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OPTIMAL LOAD SHEDDING UNDER CONTINGENCY CONDITIONS USING VOLTAGE STABILITY INDEX FOR REAL-TIME APPLICATIONS IN POWER SYSTEMS

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ABSTRACT

Power systems operating under stress may approach a collapse point resulting in blackouts. To avoid this problem corrective measures such as load shedding are required. Conventional techniques are fail to provide optimal load shed.This paper focuses on optimal load shed as well as enhancing the system voltage profile using a hybrid optimization algorithm based on the well-known Genetic Algorithm (GA) and Particle Swarm Optimization (PSO). GA has traditionally been known for its accuracy while the PSO algorithm is popular for its fast convergence time. GA algorithms require longer convergence times due to the complex nature of their cost functions; therefore, in this work PSO is applied to the GA construction to solve this problem. This result in a fast and accurate algorithm named GAPSO. This paper focuses on optimal load shed by using hybrid optimization termed as GAPSO. The proposed algorithm is utilized to minimize the total amount of load shed on the weak buses. Weak buses are identified using the Fast Voltage Stability Index. The performance of the proposed technique was assessed by simulations in MATLAB/SIMULINK under the IEEE-30 and IEEE-57 bus meshed networks. The proposed technique was also compared to the GA and PSO algorithms individually and it outperform both in terms of optimal load shed which is comparable to GA while a convergence time is comparable to PSO. Proposed technique is not only robust against system failures but is also efficient enough for real time applications.

Keywords: voltage collapse, voltage stability, power system, under voltage load shedding.

1. INTRODUCTION

Modern power systems are very heavily stressed and have plentiful arrangements of operating situations. The number of disturbances that need to be inspected has raised massively. The increasing demand for electric power has put a lot of pressure on the systems responsible for the operation and control of the highly complex power networks that exists today. One of the main causes for power blackouts is voltage instability which is attributed to insufficient generation as well as transmission capacities. The major challenges faced by power system operators include change in the nature of loads, performance of the on load tap changer transformer, the dependency on generation positioned remotely away from load centers, natural load growth, and the influence of protection and control systems. Contingency condition may be created by overloading the power system up to a certain limit leading to an outage of transmission line or a generator. Similarly, a sudden change in load value or generations may also give rise to a contingency situation. Contingency analysis gives tools for building, analysing, and managing records of contingencies and related violations [1].

The load is considered the driving force for voltage stability, e.g. When the system voltage magnitude declines, motors are used to improve its voltage magnitude by rising the amount of reactive power. However, in the extreme contingency conditions the existing reactive power sources are not sufficient to stabilize the decreasing system voltage. Furthermore, factors such as unexpected load increments or component outage causes a voltage collapse resulting in blackout state.

The two well-known methodologies used for system stability include under-frequency load shedding (UFLS) and under-voltage load shedding (UVLS). Load shedding is carried out using three different methods. Firstly a static quantity of load is shed such as under frequency load shedding [2-4]. The second approach is built on dynamic load constraints; however, the result is susceptible to the dynamic load parameters. Finally, the third approach employs optimal power flow equations in the power system static model to achieve the minimum amount of load shed.

In Power systems, load shedding schemes have long been employed to prevent frequency instability. However, to prevent voltage collapse Undervoltage load shedding schemes are commonly used. It is worth noting that rising complications of modern power systems makes it very difficult to find the appropriate load shed locations.

The success of UVLS in stabilizing a system depends on determining the optimal amount, time and location for load shedding. Shedding lesser or more than required amount of load does not arrest voltage instability and may even lead to a voltage collapse or over frequency problems, respectively. Similarly, shedding load at the wrong place may cause unnecessary interruption, loss of customer trust, and the utility revenue. The time instant at which load shedding needs to perform is also very crucial as discussed in [5]. The UVLS scheme has been proven to be robust tool in stabilizing systems suffering from low voltage magnitudes[6-8], note that voltage instability does not only influence the local load area but may also spread to the adjacent area in an interconnected power system, commonly known as cascading failures.

This paper focuses on finding the optimal amount of load shed in a minimum amount time i.e. in this work not only calculate the amount of load shed but the reduction in computational time are also achieved. Therefore, this paper proposes a hybrid technique based on the GA and PSO algorithms. The proposed technique can calculate the optimal load shed in the minimum amount of computation time. The proposed technique converts UVLS into an optimization problem which includes optimal load shed in minimum time, at selected weak buses. To restore power flow solvability the load buses are chosen based on (FVSI) value, high values of FVSI indicate weak buses, which are the most suitable candidate for load shed.

This paper is structured as follows section 2 provides a review of the existing literature relevant to this research. Section 3 explains problem formulation while section 4 introduces some preliminary background. The proposed UVLS technique is presented in section 5 whereas section 6 gives the simulation studies and results. Finally the conclusion is given in section 7.

2. LITERATURE REVIEW

A concrete approach offering the least amount and finest location of load shedding was presented in [9]. The proposed technique uses a multi-stage and non-linear approach to find the minimum load shed at each stage. Genetic Algorithms were executed in the Hydro-Quebec system to estimate the amount of load shed in[10, 11],but the approach is unable to grip a broader range of load behavior, different scenarios and short-term voltage instability problems. GA was utilized to investigatefor optimal supply restoration approach in the network of distribution system[12].Likeisealternativestudy [13]showedan optimization tool builton GA to estimate and perform load shed. To solve steady State load shedding problem a novel application of the GA presented in [14]. A new adaptive load shedding technique using GA is proposed in [15]. The load buses are ranked from the strongest to the weakest. The weakest bus is considered the best option for load shedding. The voltage stability margin is highly influence by the weakest buses in an interconnected power system. Therefore, the identification of weak buses is necessary for planning and operation of power systems in long-term studies.

Particle Swarm Optimization was combined with Simulated Annealing to form a hybrid, was implemented to tackle UVLS problem more efficiently in[16]. The technique was tested on the IEEE 14 and 118 bus test systems. However, this technique can only be used for long term voltage stability and is unsuitable for short term voltage stability. Another hybrid scheme consisting of Particle Swarm Optimisation (PSO) and Linear Programming (LP)was developed to resolve the issues of low convergence and eliminate transmission line overloading [17].The technique was implemented on the IEEE 14 bus system and had a fast convergence time. However, it was unable to solve non-linear problems. Modal analysis and PSO were combined to achieve optimal load shedding and voltage stability in[18].However, the proposed technique works well on Transmission networks only. For the distribution system, a Comprehensive Learning PSO (CLPSO) was developed to achieve an optimal partition, in case of upstream loss [19]. The proposed technique works successfully on an Egyptian 66kV, 45 bus meshed network and 33-radial bus system. The dynamics related by voltage stability are frequently slow[20], therefore, the use of static based approaches is considered as a good approximation [21-23].An adaptive under-voltage load shedding scheme using model predictive control and a technique for load shedding based on the consideration of voltage stability was proposed in [24, 25]. To prevent voltage instability a new integer value modelling of optimal load shedding was achieved through hybrid discrete particle swarm optimization by considering multi objectives, the proposed methodology was employed on IEEE 14 and 30 bus test systems[5]. Probabilistic under voltage load shedding using point estimate method was presented in[26].

Estebsari A, Pons [27] show that automatic UVLS is better to manual UVLS with the Techno-economic impacts of automatic Undervoltage load shedding under emergencies. A robust UVLS scheme proposed by combining GA and PSO to improve transmission line performance with the fitness of minimum customer interruption cost was presented in[28]. However, the proposed technique does not achieve fast convergence and optimum amount load shed. Another study combines GA and PSO to get optimal DG sizing and location in distribution networks[29].It is observed that hybrid techniques perform well for large and complex power systems and produce more optimal and quality solutions than individual techniques [30].

3. PROBLEM FORMULATION

The objective function is the sum of the weighed difference between the pre-contingency and post-contingency for the active power demands and may be formulated to minimize the total load shed at selected buses and minimization of voltage drop at all buses so that the voltage stability is maximized. The objective function is given as follows:

$$\sum_{i=1}^{N_{BUS}} \left(P_{Di}^{b} - P_{Di}^{a} \right) \tag{1}$$

$$\min\{ \sum_{i=NLS} (P_{Li} - f_i(x_{\min}) - f_i x_{\max})) \} \tag{2}$$

$V_2 - V_1$

Subject to

$$V_i - 0.9 \geq 0 \tag{3}$$

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where P_{Li} is the ith load shedding bus, $f_i(x_{\min})$ and $f_i(x_{\max})$ are the limits of minimum and maximum load shedding limits at ith load bus and V_i is the ith bus voltage which should not be less than 0.9.Equality constraints of the networks are the power flow equations.

$$P(V) = P_{Gi} - P_{di}(V) - P_i(V,\delta) = 0 \quad (4)$$

$$Q(V) = Q_{Gi} - Q_{di}(V) - Q_i(V,\delta) = 0 \quad (5)$$

$$P_i(V,\delta) = V_i \sum_{i=1}^{NB} V_j Y_{ij} \cos(\delta_i - \delta_j - \theta_{ij}) \quad (6)$$

$$Q_i(V,\delta) = V_i \sum_{i=1}^{NB} V_j Y_{ij} \sin(\delta_i - \delta_j - \theta_{ij}) \quad (7)$$

Likewise, the change in active and reactive power generation value under the base condition and for loading condition are considered as inequality constraint.

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} i = 1,2,.........NG \quad (8)$$

$$\Delta P_{Gi}^{\min} \le \Delta P_{Gi} \le \Delta P_{Gi}^{\max} \quad (9)$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} i = 1,2,.........NG \quad (10)$$

$$\Delta Q_{Gi}^{\min} \le \Delta Q_{Gi} \le \Delta Q_{Gi}^{\max} \quad (11)$$

The magnitude of all bus voltages is selected as an inequality constraint which is in the current state as well as the load shed condition.

$$V_i^{\min} \le V_i \le V_i^{\max}, i \in N_L \quad (12)$$

Notations used in above mathematical equations are explained in Table-1.

Table-1. Notations used in mathematical equations.

P_{Di}^{b}	**Active power demand at bus i multiplying with loading factor before load shed** (in stress condition)
P_{Di}^{a}	Active power demand at bus i after load shedding (unstressed condition)
P_{Gi}	Active power generated at'i^{th}' bus
Q_{Gi}	Reactive power generated at 'i^{th}' bus
P_{di}	Active power demand at'i^{th}' bus
Q_{di}	Reactive power demand at'i^{th}' bus
V	Bus voltage magnitude
V_2	Voltage after load shedding (unstressed condition)
V_1	Voltage before load shedding (In stressed condition)
δ	Phase angle
V_i	Bus voltage magnitude at i^{th} bus
V_j	Bus voltage magnitude at bus j
Y_{ij}	Admittance of line $i^{th}j^{th}$ (Ω)
δ_i	Voltage angle at i^{th} bus
δ_j	Voltage angle at j^{th} bus
θ_{ij}	Admittance angle of i^{th} j^{th} line
NB	Number of buses
N_L	Number of lines
NG	Number of generators
$P_{Gi}^{\min}$	Minimum active power generation at i^{th} bus
$P_{Gi}^{\max}$	Maximum active power generation at i^{th} bus
$Q_{Gi}^{\min}$	Minimum reactive power generation at i^{th} bus
$Q_{Gi}^{\max}$	Maximum reactive power generation at i^{th} bus
$\Delta P_{Gi}^{\min}$	Minimum change in active power at i^{th} bus
$\Delta P_{Gi}^{\max}$	Maximum change in active power at i^{th} bus
$\Delta Q_{Gi}^{\min}$	Minimum change in reactive power at i^{th} bus
$\Delta Q_{Gi}^{\max}$	Maximum change in reactive power at i^{th} bus
$V_i^{\min}$	Minimum voltage magnitude at i^{th} bus
$V_i^{\max}$	Maximum voltage magnitude at i^{th} bus

4. PRELIMINARY BACKGROUND

4.1 Fast voltage stability index

Originating from the equation of two bus network shown in Figure-1, the fast voltage stability index can be formulated as

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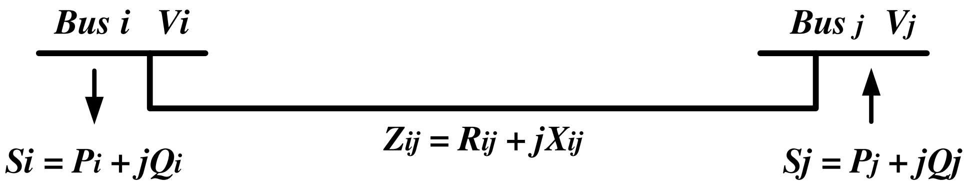

Figure-1. Model of two bus power system.

$$FVSI_{ij} = \frac{4Z_{ij}^{2}Q_j}{V_i^{2}X_{ij}} \tag{13}$$

Where X_{ij}, is line reactance between line *i* and *j*, Z_{ij} is the impedance between line *i* and *j* ,Q_j is the reactive power flow at the receiving end and V_i is the sending end voltage

The FVSI index is capable to identify critical areas in a large power system, capable to determine the point of voltage collapse, maximum permissible load, and weak bus in the system and the most critical line in an interconnected system.

The $FVSI_{ij}$ index can be estimated for any of the lines of the network and depends, basically on the reactive power. In power systems, FVSI is considered a strong index for analysing the voltage stability condition [31]. FVSI is also useful in determining power system's maximum loadability, on-line voltage stability assessment and identification of weak buses.

5. PROPOSED LOAD SHEDDING METHOD

In the field of optimization hybrid meta heuristics have emerged with superior results in terms of best fitness and computation time. The proposed scheme is based on a hybrid approach by combining GA and PSO. However, both suffer from their own individual drawbacks for example although GA is popular for producing accurate results but takes a long time to converge. Similarly PSO is popular for its short convergence time but may not always converge to the best solution. GA and PSO have been proven to be well suited for generator and line outage cases. Therefore, by proposing a hybrid scheme based on GA and PSO in this work, it is expected to combine the strengths of these techniques and produce a better algorithm than either of the algorithms deployed alone.

The longer convergence time of GA is attributed to its time consuming local search mechanism. To solve this issue, the proposed algorithm replaces the local search mechanism of GA with the global search mechanism of PSO. After obtaining the global solutions using PSO, the resulting optimum values are employed by GA to obtain the optimum value of load shed. The flow chart of proposed algorithm to obtain the optimal amount of load shed for a power system under stress is shown in Figure-2.

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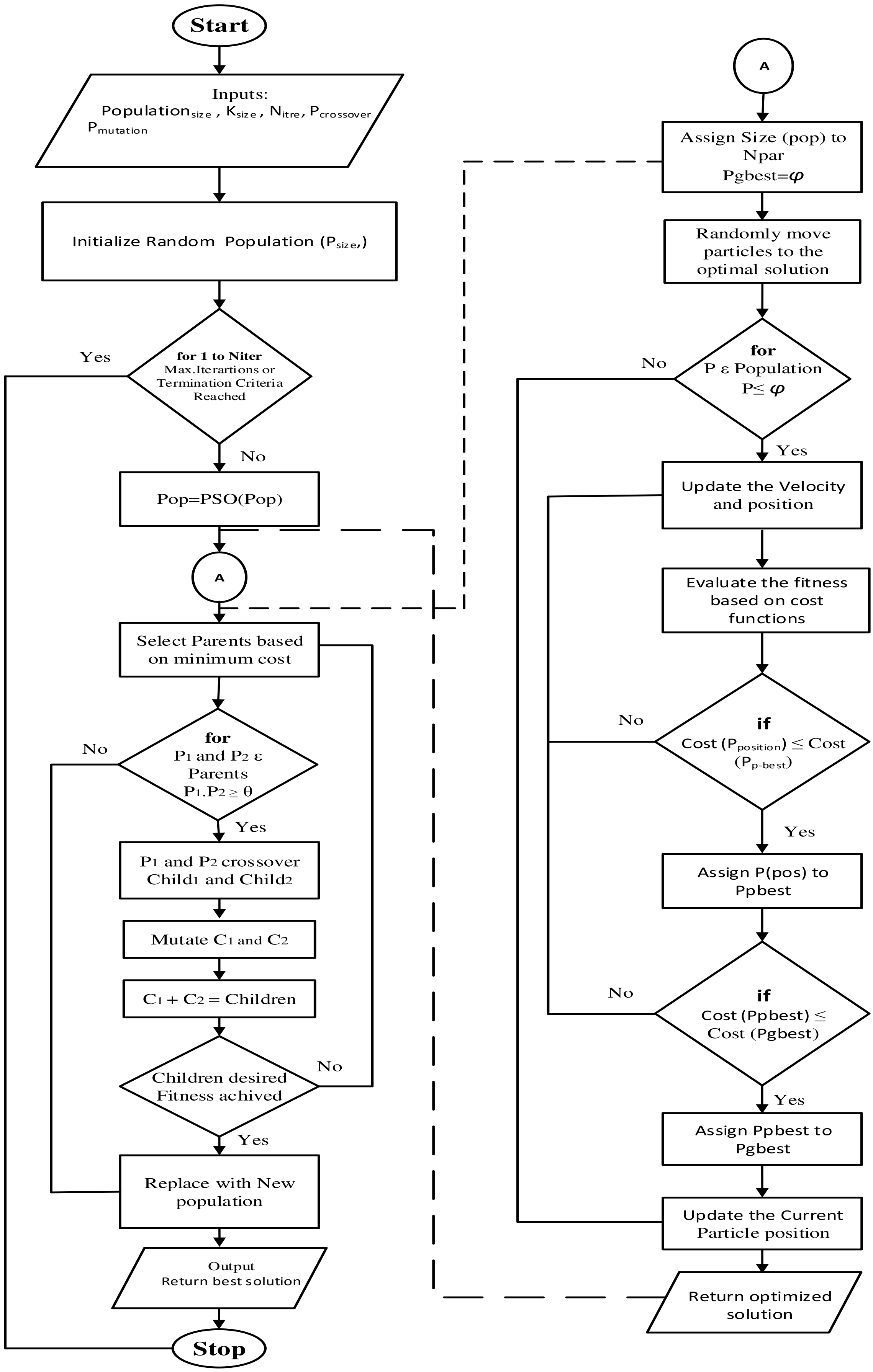

Figure-2. Flow chart GAPSO algorithm.

6. SIMULATION RESULTS (IEEE 30 BUS)

The proposed hybrid GA-PSO algorithm was examined on the IEEE 30bus test system using the MATPOWER [32, 33] toolbox in MATLAB. The system includes 6 generators with buses located at 1, 2, 5,8,11 and 13 as shown in Figure-3[34]. It is made of 41 lines, two Static VAR sources at buses 10 and 24, and 4 tap changing transformers. The base load of the system is 283.4MW and 126.20MVAR.

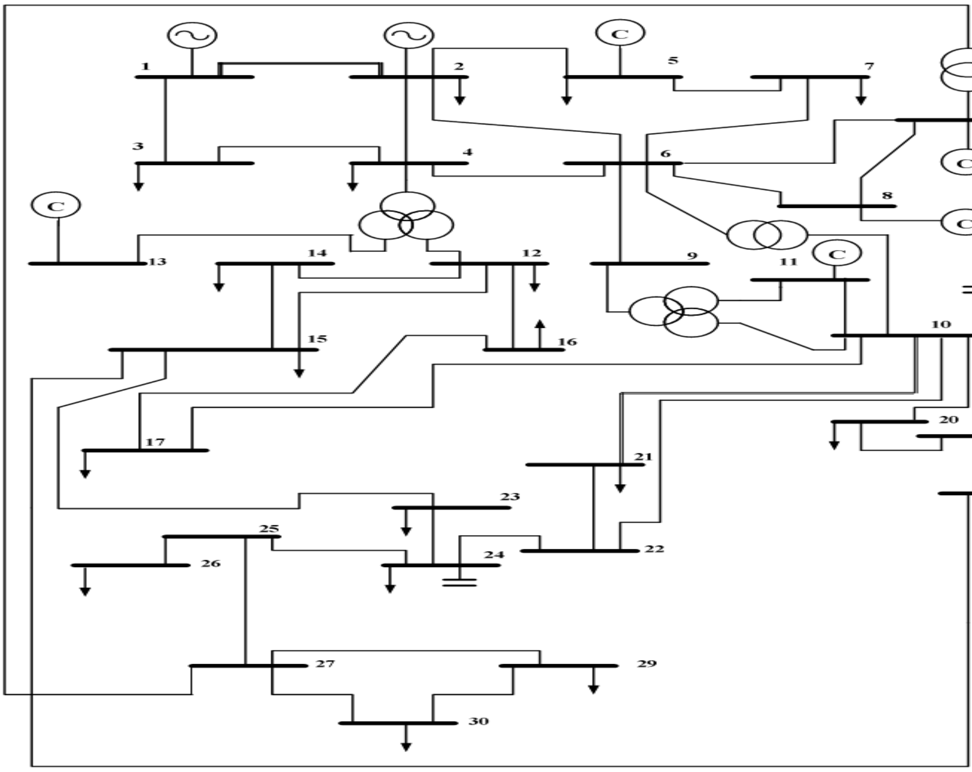

Figure-3. One line diagram IEEE 30 Bus test system[35].

In heavy loading condition when original real and reactive loads are multiplied by a loading factor of 1.58, the total load is increased to 447.772MW and 199.396MVAR. The power flow analysis is possible and the values are converged but when loading factor increased to 1.59 the power flow is not possible and the values did not converge. Total maximum possible increment of load is 450.606MW, so the total load increase at all buses by 2.834MW which is 0.01 % of thebase load 283.4MW will lead to non-solvability so it is considered as total maximum possible load shedding for this case. To investigate the performance of the proposed method and its efficiency, only shedding of load on weak buses represents the best option for restoring solvability otherwise shedding on healthy buses creates unnecessary interruption and does not restore solvability.

We suppose that the system loading is increased by 1.58 times the base case, following this disruption the power system is close to collapse point. Five weak buses are selected 30,26,29,24 and 7 for load shedding based on the highest FVSI values as tabulated in Table-2. Different loading conditions at selected buses are listed in Table-3, which would give knowledge to generate their boundary. It is clear from Table-4 and Figure-5 the minimum amount load is shed by proposed technique.

Table-2. Top five weak buses selected for load shedding.

Line	Bus	FVSI	Rank
29-30	30	0.358	1
25-26	26	0.311	2
27-29	29	0.252	3
23-24	24	0.224	4
5-7	7	0.167	5

Table-3. Different loading values for weak buses.

Bus No.	Base loading P (MW)	loading factor =1.58 solvable	loading factor=1.59 unsolvable
30	10.6	16.748	16.854
26	3.5	5.53	5.565
29	2.4	3.792	3.816
24	8.7	13.746	13.833
7	22.8	36.024	36.252

Most of the existing techniques for UVLS are based on GA, PSO or their variants. Therefore, it is sufficient to compare the proposed GA-PSO algorithm with the GA and PSO algorithms used for UVLS individually. In this work the performance of these algorithms is evaluate based on the following two matrices:

Amount of load shed: The algorithm that sheds the least amount of load is considered better

Convergence time: This represents the time require by an algorithm to complete its computation and output the optimal solution. The algorithm with minimum convergence time is considered better.

The proposed hybrid technique outperformed the GA and PSO algorithms by giving the least amount of load shed as shown in Figure-4. The proposed algorithm resulted in respectively, 30% and 60% lower load shed as compared to GA and PSO respectively. Moreover, PSO sheds the largest amount of load as compared to GAPSO and GA. Moreover, for large scale problems, the convergence time is critical. GAPSO takes least iterations to converge the problem. The convergence time for GA is 38.84 seconds, for PSO is 5.98 seconds and finally for GAPSO is 8.38 seconds as revealed in Figure-5 and Table 4. We observed that the PSO algorithm results in the least convergence time, while the convergence time of GAPSO is 28% slower than PSO. However, the GAPSO results in a convergence time which is 78% faster than GA. This shows that the convergence time of GAPSO is significantly faster than GA. Amount of load shed in all three algorithms are within the boundary limits, percentage shed values are 5, 9 and 4 by GA, PSO and GAPSO respectively. These results show that the proposed technique gives the most accurate results in the shortest possible time. The power system returns back to a safe and normal operating condition after load shed. Therefore, the proposed method can be employed for real time applications in power systems.

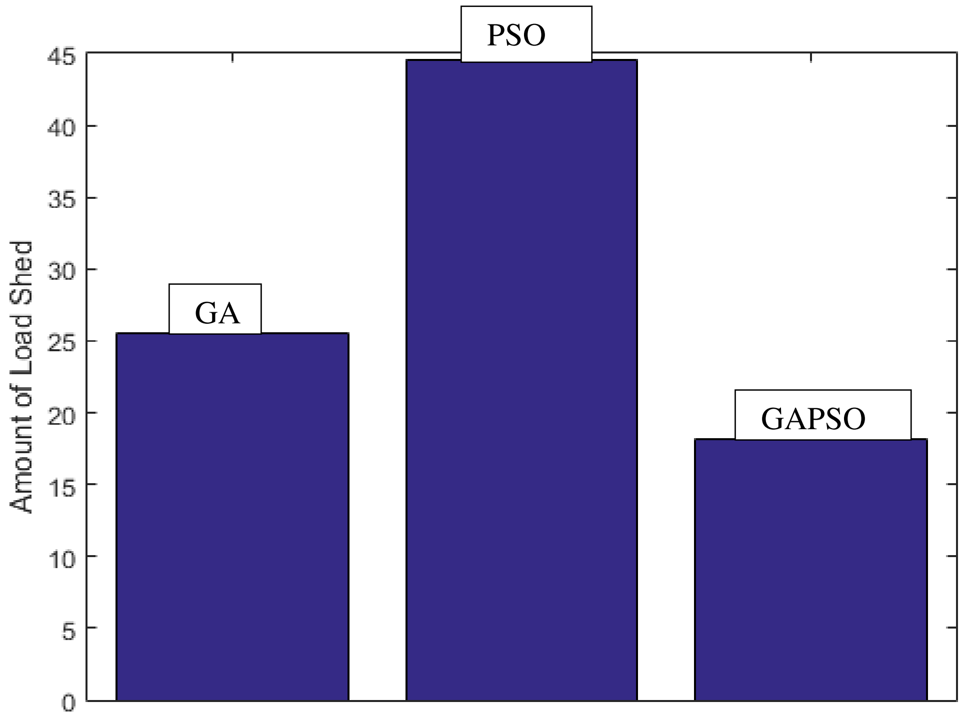

Figure- 4 Amount of load shed at weak buses (30 bus system)

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Table-4. Total amount of load shed and convergence time.

Technique	Total amount of load shed	Convergence time
GA	25.47MW	38.84 seconds
PSO	44.58MW	5.98 seconds
GAPSO	18.13MW	8.38 seconds

6.1 Simulation results (IEEE 57 bus)

The system includes 7 generators 42 loads 80 branches and 17 transformers as shown in Figure-8 [36]. The base load is 1250.80 MW and 336.40 MVAR respectively. In heavy loading condition i.e. the base load is increased to 1.5 times the increased value of load is 1876.2 MW and 504.60MVAR.The power system loading effects greatly on solvability and the system turn towards collapse as the voltage on few buses being very low.The proposed algorithm resulted in 40% and 50% lower load shed as compared to GA and PSO respectively as shown in Figure-6. Moreover, PSO sheds the largest amount of load as compared to GAPSO and GA The proposed technique converged fast as shown in Figure-7 and Table-5. Moreover GAPSO is 26% faster than GA and 66% slower than PSO. Load shed by all three algorithms are within the boundaries.

Table-5. Total amount of load shed and convergence time.

Technique	Total Amount of Load shed	Convergence time
GA	166.62MW	41.20 seconds
PSO	202.12MW	10.15 seconds
GAPSO	101.42MW	30.26seconds

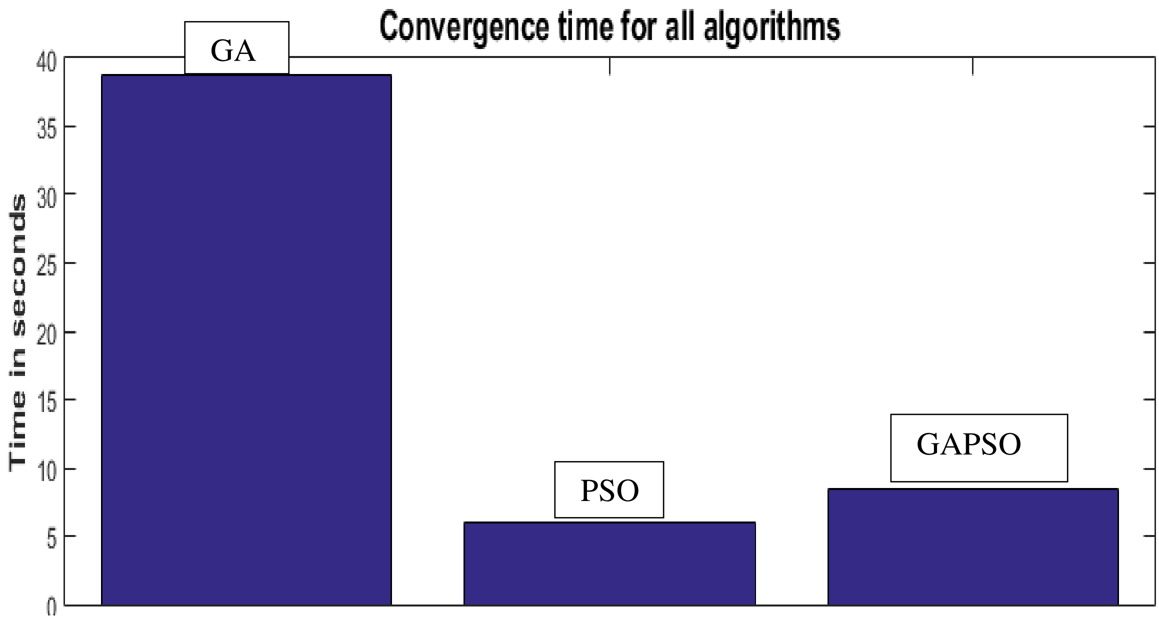

Figure-5. Convergence time (30 bus system)

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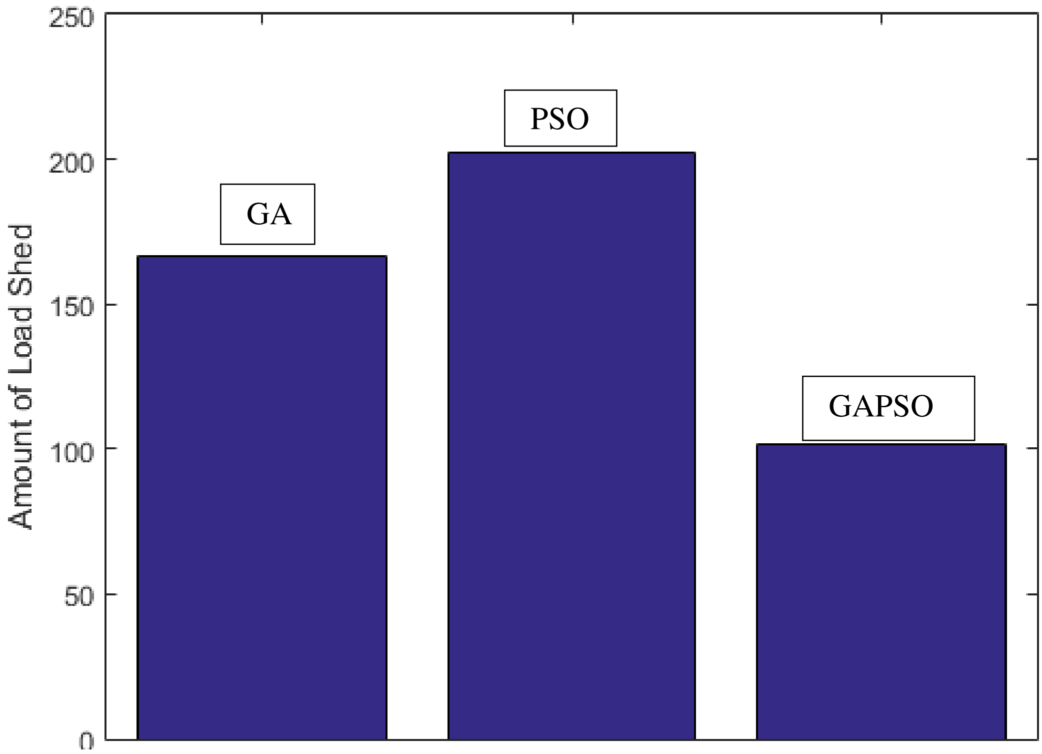

Figure-6. Amount of load shed at weak buses.(57 bus system)

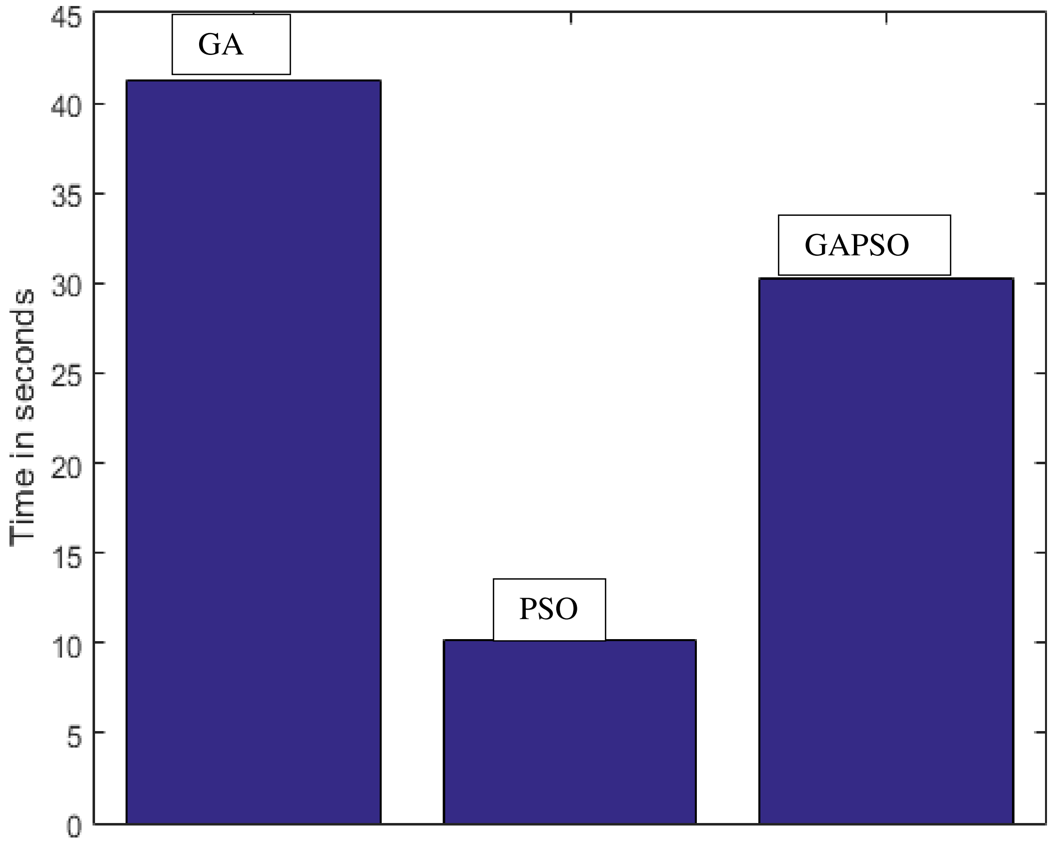

Figure-7. Convergence time.(57 bus system)

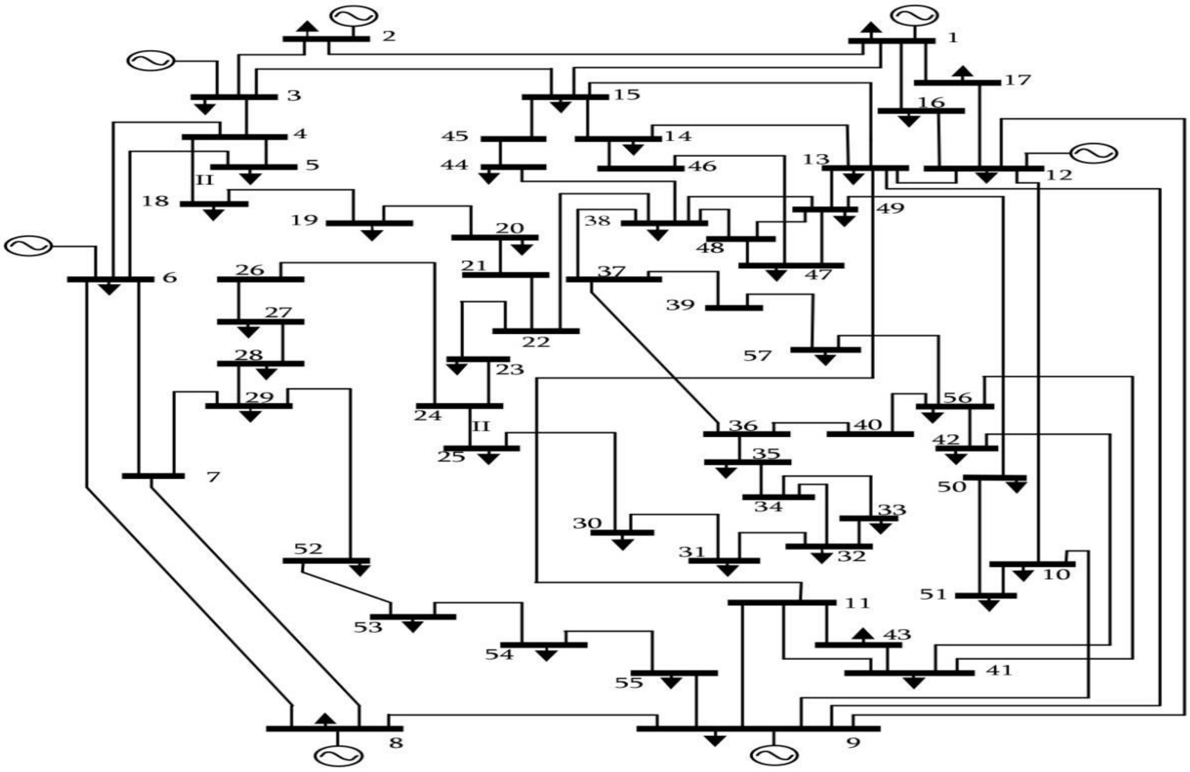

Figure-8. One line diagram IEEE 57 bus test system.

7. CONCLUSIONS

This paper proposed a hybrid GA-PSO based technique for load shedding in power systems. The proposed methodology exploits the advantages of GA and PSO techniques by combining them in a single algorithm. The proposed algorithm uses threshold values of FVSI to select the weak buses for load shedding. The performance was evaluated using the Matpower environment in MATLAB and compared with the performance of GA and PSO algorithms used individually for load shedding. The results show that the proposed algorithm was implemented on IEEE 30 and 57 bus test systems. The GAPSO algorithm sheds the minimum amount of load and has a very low convergence time. Moreover, the proposed algorithm also outperforms the GA and PSO algorithms in these two areas. Thus it can be concluded that proposed technique for load shedding can be used as an effective tool to find the optimal amount of load shed, along with minimum computation time, which may also be applicable in real time power system problems.

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