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A NOVEL LOAD SHEDDING METHOD TO IMPROVE TRANSMISSION LINE PERFORMANCE AND VOLTAGE STABILITY MARGIN

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Abstract- In this paper, a novel method based on Hybrid Genetic Algorithm and Particle Swarm Optimization (HGAPSO) technique is proposed for solving Under Voltage Load Shedding (UVLS) problem. Load curtailment as ultimate control action is performed by under voltage load shedding scheme to guarantee power system voltage stability in contingency conditions. In addition, the proposed under voltage load shedding scheme pursue improvement transmission line performance by alleviating line over loadings and active power loss objects in presence of minimization customer interruption cost. Customer interruption cost has been modeled as a quadratic function in five major load classifications. Consequently, under voltage load shedding has been modeled as multi objective problem and carried out on 14 and 57 bus IEEE test systems and results are discussed. The simulation results are checked by Particle Swarm Optimization and it shows the efficacy and advantages of proposed method.

Keywords: Under Voltage Load Shedding, Voltage Stability, Customer Interruption Cost, Multi Objective Optimization.

I. INTRODUCTION

In recent years, power system black outs around the world resulting from voltage collapse have become more repetitive because of some operational factors like system deficiencies, persistent load growing. Load shedding is the latest countermeasure to save a voltage unstable power system before pervasive blackout, when there is no control action to stop an approaching voltage collapse [1, 2]. In operation planning studies of power systems, the state of the power system analyzed by system beneficiary and performs in advance appropriate control actions to safeguard the security criteria. These control actions may be consists of voltage control resources such as transformer taps, shunt reactors or adjustments and modification of the generation dispatch such as decrease and increase of generation in several generators, and connection of off-line units [3].

In on-line voltage stability analysis, when the network is close to the load ability margin, the available control actions are ineffectual or there may not be fast enough to prevent the voltage collapse in power system. Therefore, in alarm conditions, emergency load shedding measures may be required. However, implementing of load shedding must be considered as last resort.

To be effective counter measure versus voltage instability, the two main categories consideration in load shedding as the amount of load to be shed and the location where load shed is to be shed [4-7]. The amount of load to shed is calculated by purports which is load to be shed has to be optimum. Load shedding in power system less than necessary will obviously not to be efficient in arresting voltage collapse. Also, determining the location where load to be shed is the second important factor. Some researchers are using the OPF (Optimal Power Flow) methodologies in the dynamic simulation [4, 6, 7]. In this approach, based on voltage stability viewpoint, the load buses are ranked in order of the strongest to the weakest. The weakest bus tends to be most capable to voltage instability given the practically large reactive power consumption for small reduction in bus voltage. Hence, often it is this bus that is the most appropriate candidate which is selected by load shedding initially [6].

Several works have been previously conducted on load shedding against voltage collapse. In [3], an LP-based optimization load shedding algorithm is introduced to load margin improvement. The objective function of problem consists of minimizing the total system load decrease. The load shedding algorithm selects both the optimal location of generation and load buses, and their corresponding power reduction based on first order sensitive of the load margin with respect to the load to be shed. In [8], a load shedding versus long-term voltage instability is proposed. A distributed load shedding scheme has been introduced in that approach tends to act first where voltages drop the most.

In [9], the optimum load shedding problem is formulated to purpose of minimization the sum of the squares of the variance between the connected load demands and the generated power. The supplied power based on bus voltage magnitudes is defined as a function. An approach to the load shedding scheme is introduced by increasing the number of participants in [10]. This load control mechanism is possible to divide every customer's load into interruptible and uninterruptible parts, and load shedding implemented in the interruptible part only. The optimal load reduction request is defined by minimizing the expected value of a cost function, thus taking the uncertainty about the active power absorbed by each load into account. Analytical explanation of the design of several load shedding schemes for the protection of the Hellenic Interconnected System versus the risk of voltage stability is presented in [11]. In [12], a concept of soft load shedding (SLS) for residential consumers is proposed. It takes solely a fraction of the consumers' power, even if the effort is spread over a larger number. It therefore seeks to prevent the plunge into darkness.

In this paper, a new method for load shedding based on improvement of transmission line performance is proposed. Herein, voltage stability indicator utilized to load shedding scheme to maximize security of power system against voltage collapse. This index is basically used to indicate transmission line load ability in a power system. Also, minimize of active power loss in transmission lines has great significance in objective function that is considered in this paper firstly. In addition, one of the most important categories that considered in this paper is customer interruption cost. Load buses are ranked by interruption cost and load shedding tries to minimize the cost of interruption. Consequently, load which have a lowest interruption cost is selected by proposed load shedding scheme. The amount and location of load shedding obtained from HGAPSO as optimization tool & results checked by PSO.

II. LOAD SHEDDING MODELING

The proposed under voltage load shedding is defined as an optimization problem which its objective function consist of four object. Three of them cover operational conditions and try to recovering normal operating in power system and the fourth one is economical object that try to reduce interruption costs by selecting the cheapest load from power system.

A. Eliminate Transmission Line over Loadings

To purpose of elimination transmission line over loadings, a special function is defined as follows:

$$OF_1 = \begin{cases} \sum_{i=1}^{N_{line}} 10^{5\left(\frac{S_i^P - S_i^{\max}}{S_i^{\max}}\right)} & \text{if} \quad S_i^P > S_i^{\max} \\ 0 & \text{if} \quad S_i^P \le S_i^{\max} \end{cases} \quad (1)$$

where S_i^P represent apparent power transmitted through the line in post contingency and $S_i^{\max}$ is its maximum apparent power. Exponential definition of this function allow to load shedding algorithm to pursue of alleviating transmission line over loadings effectively in compare of linear functions which debated in literatures such as [13].

B. Voltage Stability Minimization and criteria

Fast Voltage Stability Index (FVSI) [14, 15, 16] as voltage stability indicator in transmission line is proposed to utilize in under voltage load shedding. The FVSI is calculated from power flow concept in single line which consists of two bus system. Figure 1 shows the two bus power system one line diagram.

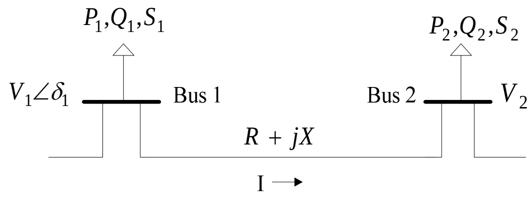

Figure 1. Two bus power system model

Fast voltage stability index is equal to:

$$FVSI = \frac{4Z^2 Q_2 X}{V_1^2 (R\sin\delta + X\cos\delta)^2} \simeq \frac{4Z^2 Q_2}{V_1^2 X} \quad (2)$$

This index varies between 0 and 1. The values close to 1 indicate instability conditions in transmission line and the values which are near to 0 indicate stability conditions. Also, this index has capability of on line voltage stability assessment which must be minimized to improvement transmission line performance. So, the second object of under voltage load shedding can be formulated as follows:

$$OF_2 = \sum_{i=1}^{N_{Line}} FVSI_i \quad (3)$$

Based on Equation (3), a summation of voltage stability indexes is minimized by under voltage load shedding to betterment system stability in viewpoint of voltage.

C. Active Power Loss Minimization

The third operational object of proposed load shedding is minimization of active power loss in power system. Load shedding that proposed so far didn't consider active power loss whilst active power loss increased extremely by transmission line congestion due to contingency event. The equation (4) displayed the third object of load shedding scheme [17, 18, 19].

$$OF_3 = \sum_{i=1}^{N_{Line}} R_i I_i^2 = = \sum_{i,j=1,2,\dots,N_{Bus}} \begin{pmatrix} V_i^2 + V_j^2 \\ -2V_i V_j \cos(\delta_i - \delta_j) \end{pmatrix} \quad (4)$$

D. Minimization of Customer Interruption Cost

There are many studies of interruption cost in literatures [20-23]. These investigations show that the interruption cost generally increases proportionally to the magnitude of load and the *r*th power of outage duration, and the rate of increase differs markedly from customer to customer. Table 1 show that the cost of an interruption load depends on its type, magnitude and the duration of customer interruption.

Table 1. Sector interruption cost [24]

User sector	Interruption Duration (min) & Cost ($/KW)				
	1 min	20 min	60 min	240 min	480 min
Larger users	1.005	1.508	2.225	3.968	8.240
Industrial	1.625	3.868	9.085	25.16	55.81
Commercial	0.381	2.969	8.552	31.32	83.01
Agricultural	0.060	0.343	0.649	2.064	4.120
Residential	0.001	0.093	0.482	4.914	15.69

This table gives the interruption cost for five discrete outage durations. In direction of load shedding purpose; the nonlinear curve between duration (minute) and costs ($) is fitted for each classes of load. Curve fitted on cost ($/kW) and time by:

$$Cost\left(\frac{\$}{\text{kW}}\right) = a\,t^2 + b\,t + c \tag{5}$$

where *a*, *b*, *c* are constant coefficients and *t* is duration of load interruption. Equation (6) shows cost of interrupted load by load shedding scheme which depends on time of interruption. Load interruption cost for each classes of load is derived as:

$$IC(\$) = \left(a\,t^2 + b\,t + c\right)\left(P_D^0 - P_D^P\right) \tag{6}$$

For the industrial customer as example, the first term of Equation (6) $at^2(P_D^0 - P_D^P)$ is an approximated cost which is proportional to the *r*th power of *t* and represents costs such as those required for plant restoration. The second term $bt(P_D^0 - P_D^P)$ is a term proportional to the interruption duration such as loss of production. The third term $c(P_D^0 - P_D^P)$ represents the fixed cost required for equipment maintenance etc.

It is supposed, which each bus includes five feeders with one class of load in each feeder. The load of each feeder is a part of total load on bus. So, this has a participation factor. Also cost of load in each bus can be formulated as:

$$\begin{aligned} Total\ Cost = {} & IC_L.PF_L + IC_I.PF_I + \\ & + IC_C.PF_C + IC_A.PF_A + IC_R.PF_R \end{aligned} \tag{7}$$

where *L*, *I*, *C*, *A* and *R* are abbreviation of load classifications. Equation (7) represents an economical weight factor for weighted load shedding. Hence, cheapest loads are selected by load shedding scheme. So, the next term of optimization problem is given as follows:

$$OF_4 = \min \sum_{i=1}^{N_{Bus}} \left(Total\ Cost_i (P_{Di}^0 - P_{Di}^P)\right) \tag{8}$$

A. Load Shedding Constraints

Load shedding scheme has been implemented on power system under feasibility and solve ability of power flow equations. Hence, power flow equations are equality constraint of load shedding which expressed in equations (9) and (10).

$$P_{Gi}^0 - P_{Di}^0 + \Delta P_{Di} = \sum_{j=1}^{N} |V_i||V_j||Y_{ij}|\cos(\delta_{ij} + \delta_j - \delta_i) \tag{9}$$

$$Q_{Gi}^0 - Q_{Di}^0 + \Delta Q_{Di} = -\sum_{j=1}^{N} |V_i||V_j||Y_{ij}|\sin(\delta_{ij} + \delta_j - \delta_i) \tag{10}$$

It is remarkable that the reactive power generation constraint is considered in power flow algorithm and it is not required to considering in load shedding modeling. The other constraint is specified in Equations (11), (12) and (13):

$$V_i^{\min} \le V_i^P \le V_i^{\max} \tag{11}$$

$$P_{Di}^{\min} \le P_{Di}^P \le P_{Di}^{\max} \tag{12}$$

$$\frac{\Delta P_{Di}}{P_{Di}^0} = \frac{\Delta Q_{Di}}{Q_{Di}^0} \quad \text{fixed power factor} \tag{13}$$

where $V_i^P, V_i^{\min}$ and $V_i^{\max}$ are bus voltage in post contingency, minimum and maximum allowable bus voltage respectively. Also the control variable that enable us to obtain an optimal solution are P_{Di} and Q_{Di}. Considering that during the implementation of load shedding the power factor is maintained constant, simplifies the modeling. There are less variables, because the relation between active and reactive power in constant power factor.

III. HYBRID GENETIC ALGORITHM AND PARTICLE SWARM OPTIMIZATION

Particle swarm optimization (PSO) is a new evolutionary computation technique first introduced by Kennedy and Eberhart in 1995 [25]. Like other stochastic searching techniques, the PSO is initialized with generating a population of random solutions, which is called a swarm. Each individual is referred to as a particle and presents a candidate solution to the optimization problem. A particle in PSO has a memory in which retains the best experience, which is gained in the renewable of search space. In this technique, each candidate solution is associated with a velocity vector [26, 27].

The velocity vector is constantly adjusted according to the corresponding particle's experience and the particle's companion's experience. Therefore, in PSO algorithm, the best experiences of the groups are always shared with all particles and so, it is expected that the particles move toward better solution areas. The *gbest*PSO is an implementation where the neighborhood is entire swarm, while *lbest*PSO refers to the implementation where a smaller neighborhood size is used. According to the above-mentioned concepts, *gbest*PSO operation can be mimicked as following:

In an n-dimensional search space, let the position and velocity of *i*th individual be represented as the vectors $x_i = (x_{i1},...,x_{id},...,x_{in})$, and $v_i = (v_{i1},...,v_{id},...,v_{in})$ respectively. The best previous experience of the i^{th} particle is recorded and represented as $pbest_i = (pbest_{i1},...,pbest_{id},...,pbest_{in})$. The best value among all individual's experience in the group is stored and referred as $gbest = (gbest_1,...,gbest_d,...,gbest_n)$. The modified velocity of each particle can be first calculated regarding to the personal initial velocity, the distance from personal best position and the distance from global best position as shown in Equation (14).

The Equation (14), determines the direction, which the ith particle can be taken along. Therefore, the new position of that particle can be determined using Equation (15) [28].

$$v_{id}^{(t+1)} = \omega . v_{id}^{(t)} + c_1 . \text{rand}_1().(pbest_{id} - x_{id}^{(t)}) + c_2 . \text{rand}_2().(gbest_d - x_{id}^{(t)}) \quad (14)$$

$$x_{id}^{(t+1)} = x_{id}^{(t)} + v_{id}^{(t+1)} \quad (15)$$

In these equations i=1, 2, …, m is the index of each particle. The t is iteration number. The constants c_1 and c_2 are the weighting factors of the stochastic acceleration terms, which pull each particle toward *pbest* and *gbest* positions. Reference [29] has introduced the parameter w into the PSO's equation to improve its performance. Suitable selection of inertia weight w in (14) provides a balance between global and local explorations, thus, requiring less iteration on average to find a sufficiently optimal solution. As originally developed, w often decreases linearly from about 0.9 to 0.4 during a run. In general, the inertia weight w is set according to the following equation:

$$\omega^{(t+1)} = \omega^{\max} - \frac{\omega^{\max} - \omega^{\min}}{t_{\max}} . t \quad (16)$$

where, $t_{\max}$ is the maximum number of iterations and t is current iteration number.

Hybrid PSO has the advantages of both PSO and GA. Here in the PSO algorithm, the reproduction technique of Genetic is used to produce the best child from the worst parent [30]. The positions of the children are updated using the following equations:

$$child1(x_{id}^{(t)}) = pi \times parent1(x_{id}^{(t)}) + (1 - pi) \times parent2(x_{id}^{(t)}) \quad (17)$$

$$child2(x_{id}^{(t)}) = pi \times parent2(x_{id}^{(t)}) + (1 - pi) \times parent1(x_{id}^{(t)}) \quad (18)$$

The velocity vectors of the children calculated as follows:

$$child1(v_{id}^{(t)}) = (parent1(v_{id}^{(t)}) + parent2(v_{id}^{(t)})) \times \frac{\left| parent1(v_{id}^{(t)}) \right|}{\left| parent1(v_{id}^{(t)}) + parent2(v_{id}^{(t)}) \right|} \quad (19)$$

$$child2(v_{id}^{(t)}) = (parent1(v_{id}^{(t)}) + parent2(v_{id}^{(t)})) \times \frac{\left| parent2(v_{id}^{(t)}) \right|}{\left| parent1(v_{id}^{(t)}) + parent2(v_{id}^{(t)}) \right|} \quad (20)$$

where pi is a uniformly distributed random number between $[0,1]$.

IV. IMPLEMENTATION OF UNDER VOLTAGE LOAD SHEDDING ON HGAPSO

The HGAPSO tries to find optimum load shedding pattern. The flowchart of under voltage load shedding is displayed by Figure 2.

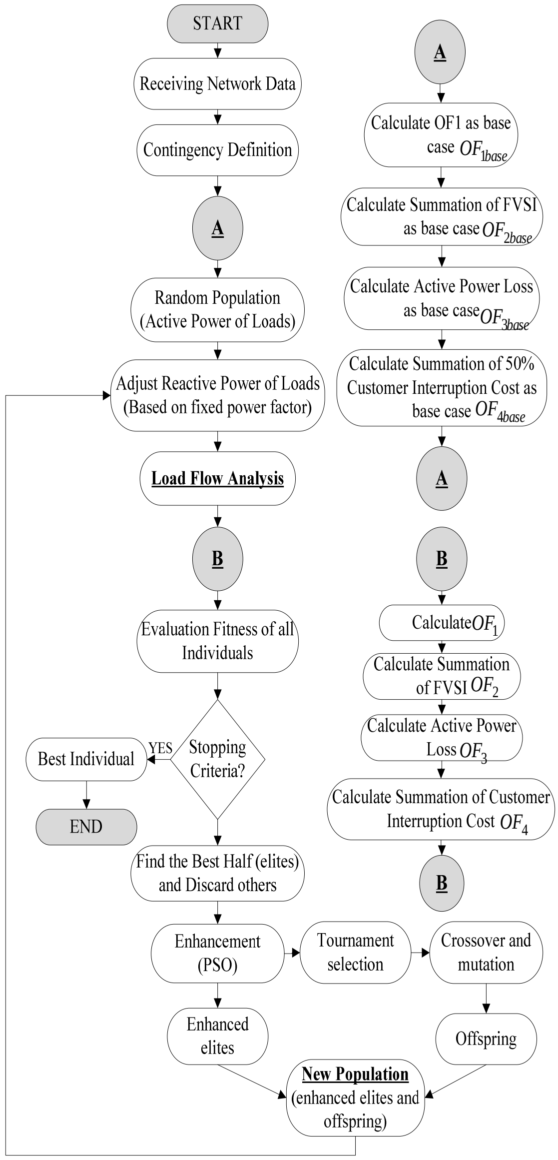

Figure 2. The Flowchart of proposed under voltage load shedding

A. Initialization

It is supposed that $P_{Di}^{\min} = 0.5 P_{Di}^{0}$ for all buses. This equation means that, load shedding in bus i, cannot be greater than 50 percent of load demand in this bus. Also in this paper, the interruption time for each classes of load is 30 minutes. Toolbox has been developed for any durations of load interruption with Matlab software.

B. Fitness Evaluation

The fitness function is calculated using Equation (1)-(13). Also, it is considered that following equation is a multi-objective function with its constraints:

$$\min(f_1(x), f_2(x), ..., f_M(x))$$

$$\text{subject to:} \begin{cases} h_k = b \\ x^{(L)} \le x \le x^{(U)} \end{cases} \quad (21)$$

In this paper to solve multi objective problem, Equation (21) is changed to no constraint function with penalty factors as follows [31, 32]:

$$\min[(f_1(x), f_2(x), f_3(x), f_4(x)) \quad \lambda(b-h_k)+\lambda_x \sum_{N_x^{\lim}} (\Delta x)^2] \tag{22}$$

$$\Delta x = \begin{cases} x - x^{(U)} \text{ if } x > x^{(U)} \\ x^{(L)} - x \text{ if } x < x^{(L)} \end{cases}$$

Based on optimization methodology which is described above, the fitness function of under voltage load shedding is defined as Equation (23).

$$Fitness = \text{minimize} \begin{bmatrix} k_1 \frac{OF_1}{OF_{1base}} + k_2 \frac{OF_2}{OF_{2base}} \\ +k_3 \frac{OF_3}{OF_{3base}} + k_4 \frac{OF_4}{OF_{4base}} \\ +\lambda f(V_i^P) \end{bmatrix} \tag{23}$$

where k_1, k_2, k_3, k_4 are arbitrary gains factor of normalized objects and λ is penalty factor of constraint. Also, $f(V_i^P)$ represent defined penalty function and it described as Equation (24).

$$F_v(V_i^P) = \begin{cases} V_i^P - V_i^{\max} & \text{if } V_i^P > V_i^{\max} \\ V_i^{\min} - V_i^P & \text{if } V_i^P < V_i^{\min} \\ 0 & \text{if } V_i^{\min} < V_i^P < V_i^{\max} \end{cases} \tag{24}$$

V. SIMULATION RESULTS

The proposed methodology of under voltage load shedding is implemented over the IEEE 14 bus and 57 bus test system [32]. The optimization models are solved using two evolutionary methods.

The first approach is based on HGAPSO and the second one is based on PSO. However, the HGAPSO heuristic optimization method has not been applied to the under voltage load shedding problem yet. The 14 bus test system is small power system and suitable to primary assessment of proposed load shedding and the 57 bus test system is a relatively medium scale power system that is suitable to verify the computational efficiency and optimality of load shedding.

A. The IEEE 14 Bus System

The IEEE 14 bus network one line diagram, as well as data for generators, demands and transmission lines can be found in [33]. It is assumed that the system loading is in base case. In this situation, a disturbance causes the contingency and the outage of line 1-2. Following this disturbance, extreme over load in line 1-5 is occurred and its voltage stability index shows the instability conditions. Some of network condition in post and pre contingency before performs of load shedding scheme are shown in Table 2.

Table 2. IEEE 14 bus indexes in pre and post contingency conditions

Power system states	Minimum bus voltage (pu) (Bus No.)	Maximum FVSI (sending and receiving ends)	Transmission line over loadings (MVA)	Active power loss (MW)
Pre contingency	0.9620 (14)	0.1791 (2-3)	0	16.03
Post contingency	0.9281 (5)	1.0829 (1-5)	171.0077	54.11

The Voltage stability index show alarm conditions and there is no control action available, the collapse is inevitable ignoring that the extreme over loading causes to trip the over loaded line and beginning cascading outages in lines, if the load shedding did not applied to power system quickly. The optimal pattern of load shedding in load buses is tabulated in Table 3.

Table 3. The results of implementing under voltage load shedding on 14 bus test system

	HGAPSO		PSO	
	The amount of load and the shedding percentage			
Load Buses	Bus Voltage (pu)	Optimal coordinated pattern of load shedding	Bus Voltage (pu)	Optimal coordinated pattern of load shedding
2	1.0000	0 (0%)	1.0000	0 (0%)
3	1.0000	47.1000 (50.00%)	1.0000	47.1000 (50.00%)
4	0.9728	20.2834 (42.43%)	0.9728	20.2834 (42.43%)
5	0.9679	3.8000 (50.00%)	0.9679	3.8000 (50.00%)
6	1.0000	0 (0%)	1.0000	0 (0%)
9	0.9993	14.7500 (50.00%)	0.9993	14.7500 (50.00%)
10	0.9923	0 (0%)	0.9923	0 (0%)
11	0.9942	1.7500 (50.00%)	0.9942	1.7500 (50.00%)
12	0.9857	0 (0%)	0.9857	0 (0%)
13	0.9825	0 (0%)	0.9825	0 (0%)
14	0.9778	3.7388 (25.09%)	0.9778	3.7388 (25.09%)
Total amount of load shedding (MW)		91.4222		91.4225
Agricultural load (MW)		9.1222		9.1222
Industrial load (MW)		15.3728		15.3729
Commercial load (MW)		20.6039		20.6039
Residential load (MW)		34.3197		34.3198
Large users load (MW)		12.0036		12.0037
Total customer interruption cost ($)		204916.4097		204917.0151
Maximum FVSI (Line)		0.3659 (1-5)		0.3659 (1-5)
Active power loss (MW)		13.7761		13.7760

Based on results of load shedding, whole of transmission line over loadings is removed from network and the voltage stability index has been improved by 66.21% decreasing on this index. In this situation, 91.4222 MW load curtailment causes to decreasing active power loss in presence of minimum customer interruption cost. Figure 3 shows the convergence of HGAPSO and PSO algorithm to find optimum pattern of load shedding scheme.

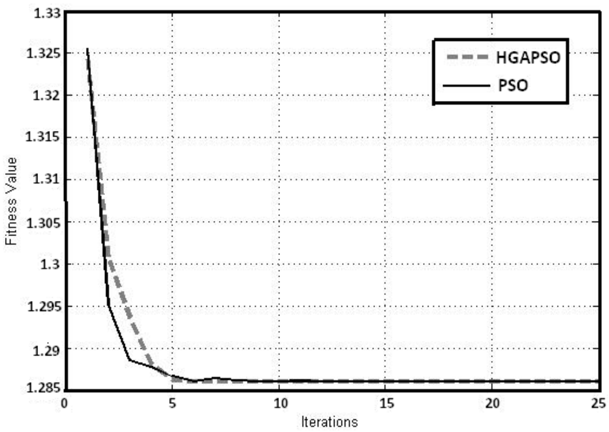

Figure 3. Compare of HGAPSO and PSO convergence (14 bus system)

B. The IEEE 57 Bus Test System

The IEEE 57 bus test system consists of 7 generators, 80 branches and 42 loads, the detailed characteristics of 57 bus test system are given in [33].

It is assumed that the power system loading is increased to 1.2 times the base case and the line 1-15 tripped in reason of disturbance occurrence. This contingency causes over load on lines 1-2, 2-3, 1-16, 3-15, 12-17 and 12-16, respectively. The indexes of 57 bus test system are shown by Table 4 in post and pre contingency occurrence.

Table 4. IEEE 57 bus indexes in pre and post contingency conditions

Power system states	Minimum bus voltage (pu) (Bus No.)	Maximum FVSI (sending and receiving ends)	Transmission line over loadings (MVA)	Active power loss (MW)
Pre contingency	0.9377 (31)	0.2391 (13-49)	0	28.18
Post contingency	0.8774 (31)	0.6004 (2-3)	339.4542	109.29

In this situation, over load is divided into several transmission lines and because of this, the voltage stability index shows the better conditions in compare of 14 bus system. However, the amount of transmission line over loadings is high and it able to lead system to collapse. Also, Active power loss is increased and it may be produce pressure on power system components. In many states, the active power loss may causes to decrease thermal stability of transmission lines. The optimal pattern of load shedding in load buses is tabulated in Table 5. Based on the results that tabulated on Table 4, proposed load shedding provides voltage stability by 45.63% decreasing in voltage stability index in presence of alleviating transmission line over loadings. Here, similar to previous study, the global convergence of HGAPSO is compared to the PSO method (Figure 4).

Table 5. The results of implementing under voltage load shedding on 57 bus test system

	HGAPSO		PSO	
	The amount of load and the shedding percentage			
Load Buses	Bus Voltage (pu)	Optimal coordinated pattern of load shedding	Bus Voltage (pu)	Optimal coordinated pattern of load shedding
1	1.0000	0 (0%)	1.0000	0 (0%)
2	1.0000	1.1589 (32.19%)	1.0000	0 (0%)
3	1.0000	0 (0%)	1.0000	0 (0%)
5	0.9980	7.8000 (50.00%)	0.9981	7.8000 (50.00%)
6	1.0000	13.8983 (15.44%)	1.0000	44.1120 (49.01%)
8	1.0000	0 (0%)	1.0000	0 (0%)
9	1.0000	0 (0%)	1.0000	0 (0%)
10	0.9931	2.1453 (35.75%)	0.9893	3.0000 (50.00%)
12	1.0000	0.0002 (0%)	1.0000	0 (0%)
13	0.9826	10.8000 (50.00%)	0.9812	10.8000 (50.00%)
14	0.9741	0.2131 (1.69%)	0.9717	0 (0%)
15	0.9847	13.2000 (50.00%)	0.9816	0 (0%)
16	0.9801	0 (0%)	0.9808	0 (0%)
17	0.9729	0 (0%)	0.9737	0 (0%)
18	1.0335	16.3200 (50.00%)	1.0329	16.3200 (50.00%)
19	1.0032	1.9800 (50.00%)	0.9969	1.9800 (50.00%)
20	0.9920	1.3800 (50.00%)	0.9824	0 (0%)
23	1.0325	0.0021 (0.03%)	1.2082	0 (0%)
25	1.0288	3.0788 (40.73%)	1.0295	3.7800 (50.00%)
27	1.0051	5.5800 (50.00%)	1.0072	5.5800 (50.00%)
28	1.0153	2.7600 (50.00%)	1.0188	2.7600 (50.00%)
29	1.0242	10.2000 (50.00%)	1.0286	10.2000 (50.00%)
30	1.0129	0.0455 (1.05%)	1.0126	0 (0%)
31	0.9986	3.4800 (50.00%)	0.9962	3.4800 (50.00%)
32	1.0076	0.9600 (50.00%)	1.0019	0.9600 (50.00%)
33	1.0063	2.2800 (50.00%)	1.0006	2.2800 (50.00%)
35	1.0029	3.6000 (50.00%)	0.9961	0 (0%)
38	1.0355	8.4000 (50.00%)	1.0309	8.4000 (50.00%)
41	1.0173	0.0859 (1.14%)	1.0233	3.7800 (50.00%)

42	1.0015	4.2600 (50.00%)	1.0072	4.2600 (50.00%)
43	1.0256	0.8455 (35.23%)	1.0280	1.2000 (50.00%)
44	1.0346	7.2000 (50.00%)	1.0283	0 (0%)
47	1.0518	17.8200 (50.00%)	1.0483	17.8200 (50.00%)
49	1.0553	10.8000 (50.00%)	1.0521	10.8000 (50.00%)
50	1.0473	12.6000 (50.00%)	1.0428	12.6000 (50.00%)
51	1.0634	10.8000 (50.00%)	1.0570	0 (0%)
52	0.9961	2.5533 (43.42%)	1.0127	0 (0%)
53	0.9857	1.5120 (6.30%)	1.0116	12.0000 (50.00%)
54	1.0152	2.4600 (50.00%)	1.0298	2.1916 (44.54%)
55	1.0494	0 (0%)	1.0538	3.8864 (47.63%)
56	1.0039	4.5600 (50.00%)	1.0092	4.5600 (50.00%)
57	0.9974	0 (0%)	1.0072	4.0200 (50.00%)
Total amount of load shedding (MW)		184.7788		198.5700
Agricultural load (MW)		28.8012		29.5501
Industrial load (MW)		23.9291		37.6301
Commercial load (MW)		35.3910		26.9099
Residential load (MW)		82.4836		94.3245
Large users load (MW)		14.7890		10.7032
Total customer interruption cost ($)		337834.7805		369156.6052
Maximum FVSI (Line)		0.3264 (2-3)		0.3050 (2-3)
Active power loss (MW)		48.8198		45.8001

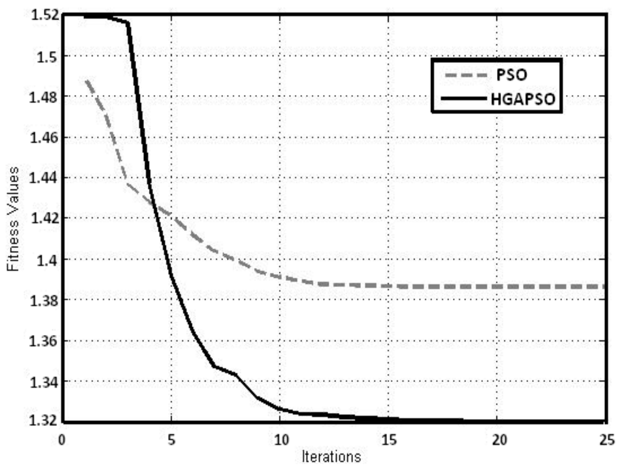

Figure 4. Compare of HGAPSO and PSO convergence (57 bus system)

V. CONCLUSIONS

An optimal under voltage load shedding to provide voltage stability is proposed and solved using hybrid genetic algorithm and particle swarm optimization technique. The main object of proposed load shedding is improvement transmission line performance in contingency conditions by alleviating transmission line over loadings, maximization of its voltage stability and minimization active power loss. Also, the economical object is considered to purpose of minimization of customer interruption cost that conflicted by the other objects. Despite of operational objects, economical object tries to minimize load curtailment in power system. It is shown that the hybrid genetic algorithm and particle swarm optimization can identify a global optimum solution in compare of traditional PSO. The properties of proposed scheme can qualify this under voltage load shedding to be used in power system applications that need to applying optimal load shedding.

NOMENCLATURES

S_i^P : Apparent power transmitted through the line

Z : Transmission line impedance

X : Transmission line reactance

R : Transmission line resistance

Q_2 : Reactive power on receiving bus

V_1 : Voltage on sending bus

δ : Angle difference between sending & receiving buses

V_i : Voltage magnitude of bus *i*

δ_i : Voltage angle of bus *i*

V_j : Voltage magnitude of bus j

δ_j : Voltage angle of bus *j*

Y_{ij} : Magnitude of *i*th and *j*th component of admittance matrix

φ_{ij} : Angle of *i*th and *j*th component of admittance matrix

P_D^0 : Demand active power in initial state

P_D^P : Demand active power in post contingency condition

PF : Participation factor of each load classification

P_{Gi}^0 : Active power generation of bus i in initial condition

Q_{Gi}^0 : Reactive power generation of bus i in initial condition

V_i^P : Voltage at bus i in post contingency

$V_i^{\min}$: Minimum allowable voltage at bus *i*

$V_i^{\max}$: Maximum allowable voltage at bus *i*

$parent1(x_{id}^{(t)})$: Position vector of a randomly chosen particle to take part in the reproduction process

$parent2(x_{id}^{(t)})$: Position vector of randomly chosen particle to be the other parent in the reproduction process

$child1(x_{id}^{(t)})$: Position vector of the first offspring

$child2(x_{id}^{(t)})$: Position vector of the second offspring

$parent1(v_{id}^{(t)})$: Velocity vector of the first parent

$parent2(v_{id}^{(t)})$: Velocity vector of the second parent

$x^{(U)}$: Upper boundary of *x*

$x^{(L)}$: Lower boundary of *x*

REFERENCES

[1] C.W. Taylor, “Power System Voltage Stability”, New York, McGraw-Hill, EPRI Power Engineering Series, 1994.
[2] T. Van Cutsem, C. Vournas, “Voltage Stability of Electric Power Systems”, Boston, MA, Kluwer, 1998.
[3] F.M. Echavarren, E. Lobato, “A Load Shedding Algorithm for Improvement of Load Margin to Voltage Collapse”, IEEE Bologna Power Tech Conference, Italy, Vol. 1, 2003.
[4] C. Moors, D. Lefebvre, T. Van Custem, “Load Shedding Controllers against Voltage Instability: A Comparison of Design”, IEEE Porto Power Tech Conference, 10-13 September 2001.
[5] D. Lefebvre, S. Bernard, T. Van Custem, “Under-Voltage Load Shedding Scheme for Hydro-Quebec System”, Power Engineering Society General Meeting, Vol. 4, pp. 13-17, 6-10 Jan. 2004.
[6] S.S. Ladhani, W. Rosehart, “Undervoltage Load Shedding for Voltage Stability: Overview of Concepts and Principles”, Power Engineering Society General Meeting, Vol. 1, pp. 1597-1602, 6-10 June 2004.
[7] Z. Gajick, D. Karlsson, C . Andrieu, P . Carlsson, N.R. Ullah, “Intelligent Load Shedding”, Critical Infrastructures for Sustainable Power, Deliverable 1.5, 2005.
[8] B. Otomega, T. Van Cutsem, “Undervoltage Load Shedding Using Distributed Controllers”, IEEE Transaction on Power Systems , Vol. 22, No. 4, pp. 1898-1907, Nov. 2007.
[9] M.A. Mostafa, M.E. El-Hawary, “A Computational Comparison of Steady State Load Shedding Approaches in Electric Power Systems”, IEEE Trans. on Power Systems, Vol. 12, No. 1, Feb. 1997.
[10] R. Faranda, A. Pievatolo, E. Tironi, “Load Shedding: A New Proposal”, IEEE Trans. on Power Systems, Vol. 22, No. 4, Nov. 2007.
[11] V.C. Nikolaidis, C.D. Vournas, “Design Strategies for Load Shedding Schemes Against Voltage Collapse in the Hellenic System”, IEEE Trans. on Power Systems, Vol. 23, No. 2, May 2008.
[12] D. Craciun, S. Ichim, Y. Besanger, “A New Soft Load Shedding: Power System Stability with Contribution from Consumers”, IEEE Bucharest Power Tech Conference, Bucharest, Romania, pp. 1-6, 28 June - 2 July, 2009.
[13] M. Tarafdar Hagh, S. Galvani, “A Multi Objective Genetic Algorithm for Weighted Load Shedding”, Proceeding of ICEE 2010, pp. 867-873, May 2010.
[14] R. Tiwari, K.R. Niazi, V. Gupta, “Line Collapse Proximity Index for Prediction of Voltage Collapse in Power Systems”, International Journal of Electrical Powers and Energy Systems, Vol. 4, pp. 105-111, Oct. 2012.
[15] R.A. Zahidi, I.Z. Abidin, Y.R. Omar, N. Ahmad, A.M. Ali, “Study of Static Voltage Stability Index as an Indicator for Under Voltage Load Shedding Schemes”, Proceeding of ICEE 2009, 3rd International Conference on Energy and Environment, Malacca, Malaysia, pp. 256-261, 2009.
[16] R. Verayiah, A. Ramassamy, H.I. Zainal Abidin, I. Musirin, “Under Voltage Load Shedding (UVLS) Study for 746 Test Bus System”, Proceeding of ICEE 2009, 3rd International Conference on Energy and Environment, Malacca, Malaysia, pp. 98-102, 2009.
[17] M. Rezaei Estabragh, M. Mohammadian, M. Rashidi Nejad, “An Application of Elitist Based Genetic Algorithm for SVC Placement Considering Voltage Stability”, International Review on Modeling and Simulations (IREMOS), Vol. 3, No. 5, pp. 938-947, Oct. 2010.
[18] M. Rezaei Estabragh, M. Mohammadian, “Multi Tasking Optimal Placement and Sizing of Distributed Generations”, International Review of Electrical Engineering (I.R.E.E), Vol. 6, No. 7, pp. 3081-3090, Nov.-Dec. 2011.
[19] M.H. Hemmatpour, M. Mohammadian, “Incorporating SVC Planning to Reconfiguration Based on Voltage Security Margin”, International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 10, Vol. 4, No. 1, pp. 1-10, March 2012.
[20] W. Wahgdee, R. Billinton, “Utilization of Time Varying Event Based Customer Interruption Cost Load Shedding Schemes”, International Journal of Electrical Power and Energy Systems, pp. 769-775, Sept. 2004.
[21] A. Chowdhury, D. Koval, “Customer Interruption Cost Models for Load Point Reliability Assessment”, Power Distribution System Reliability: Practical Methods and Applications, Wiley-IEEE Press, 1st Edition, pp. 337-356, 2009.
[22] S.B. Choi, D.K. Kim, S.H. Jeong, H.S. Ryu, “Evaluation of the Customer Interruption Cost Taking Into Consideration Macroeconomic Approach in Korea”, International Conference Power System Technology, Vol. 4, pp. 2358-2362, Oct. 2002.
[23] N. Liu, L. Zhang, X. Han, “Unit Commitment Considering Expected Customer Interruption Cost”, Probabilistic Methods Applied to Power Systems (PMAPS), pp. 120-125, June 2010.
[24] R.F. Ghajar, R. Billinton, “Economic Costs of Power Interruptions: A Consistent Model and Methodology”, International Journal of Electrical Power & Energy Systems, Vol. 28, No. 1, pp. 29-35, Jan. 2006.
[25] J. Kennedy, R. Eberhart, “Particle Swarm Optimization”, IEEE International Conference on Neural Networks, Piscataway, NJ, pp. 1942-1948, 1995.
[26] R. Eberhart, Y. Shi, “Particle Swarm Optimization: Development, Application and Resources”, IEEE Congress on Evolutionary Computation, Vol. 1, pp. 81-86, 2001.
[27] M. Rezaie Estabragh, M. Mohammadian, “Active Power Generation Pattern via Considering Voltage Stability Margin Improvement”, ICEE, pp. 1-6, May 2012.
[28] H. Shayeghi, A. Ghasemi, “Application of MOPSO for Economic Load Dispatch Solution with Transmission Losses”, International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 10, Vol. 4, No. 1, pp. 27-34, March 2012.

[29] Y. Shi, R. Eberhart, "A Modified Particle Swarm Optimizer", IEEE world Congress on Computational Intelligence, pp. 69-73, 1998.
[30] M. Settles, T. Soule, "Breeding Swarms: A GA/PSO Hybrid", Genetic and Evolutionary Computation Conference, Washington, DC, pp. 25-29, 2005.
[31] M. Rezaie Estabragh, "Generation Scheduling Based on Constraint of Static Voltage Stability", M.Sc. Dissertation, Shahid Bahonar University of Kerman, Iran, 2011.
[32] M. Rezaie Estabragh, M. Mohammadian, "Optimal Allocation of DG Regarding to Power System Security via Differential Evolution Technique", in Jordan. 2011, IEEE Jordan Conference on Applied Electrical Engineering and Computing Technologies (AEECT 2011), pp. 26-31, 2011.
[33] Power System Case Archive, www.ee.washington. edu .

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