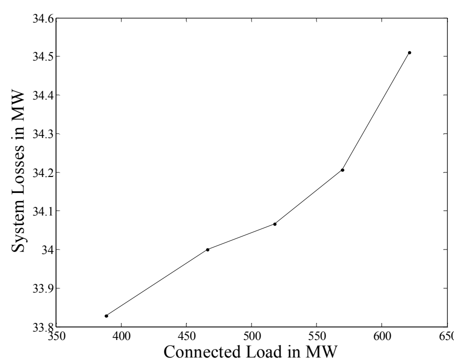

Fig. 6 (b). System Losses of IEEE14-Bus System under Overload Conditions using SFL Algorithm.

In Refs [1,5] the maximum voltages vary between 1.1352 pu and 0.974 pu. and the minimum voltage increases from 0.77 pu to 0.95 pu. The maximum voltage reported in Ref [2] is constant at 1.2 pu and the minimum voltage increase from 1.1096 pu to 1.1104 pu.

4.1.2. IEEE 30-bus system:

This system consists of 41 lines, three generators, three synchronous condensers, two static capacitor and three transformers. The generated reactive power limits are:

$-20 \leq Q_{G1} \leq 43, \qquad -10 \leq Q_{G8} \leq 30,$

$-20 \leq Q_{G2} \leq 43, \qquad -10 \leq Q_{G11} \leq 45,$

$-20 \leq Q_{G5} \leq 50, \qquad -10 \leq Q_{G13} \leq 50,$

The generated active power limits are:

$0 \leq P_{G1} \leq 175, \qquad 0 \leq P_{G2} \leq 70 \qquad 0 \leq P_{G5} \leq 75$

The supplied power by the NR method with VDLM used in this paper under normal operating conditions is 281.579 MW for a connected load of 283.40 MW. The reactive power supplied by the method used in this paper is 125.3110 MVAR. The supplied powers in Refs. [2] , [3] and [5] are 283.30 MW , 284.340 MW and 279.910 MW respectively for a connected load of 283.40 MW. In Ref [1] the supplied power is 279.910 MW for the same connected load. The reactive power supplied by the methods reported in Refs [2], [3] and [5] are 126.20 MVAR, 127.130 MVAR and 124.930 MVAR respectively. The deficit in the supplied power obtained in this paper and in Refs. [1],[3] and [5] represents the effect of using a VDLM to express the active power.

The total active and reactive power generation obtained under normal operating condition by the NR method with VDLM used in this paper is 290.00 MW and 125.540 MVAR respectively. The total real power loss obtained here is 9.44 MW. Whereas the total active power generation obtained by the method reported in Refs [2], [3] and [5] for the normal operating conditions were 294.840 MW, 292.070 MW and 289.450 MW respectively. The corresponding reactive power generation reported in these Refs [2], [3] and [5] were 121.49 MVAR, 123.30 MVAR and 125.540 MVAR respectively. 11.5363 MW, 10.6598 MW and 11.4053 MW are the respective total active power losses reported in the Refs [2], [3] and [5].

The bus voltages vary between 0.970 pu and 1.082 pu in the proposed approach whereas the voltages vary from 0.9349 pu to 1.10 pu in Ref. [1,5], 0.9247 pu to 1.10 pu in Ref. [2] and 0.9319 pu to 1.088 pu in Ref. [3].

a) Loss of generation contingencies

An abnormal operating condition representing the loss of 60 MW or 20.35% of normal generation is considered here. The amount of load shed and the supplied active power demand obtained using the proposed SFLA is 41.069 MW or 14.496 % of the nominal load and 241.53 MW respectively. Whereas the load shed and the supplied active power demand in Refs [1] and [5] are 42.69 MW or 15.07 % of the nominal load and 240.60 MW respectively. For the same generation loss, the amount of load shed and the supplied power in Ref. [2] are 40.73 MW or 14.38% of the nominal load and 242.67 MW respectively. It can be observed that the proposed approach has yielded lower amount of load shed when compared with the Refs [1] and [5]. Reactive powers supplied by the proposed SFL algorithm and by the methods used in the Refs [2], [3] and [5] are 106.834 MVAR, 108.170 MVAR, 115.940 MVAR and 109.320 MVAR respectively.

The total active and reactive power generation obtained by the proposed SFL algorithm for this case is 250 MW and 125.54 MVAR respectively. The corresponding active power loss obtained by this approach is 8.388 MW.

Whereas the total active power generation obtained by the method reported in Refs [2], [3] and [5] for this loss of generation contingency were 250 MW, 250.00 MW and 250 MW respectively. The corresponding reactive power generation reported in these Refs [2], [3] and [5] were 85.960 MVAR, 119.780 MVAR and 125.540 MVAR respectively. The corresponding active power losses reported in the Refs [2], [3] and [5] are 7.4302 MW, -6.7483 MW and 9.4087 MW respectively.

Figure 7 shows the convergence characteristics of the proposed SFL algorithm for the test system operated under the abnormal operating condition representing loss of generation of 60 MW. The maximum number of iterations to converge for the proposed approach is 11.

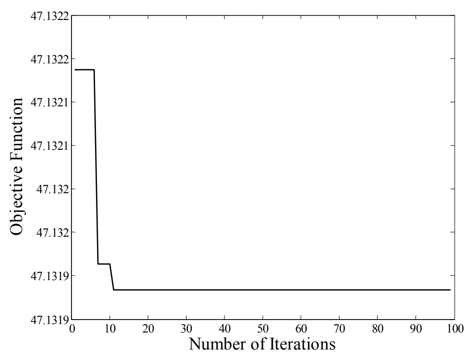

Fig. 7. Convergence Characteristics of SFL Algorithm for IEEE 30-Bus System under Loss of Generation of 60 MW.

The bus voltages vary between 0.997 pu and 1.082pu in the proposed SFLA.Whereas the voltages vary from 0.8920 pu to 1.0630 pu in Ref. [1,5], 0.99806 pu to 1.10 pu in Ref. [2].

b) Range of generation deficits contingency

The test system is also subjected to contingencies characterized by generation deficits. The range of generation is varied from 300 MW to 190 MW, with a connected load of 283.3 MW, which means, the resulting generation deficit varies from 0 to 93.3 MW. Figure 8 shows the convergence characteristics of the proposed SFL algorithm for the generation of 190 MW and the minimum iterations being 27.

Figure 9(a) shows the total supplied power obtained by the proposed SFL algorithm decreases from 281.5 MW at 290 MW generations to 185.76 MW at 190 MW generations and Fig. 9(b) shows the corresponding active power loss decreases from 9.25 MW to 3.12 MW. Whereas the total supplied power in Refs. [1] and [5] decreases from 279.82 MW at 300 MW generation to 183.25 MW at 190 MW generation with corresponding active power losses decrease from 9.437 MW to 4.24 MW and in Ref [2] the supplied power decreases from 283.3 MW at 300 MW generation to 186.06 MW at 190 MW generation with the corresponding active power losses decrease from 9.87 MW to 3.94 MW for the same range of generation deficits.

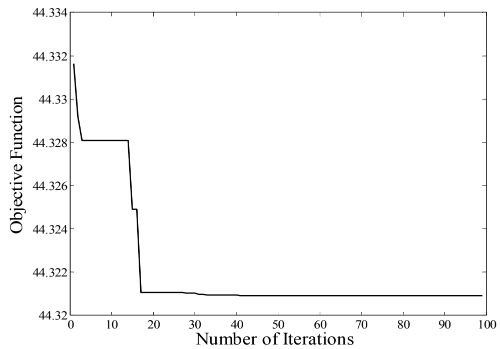

Fig. 8. Convergence Characteristics of SFL Algorithm for IEEE 30-Bus System under Generation Deficits Contingency

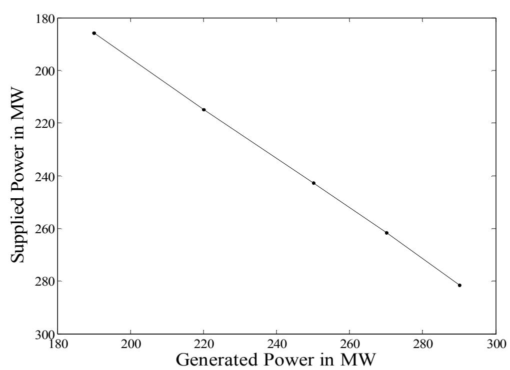

Fig. 9 (a). Optimal Supplied Load for IEEE 30-Bus System under Generation Deficit Contingency using SFL Algorithm.

The maximum bus voltage obtained by the proposed SFL algorithm for this generation contingency remains constant at 1.061 pu and the minimum voltage varies between 1.06pu and 0.984pu.Whereas in Refs. [1] and [5] the maximum voltage decreases from 1.1 pu to 0.8786 pu and the minimum voltage magnitude varies from 0.9353 pu to 0.77 pu and in Ref [3] the maximum voltage is constant at 1.1 pu and minimum voltage magnitude increases from 0.9576 pu to 1.0125 pu.

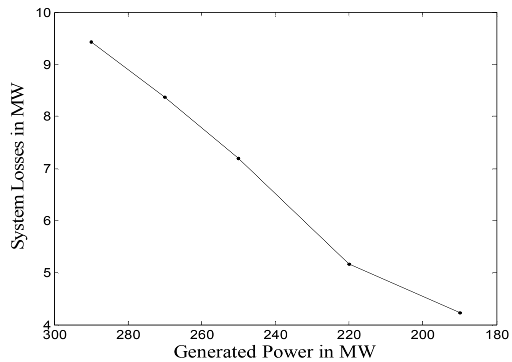

Fig. 9 (b). System Losses for IEEE 30-Bus System under Generation Deficit Contingency using SFL Algorithm.

For IEEE 30 bus system, bus 5 is the bus with heaviest load and bus 8 is the bus with second heaviest load. The supplied powers by the proposed SFL approach at bus 5 and bus 8 are 88.21 MW and 25.34 MW respectively at a generation of 250 MW. In Refs [1] and [5] the supplied powers at bus 5 and at bus 8 are 88.46 MW and 26.89 MW respectively . The supplied power at bus 5 in Ref [2] is 80.70 MW and at bus 8 it is 25.80 MW. The proposed approach supplies more power at the heaviest loaded buses- bus 5 as compared to Refs.[2].

c) Overload contingency

We consider overloading up to 41.65 % above the maximum available generation of 320 MW. This corresponds to a connected load between 311.63 MW (110% of the nominal connected load) to 453.26 MW (160 % of the original connected load). Figure 10 shows the minimum iterations to converge is 31 corresponding to connected load of 425.1 MW. For this contingency the supplied load obtained using the proposed method decreases from 308.018 MW at 110% overload to 307.735 MW at 160 % overload. Whereas for the same range of overload contingencies, the supplied power decreases from 306.836 MW to 304.562 MW and from 309.19 MW to 304.562 MW in Refs [1,5] and Ref [2] respectively. Figure 11(a) shows the decrease in supplied power from 308.018 MW at 110% overload to 307.735 MW at 160 % overload for the proposed SFL approach.

For this range of overload contingencies the system losses obtained by the proposed method increases from 11.982 MW to 12.268 MW which is shown in Fig. 11(b). Whereas the system losses for this condition reported in Refs[1,5] and Ref[2] increases from 13.164 MW to 15.438 MW and from 10.81 MW to 10.62 MW respectively.

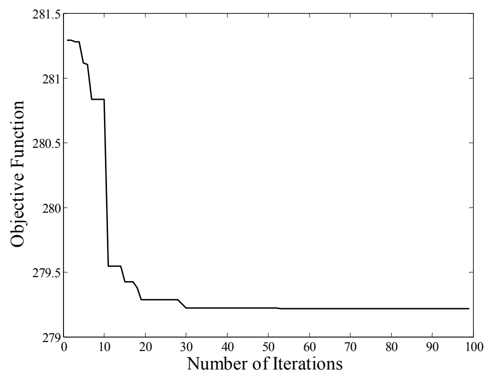

Fig. 10. Convergence Graph of SFL Algorithm for 30-Bus System under Overload Conditions.

The proposed approach supplies 106.024MW to bus 5 and 33.531 MW to bus 8. Whereas Ref [1, 5] supplies 111.9 to bus 5 MW and 34.6 MWMW to bus 8. Ref [2] supplies 102.761 MW and 32.92 MW to buses 5 and 8 respectively. So, during the overload contingency considered the proposed method supplies more power to these heaviest load buses as compared to the power supplied by the method reported in Ref [2]. A better voltage profile is obtained by the proposed method during this contingency. Maximum voltage obtained using the proposed approach is constant at 1.082pu and the minimum voltage increases from 0.961 to 0.963pu.

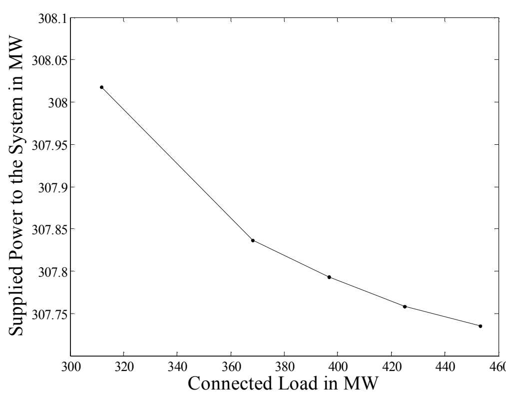

Fig. 11(a). Optimal Supplied Power for IEEE 30-Bus System under Overload Conditions using SFL Algorithm.

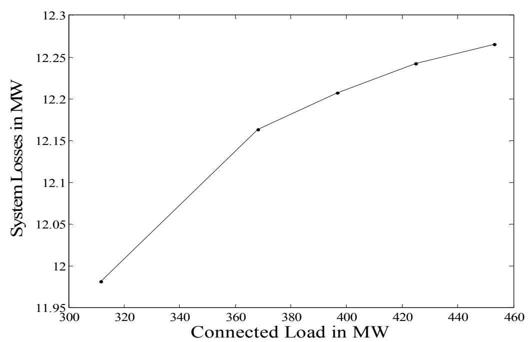

Fig. 11(b). System Losses of IEEE 30-Bus System under Overload Conditions using SFL Algorithm.

In Refs [1,5] the maximum voltages vary between 1.094pu and 0.943pu. and the minimum voltage increases from 0.77 pu to 0.93pu. The maximum voltage reported in Ref[2] is constant at 1.1pu and the minimum voltage increase from 0.9634 pu to 0.9797pu.

5. Conclusions

In this paper a steady state optimal load shedding strategy using a memetic meta-heuristic algorithm known as shuffled frog leaping algorithm has been presented. The proposed approach has been tested on IEEE 14 and 30bus test systems. The results obtained by the proposed approach are compared with those obtained by conventional methods. The comparison is done on the basis of supplied power, system losses, total load shed and the minimum and maximum bus voltages. The results presented show that the proposed approach provides more supplied power and better voltage profile as compared with those of other methods. Also, the proposed method supplies more power to the heaviest load buses in the case of IEEE 14 and 30 bus test systems, as compared with the power supplied by the other methods.

The SFLA consist of both local search and global information exchange. The algorithm consists of a set of interacting virtual population of frogs partitioned in to different memeplexes. An independent local search in each memeplex is carried out simultaneously, which improves the exploitation characteristics. The exploration characteristic of the algorithm is enhanced by the periodical shuffling of the memeplexes and the random generation of virtual frogs. These characteristics have improved the effectiveness and efficiency of the proposed algorithm in order to obtain better solutions in terms of quality and accuracy.

Based on these outcomes, it can be concluded that the proposed shuffled frog leaping algorithm can be considered as an effective alternative approach for optimal load shedding.

References

1. Mostafa, M.A.; El-Harwary, M.E.; Mbamalu, G.A.N.; Mansour, M.M.; El-Nagar, K.M.; and El-Arabaty A.M. (1997). A computational comparison of steady state load shedding approaches in electric power systems. *IEEE Transactions on Power Systems*, 12(1), 30-37.
2. Hajdu, L.P.; Peschon, J.; Tinney, W.F.; and Piercy, D.S. (1968). Optimal Load-Shedding Policy for Power Systems. *IEEE Transaction on Power Apparatus and Systems*, 87(3), 784-795.
3. Palaniswamy, K.A.; Misra, K.B.; and Sharma, J. (1985). Optimum load shedding taking into account voltage and frequency characteristics of loads. *IEEE Transaction on Power Apparatus and Systems*, 104(6), 1342-1348.
4. Mosatafa, M.A.; El-Harwary, M.E.; Mbamalu, G.A.N.; Mansour, M.M.; El-Nagar, K.M.; and El-Arabaty A.M. (1995). Optimal dynamic load shedding using a Newton based dynamic algorithm", *Electric Power Systems Research*, 34(1), 157-163.
5. Mosatafa, M.A.; El-Harwary, M.E.; Mbamalu, G.A.N.; Mansour, M.M.; El-Nagar, K.M.; and El-Arabaty A.M. (1996). Steady-state load shedding schemes: a performance comparison. *Electric Power Systems Research*, 38(1), 105-112.
6. Subramanian, D.K. (1971). Optimum Load Shedding Through Programming Techniques. *IEEE Transactions on Power Apparatus and Systems*, 90(1), 89-95.
7. Chan, S.M.; and Schweppe, F.C. (1979). A Generation Reallocation and Load Shedding Algorithm. *IEEE Transactions On Power Systems*, 98(1), 26-34.
8. Chan, S.M.; and Yip, E. (1979). A solution of the Transmission Limited Dispatch Problem By Sparse Linear Programming. *IEEE Transactions On Power Systems*, 98(3), 1044-1053.
9. Medicherla, T.K.P.; Billinton R.; and Sachdev, M.S. (1979). Generation Rescheduling and Load Shedding to Alleviate Line Overloads-Analysis. *IEEE Transactions On Power Apparatus and Systems*, 98(1), 1876-1884.
10. Medicherla, T.K.P.; Billinton R.; and Sachdev, M.S. (1981). Generation Rescheduling and Load Shedding to Alleviate Line Overloads-System Studies. *IEEE Transactions on Power Apparatus and Systems*, 100(1), 36-41.
11. Freris, L.L.; and Sasson, A.M. (1968). Investigation of Load Flow Problem. *Proceedings of the Institution of Electrical Engineers*, 115(10), 1459-1470.
12. Okamum, M.; O-ura, Y.; Hayashi, S.; Uemura, K.**;** and Ishiguro, F. (1975). A New Power Flow Model and Solution Method Including Load and Generator Characteristics and Effects of System Control Devices. *IEEE Transactions on Power Apparatus and Systems*, 94(1), 1042-1050.
13. Arya, L.D.; and Pushpendra Singh, L.S. (2012). Differential evolution applied for anticipatory load shedding with voltage stability considerations. *Electrical Power and Energy Systems*, 42 (1), 644-652.
14. Sadati, N.; Amraee, T.; and Ranjbar, A.M. (2009). A global Particle Swarm-Based-Simulated Annealing Optimization technique for under-voltage load shedding problem. *Applied Soft Computing*, 9(1), 652-657.
15. Jiyu Deng.; and Junyong Liu. (2012). A Study on a Centralized Under-Voltage Load Shedding Scheme Considering the Load Characteristics.

International Conference on Applied Physics and Industrial Engineering-Physics Proceedia, 24(1), 481- 489.

16. Zuhaila Mat Yasin.; Titik Khawa Abdul Rahman.; and Zuhaina Zakaria. (2012). Multiobjective Quantum-Inspired Evolutionary Programming for Optimal Load Shedding. *IEEE Control and System Graduate Research Colloquium (ICSGRC)*, 160-165.
17. Mark, A.; Michael, JS.; Gary Schauerman.; and Bernard Cable. (2014). Design of Priority- Based Load Shed Scheme and Operation Tests. *IEEE Transactions on Industry Applications*, 50(1), 182-187.
18. Adolfo, R.E.; Erick Moreno, C.; and Kory, W.H. (2014). Topology Control for Load Shed Recovery. *IEEE Transactions on Power Systems*, 29 (2), 908-916.
19. Yan Xu.; Zhao Yang Dong.; Fengji Luo.; Rui Zhang.; and Kit Po Wong. (2014). Parallel-differential evolution approach for optimal event-driven load shedding against voltage collapse in power systems. *IET Generation Transmission and Distribution*, 8(4), 651-660.
20. Feng, Z.; Ajjarapu, V.; and Maratukulam, D. (2000). A comprehensive approach for preventive and corrective control to mitigate voltage collapse. *IEEE Transaction on Power System*, 15 (2), 791–797.
21. Wang, Y.; Pordanjani, I.R.; Li,W.; Xu,W.; and Vaahedi, E. (2011). Strategy to minimize the load shedding amount for voltage collapse prevention. *IET Generation Transmission and Distribution*, 5 (3), 307-313.
22. Wang, Y.; Pordanjani, I.R.; Li,W.; Xu,W. (2011). An event-driven demand response scheme for power system security enhancement. *IEEE Transaction on Smart Grid*, 2(1), 23-29.
23. Shayanfar, H.A.; Jahani, R.; Olamazi, J. (2010). Comparison of Modified Shuffled Frog Leaping Algorithm and other Heuristic Methods for Optimal Placement of UPFC in Electrical Power Systems. *Australian Journal of Basic and Applied Sciences*, 4(11), 5590-5598.