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Optimal Under-Frequency Load Shedding Scheme Based on PSO

طرح الحمل الأمثل نتيجة انخفاض التردد باستخدام أسراب الجسيمات

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KEYWORDS:
Frequency stability, Under frequency Load shedding, Particles swarm optimization (PSO).

***الملخص العربي*:- تواجه منظومة القوى الكهربية كثير من التحديات و المشاكل و ذلك من أجل المحافظة على استقرارها أثناء ظروف التشغيل المختلفة. و من المعلوم أن زيادة الأحمال عن القدرات المتولدة تؤثر على استقرار منظومة القوى و يحدث بها الكثير من الاضطرابات. هذه الاضطرابات قد تؤدى إلى فصل بعض أو كل الأحمال نتيجة انخفاض التردد و ذلك للحفاظ على ريش التربينات من الاجهادات الميكانيكية الزائدة عليها و الاهتزازات. لذلك كان من الضرورى الفصل الفورى للأحمال لحماية التربينات و عدم حدوث تعتيم/ فصل كامل للأحمال. لذلك يقدم هذا البحث طريقة لطرح الأحمال على مراحل مختلفة باستخدام أمثلة حشد الجزيئات. هذه الطريقة تهدف لتقليل الأحمال عند كل الأحمال. و تم تطبيق هذه الطريقة نظام معيارى ذو تسعة قضبان لتحقيق الهدف من تلك الطريقة.**

***Abstract*— Power system stability represents a significant challenge for security of system operation. When the load exceeds the generation, the system stability is affected. This can lead to cascading outages and shut-down of a major part of the power system that results in frequency decaying. Fast load shedding is the best way to avoid cascading outages and power system blackout. This paper proposes a novel scheme to control the optimal sheddable amount of the load at each stage for the under-frequency relay using Particle Swarm Optimization (PSO) technique. The proposed technique can be used to minimize the sheddable amount of loads at all stages. The proposed technique is applied to two different systems; IEEE 9-bus and IEEE 39-bus test system to verify its accuracy and effectiveness. The attained results prove the effectiveness of the proposed scheme to achieve the prescribed objectives. The comparison between the two systems is done.**

I. INTRODUCTION

Electrical energy plays a significant role in industrial and technological scopes. The quality and continuity of electrical energy supply represent an unavoidable request to all end users. Besides the total blackout or partial outages of service can enforce severe social and economic losses. Consequently, there are various considerations that clarify the critical needs for system reliability and stability [1].

Load shedding is considered as an emergency control which is applied to keep stability of the power system or to avoid a blackout by diminishing power system load to fit the power generation supply in some parts of the system [2]. The load shedding disconnects the non-critical loads from the peak load/generation curve when an imbalance occurs thereby preserving the balance between load and generation [3]. Nowadays, the importance of load shedding techniques has increased due to the deficiency of acceptable spinning reserve margins, and tie-lines capacities [4]. The loss of stability and consequently load shedding are occurred due to voltage collapse or frequency decaying. There are two main schemes of load shedding: the under-voltage load-shedding (UVLS) which is applied to prevent the voltage collapse and the under-frequency load-shedding (UFLS) which is applied to prevent frequency decaying.

The frequency of the power system is one of the most significant system operating parameters. A comparatively big change in the frequency results in serious effects on generators and security of power systems operation. Under-frequency load

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shedding (UFLS), represents one of the most usable procedure to avoid frequency decay or voltage collapse and hence ensure system security [1]. There are many load shedding techniques that are widespread discussed in many researching and industrial works. These techniques can be classified into traditional and intelligent techniques. In traditional techniques, the first stage of load shedding will be executed when the frequency is lesser than the first setting point. If the frequency continues in decaying, this means that; the first stage of load shed is insufficient and hence the second stage must begin. The second stage will be executed when the frequency is lesser than the second setting point. Again, if the frequency continues in decaying, the next load shed stages will take place until the normal frequency value is recovered. Finally, if the frequency decays to its first load shedding stage, the restoration of the normal operation in power system will be achieved [5-6]. These techniques are too slow and have many drawbacks include ineffectively calculation of the correct amount of load to be shed. These drawbacks lead to either excessive or insufficient load reduction.

Several artificial intelligent techniques are used to optimize the UFLS relay parameters setting and to determine the necessary load shedding in all steps simultaneously. Artificial Neural Networks (ANNs) were used for solving load shedding problem [7-8]. Unfortunately, ANN-based methods cannot be guaranteed to consider all the available scenarios, as they require a long time to deal with all these scenarios. They may fail to predict accurate results for unknown or varying cases and a complex network structure is required. Ref. [9] applied neural networks for reducing the under-frequency load shedding at small islanded power systems applying field data. A new intelligent UFLS gradient frequency method using fuzzy decision making was introduced in [10] to determine the amount of load shedding. The membership parameters of Fuzzy logic control require prior system knowledge. Otherwise, it may fail to provide optimum load shedding. Fuzzy logic control algorithms are quite understandable and they are often robust, in the sense that they are not very sensitive to changing environments.

Genetic algorithm (GA) has been applied to minimize the shed load and maximize the lowest swing frequency [11-12]. The UFLS scheme with GA involved a constant maximum load to be shed [11]. The GA is applied in addition to fuzzy logic for distributing the loads in UFLS scheme [12]. Ref. [13] applied hierarchal GA with constraints of UFLS relay parameter. GAs take a long time to determine the load shedding amount and evaluate the individuals. This relative slowness limits their usage for online application. Moreover, GA may have a trouble in finding the exact global optimum. GAs require large number of response (fitness) function evaluations depending on the number of individuals and the number of generations [13].

Ant Colony Optimization (ACO) method was applied to minimize the size of shed loads in a dynamic response. However, the ACO is only applicable for discrete problems and the theoretical analysis is difficult. Ref. [14, 15] applied a novel adaptive load shedding (ALS) method using Support Vector Machines (SVM) and Monte Carlo algorithm.

This paper presents a novel method based on PSO technique to obtain the optimal parameters of under-frequency load shedding. The DigSilent power factory software is used to simulate the power system model. Additionally, a MATLAB code is built with PSO algorithm to optimize the UFLS parameters. The PSO technique is applied in a Single Objective PSO (SOPSO) to minimize the amount of the load shedding. The proposed PSO technique is a closed loop emergency control as it depends upon feedback control of the power system parameters. In this technique, the power system parameters can be used and processed in online and offline conditions. Moreover, a comparison between the two models; 9-bus and 39 bus systems [16] are included in the paper.

II. PROBLEM STATEMENT

When the frequency of power system decays to some presetting value, the UFLS relays begin to make the load shedding in accordance with their pre-selected size. The UFLS relay setting is built on some constant or variable values taken from off-line simulation outcomes. The amount and stages of the load shedding technique must be performed by studying the feasible system cases/scenarios that may need load shedding [17]. In designing UFLS relays, the following four parameters should be taken into consideration:

A. Block size of load shedding

The block size of load shedding at all stages is a significant parameter in load shedding. Traditionally, the block size of load shedding at all stages is enhanced while the frequency decayed. It means that the frequency used as a criterion for load shedding. Before the system reaches a breakdown, it is unacceptable to shed too much and/or less load if the disorder is unknown [18]. The shedding loads will lead to restore the normal value of frequency. The magnitude of the disturbance can be exactly concerned to the average rate of system frequency decay. Consequently, the average rate of system frequency decaying can be used as an indicator of the severity of the disturbance.

B. Frequency Threshold

The frequency response includes: frequency decay, rate of frequency decaying and final frequency in each load shedding stage. These frequencies must be precisely calculated to make an accurate decision in power system [11, 12].

C. Number of load shedding stages

The number of load shedding stages and the block size of each stage. UFLS relay setting is based on some fixed or variable values at each load shedding stage. Consequently; if the number of load shedding stages increases, it must shed larger load size to recover frequency stability [11, 12].

D. Time delay for each stage

The continuity of frequency decay will increase the mechanical stress on turbine blades that may be damaged. This is especially true in case of larger disturbances, which may cause the frequency to decay faster than the smaller load upsets. Therefore, as the size of the disturbance increases, there is a greater need for rapid action [11].

III. UFLS PARAMETER CALCULATION

The existing load shedding techniques are divided into static and dynamic load shedding types. In the first technique, a constant step size is taken for each stage. In the second one, a variable step size is taken for each stage. Two factors can be used as disturbance indicator: the first one is the overloading ratio or load excess factor, and the second indicator is the average Rate Of Change Of Frequency ($ROCOF_i$).

The overloading ratio (L_i) is an indicator of load encroachment and system unbalance. It is a percentage ratio between overload and remaining generation power and can be expressed as [19]:

$$L_{\mathrm{i}} = \frac{\sum P_{Li} - \sum P_{Gi}}{\sum P_{Gi}} \tag{1}$$

Where P_{Li} is the increase of active load power and P_{Gi} is the deficient active generation power.

The average rate of change of frequency refers to the rate of frequency decaying and can be expressed as:

$$ROCOF_i = \frac{f_{(\mathrm{i}+1)} - f_{\mathrm{i}}}{t_{(\mathrm{i}+1)} - t_{\mathrm{i}}} = \frac{pL_{\mathrm{i}}}{H_{\mathrm{i}}} \frac{f_{(\mathrm{i}+1)} - f_{\mathrm{i}}}{(1 - \frac{f_{(\mathrm{i}+1)}{}^2}{f_{\mathrm{i}}{}^2})} \tag{2}$$

Where

i : number of changes of system due to frequency decline,

p : the power factor,

H_{i} : inertia time constant,

L_{i} : load excess factor at any changes of system,

f_{i} and t_{i} : frequency and time at any changes of system,

$f_{(\mathrm{i}+1)}$ and $t_{(\mathrm{i}+1)}$: frequency and time at the next changes of system.

In an inter-tied power system, which contains many generators, the system inertia constant H_{sys} can be computed by using the next equation [2]:

$$H_{sys} = \frac{H_1 MVA_1 + H_2 MVA_2 + \cdots + H_n MVA_n}{MVA_1 + MVA_2 + \cdots + H_n MVA_n} \tag{3}$$

The frequency variation at any change in system is calculated as:

$$\Delta f_{\mathrm{i}} = f_{\mathrm{i}} - f_{(\mathrm{i}+1)} \tag{4}$$

The percentage of load shedding can be calculated as:

$$\alpha = -ROCOF_i * \frac{2H_{\mathrm{i}}}{f_n} \tag{5}$$

The power in (MW) that must be shed at each stage is:

$$P_{LSi} = P_{Li;total} * \alpha_i \tag{6}$$

where $P_{Li;total}$ is the total load before any changes of system.

After each load shedding step, the load power in (MW) can computed by:

$$P_{Li;new} = P_{Li;total} - P_{LSi} \tag{7}$$

where $P_{Li;new}$ is the total load power after any changes of system.

When the UFLS relay senses the occurrence of under frequency then it sends a tripping signal to the circuit breaker. Sometimes this takes some time called a decaying time due to frequency decaying. It can be optimized by minimizing it in order to make a fast response of tripping.

$$d_i = \frac{\Delta f_{\mathrm{i}}\ [Hz]}{ROCOF_i\ [\frac{Hz}{s}]} \tag{8}$$

Equation (8) illustrates how to compute the delaying time (d_i) by sensing the frequency decaying and circuit breaker connected loads at each stage.

There is also a delaying time due to mechanical movement of circuit breaker contacts before tripping. This mechanical movement is slow. It takes more cycles as it results in more frequency decaying. This number of cycles depends on disturbance classes that is determined by $ROCOF_i$ at each load shedding step. It must be taken in account with all other values at each load shedding step [2].

$$t_{trip} = \frac{No. of\ cycles}{duration\ of\ one\ cycle\ (normalfrequency)} \tag{9}$$

where t_{trip} is the delaying trip time of the mechanical movement of circuit breaker. During breaker tripping the frequency decay can be represented as:

$$f_{trip} = t_{trip} * ROCOF_i \tag{10}$$

All frequency values will decay during breaker tripping and hence;

$$f_{(\mathrm{i}+1),\mathrm{mod}} = f_{(\mathrm{i}+1)} - f_{trip} \tag{11}$$

Frequency deviation during breaker tripping is expressed as:

$$\Delta f_{\mathrm{i,mod}} = f_{\mathrm{i}} - f_{(\mathrm{i}+1),\mathrm{mod}} \tag{12}$$

The decaying time during breaker tripping can be computed as:

$$d_{i,mod} = \frac{\Delta f_{\mathrm{i,mod}}}{ROCOF_i} \tag{13}$$

Assume safety margin (*SM*) = 0.2 Hz, then

$$f_{sh,i} = f_{(\mathrm{i}+1),\mathrm{mod}} - SM \tag{14}$$

Where $f_{(\mathrm{i}+1),\mathrm{mod}}$ is the frequency at the next changes of system taking in consideration the trip time of circuit breaker. $f_{sh,i}$ is the desired shedding frequency decay taking in consideration the safety margin.

The ratio between loading power and frequency represents load reduction coefficient and can be computed by the following equation:

$$dec_i = \frac{L_0 - L_{\mathrm{i}}}{(1 + L_0)(1 - \frac{f_{sh,i}}{f_0})} = \frac{1 - P_{Li}/P_{\mathrm{L}0}}{1 - f_{sh,i}/f_0} \tag{15}$$

Where

dec_i : load reduction coefficient,

L_0 : initial overload ratio,

L_{i} : i<u>th</u> stage overload ratio

f_0 : initial frequency,

$P_{\mathrm{L}0}$: Initial loading power at and at shedding the loads from the power system

P_{Li} : Loading power at i<u>th</u> shedding stage

The load reduction coefficient is used to determine the lowest swing frequency using the following equation:

$$f_\infty = f_0 \left[1 - \frac{L_0}{dec_i(1 + L_0)}\right] \tag{16}$$

where f_∞ is lowest swing frequency.

When a disturbance is happened in the power system, the dynamic and transient responses are controlled by two main dynamic loops. First loop is excitation loop (including AVR), this loop controls the generator reactive power and voltage. The excitation loop is operating via the excitation current regulation. The second loop is a frequency loop (including LFC), this loop controls active power and frequency when the system is exposed to a disturbance. The frequency loop is operating via the regulation of the governor. When the frequency decreases to the lowest swing frequency, the control devices try to rapidly raise it to the normal value but they fail. The voltage is decreased by the controlling devices as a result the load power decrease to make a balance between generation and loads but these controlled devices failed. The PowerFactory DigSilent program is used to connect element’s models within a dynamic system for all synchronous generators, turbines, exciters governors and other devices. This dynamic model is used to evaluate load shedding to restore the desired frequency [20].

IV. PROBLEM FORMULATION

The following considerations must be considered when designing the UFLS relay parameters before evaluating the objective function and constrains.

A. UFLS algorithms assumptions

1) The “amount of shed load allowed” is recognized with a “percentage of load allowed to be shed” for each scenario.
2) The load shedding for each scenario must not exceed an identical system load multiplied by the percentage reached.
3) A sufficient number of these stages must be considered to prevent overestimated or underestimated thresholds
4) The achieved and allowed percentage of load shedding, the number of stages, and the delayed interval for each stage must be confirmed for all proposed scenarios.

There are different interferences among the parameters of delayed interval, frequency decay, and load shed block size. These interferences will vary according to the status of the power system and the type of synchronously interconnected equipment. A long-delayed time will result in a small load shedding but likely a serious swing frequency.

B. Objective function and constrains

The objective function is objective nonlinear one. It is maximizing the amount of load to be shed (Eq. 6). The objective function is a function of the amount of both load shedding at each stage, frequency decay, rate of frequency decaying, final frequency in each load shedding stage, the number of load shedding stages and delayed interval for all stages. The objective function can be written as follows:

$$\text{OF}=Min\ [\,f(\alpha, s, d, P)] \tag{17}$$

Where f is the function of block size of load shedding at abnormal cases. The problem constraints include power flow limits, percentage of allowable load shedding, number of load shedding stages and time delay of each stage and can be expressed as:

$$P_{\min ij} < P_{ij} \le P_{\max ij} \tag{18}$$

$$\alpha_{min} \le \alpha \le \alpha_{max} \tag{19}$$

$$s_{min} \le s \le s_{max} \tag{20}$$

$$d_{min} \le d \le d_{max} \tag{21}$$

Where:

P_{ij} : power flowing in a transmission line between the buses i and j.

$P_{\min ij}$ &$P_{\max ij}$: minimum and maximum flowing power in the line between the buses i and j respectively.

α : percentage of allowable load shedding,

α_{min} & α_{max} : lower and upper limits of a percentage of allowable load shedding.

s : number of the load shedding stages

s_{min} & s_{max} : lower and upper limits of the load-shedding stages number

d : the period of delayed intervals

d_{min} & d_{max} : lower and upper limits of the vector of delayed intervals

In this paper, PSO optimization technique is applied to obtain the objective function by generating the expected values required to reach satisfied parameter values. The PSO technique produces randomly many particles differ in their limits and then chooses the corresponding fittest solutions simultaneously.

V. PROPOSED UFLS ALGORITHMS

The aforementioned suggested method can be extended to consider various load shedding at all stages. The PSO technique produces randomly many particles ranged in their limits and chooses the corresponding fittest solutions simultaneously. The PSO algorithm always update its particles to attain the new attraction between the swarm. This updating supports the continuity of iteration until it reaches the best solution. The position identical to the best fitness is known as personnel solution (p_{best}), and the best one of these personnel solutions is called global solution (g_{best}).

A. Updating values of PSO and population size

The objective functions can be modified or updated to reproduce new swarms (iterations) up to reach fitness values. The variables (P_{ij}), α, s, and d are often ranged in their limits during the PSO iterations. In other words, constraints inequalities of UFLS are always satisfying. However, constraints inequalities of min-max problem may be violated because of solutions f achieved from the DigSilent power factory software package.

The population size for a new generation, particles number, personal best attraction [P_{best}], and Neighborhood best attraction [local best] control the convergence speed and optimality for PSO. In a general way, a large population size can cause high accuracy but it increases the CPU scanning duration for convergence. In this work, the personal best attraction and the neighborhood best attraction are close to 0.9 and 0.01, respectively. The total number of the load shedding stages is smaller than 20. The delayed time of the load-shedding stages is assumed to be within [0, 0.2] seconds.

The first shedding frequency is selected as a minimum allowable operating frequency i.e. the pick-up or the trigger of first stage relay. Many utilities have set the first step of load shedding at 49.2 Hz [19]. This value is chosen to fit with the power-quality standard of countries. This choice was made based on several reasons. Firstly, all of the larger turbine-generators on the system are not rated for continuous operation below 49.2 Hz due to turbine blade stress limitations and its lifetime. Thus, setting the initial load shedding frequency at a relatively high value, such as 49.2 Hz, tends to limit the maximum frequency deviation. Secondly, a load-shedding program starting at 49.2 Hz would be more effective in minimizing the depth of the under-frequency response for a heavy overload than would a similar program which had a lower first shedding frequency. Thirdly, the first shedding frequency should not be too close to normal frequency. In this way, the tripping on severe but non-emergency frequency swings can be avoided. In this paper, the 49.2 Hz is also selected as shedding frequency at the first step shedding frequency.

The first step in applying the proposed algorithm is to read the system data with largest peak load and the hardest contingency scenario. Then set the parameters of the algorithm and initialize the population of individuals with α, s, d and (P_{ij}). Then evaluate the fitness function value by defining the g_{best} and p_{best} for all particles and updating the particles position for all individuals until obtain the g_{best}. The figure 1 demonstrates the flowchart of the proposed UFLS algorithm.

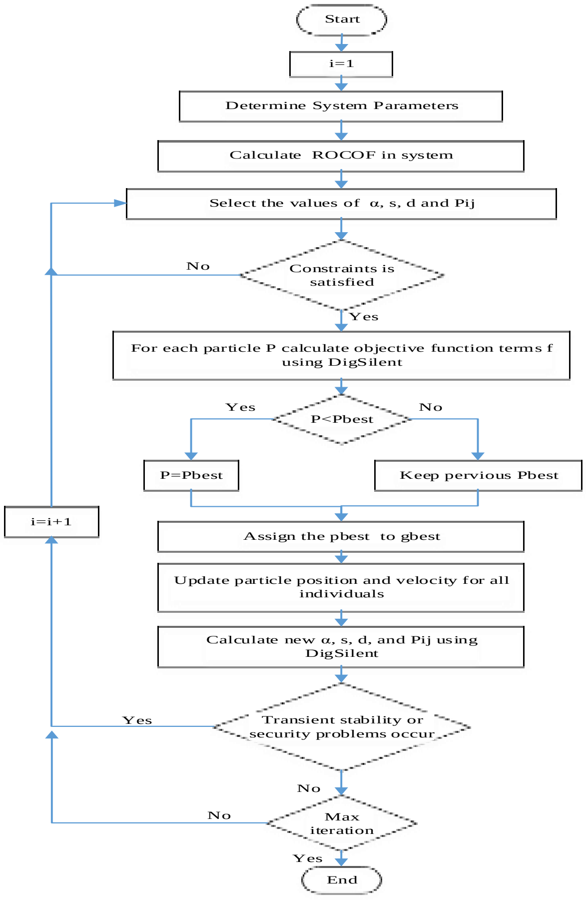


Fig. 1. Flow chart of the proposed UFLS algorithm

VI. TEST SYSTEMS

The traditional load shedding scheme is implemented with DigSilent software package. The load shedding scheme is studied using mid-term RMS simulation in a real time as a dynamic and displayed the results. It will be applied to IEEE 9-bus and 39-bus test systems. The proposed UFLS scheme is used a Matlab software program package to execute the SOPSO algorithm.

A. *Test system I: IEEE 9-bus test system*

Figure 2 shows a single line diagram of the IEEE 9-bus test system. In this system, which generator G_1 is a hydraulic turbine type with 247.5 MW maximum power, generator G_2 is a gas turbine type with 163.2 MW maximum power, generator G_3 is a thermal turbine type with 108.8 MW maximum power. The load connected at buses 5, 6, and 8 are 125 MW, 90 MW and 100 MW respectively. Bus 1 is assumed to be a slack bus.

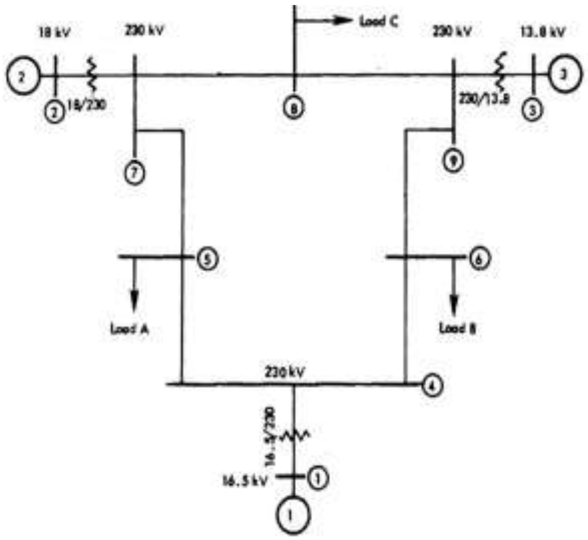


Fig. 2. IEEE 9-bus system modelling

B. *Test system II: IEEE 39-bus test system*

The 39-bus New England Power System consists of 10 generators, 29 load buses and 46 transmission lines. The total generation power is 6140.81 MW. It is divided as the following 1000 MW, 520.81 MW, 650 MW, 632 MW, 508 MW, 650 MW, 560 MW, 540 MW, 830 MW and 250 MW for generators from 1:10 respectively. The total load is 6097.1 MW. Bus 39 is assumed to be a slack bus. Figure 3 illustrates single line diagram of the system.

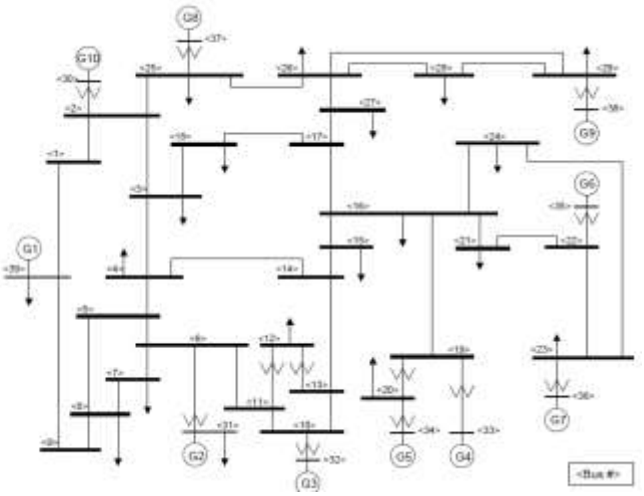


Fig.3. IEEE 39-bus system

VII. SIMULATION AND RESULTS

A Matlab program is developed to represent the proposed UFLS algorithm. The program is applied to the IEEE 9-bus and 39-bus systems to obtain the optimum values of the percentage of allowable load shedding(α), number of load-shedding stages (s), and interval of delayed time (d) and (P_{ij}). To validate the accuracy of the proposed algorithm it will be applied in two scenarios. In the first scenario, the problem is solved by applying the traditional UFLS system without any optimization using DigSilent power factory program. The scenario is performed on different number of load shedding stages when G1 and G2 are lost. In the second scenario, the proposed algorithm is applied by a single objective PSO with minimum amount of load shedding.

A. *Result of IEEE 9-bus test system*

Two case studies are implemented on the IEEE 9-Bus system. First case study applies the UFLS using the conventional technique based on the DigSilent software package. Second case study applies the proposed method based on the PSO technique.

Case 1: Traditional UFLS without optimization

The setting of the UFLS relay is designed and solved using system dynamic equations in DigSilent software package. Table I illustrates the simulation results in case of G1 and G2 outage by DigSilent simulation. The simulation is done at 20 seconds, the generators trip after 5s and the load shedding signals are occurred at 6 s.

By applying one stage of UFLS, the system is still unable to restore its stability. So, the multi-stages of load shedding must be implemented. Table I shows the amount of load shedding for different stages and the frequency limit in each stage.

TABLE I
RESULTS OF SCENARIO 1 FOR DIFFERENT LOSS OF GENERATIONS.

Amount of LS [%]	No. of LS stages	Frequency stage limit
63.464	2	49.2- 48.7
62	3	49.2- 48.7- 48.4
62.871	4	49.2- 48.7- 48.4 -48.1

The minimizing of the amount of shed load at 4-stages is better than at 2 and 3 stages but the lowest swing frequency is not the greatest which act as bad factor. It exposes the turbine blades for failing mechanical stress and reduces the continuity of loads without disconnecting loads from customers for more times. From these results, it is shown that, the setting of the UFLS relay parameters will conflict with each other's.

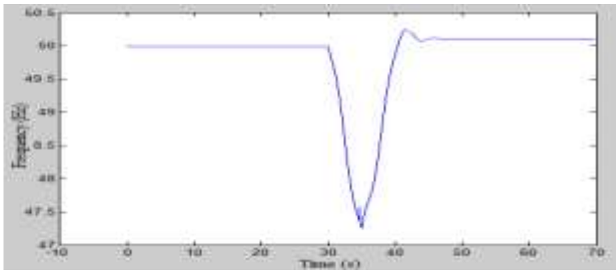
Case 2: Optimal UFLS with Considering Minimal amount of load shedding

This scenario takes into consideration the minimum amount of load shedding as an objective function. It can be attained by solving the equations (17) – (21). This scenario will be applied for different loss of generations at different times (30, 1.2 and 5 seconds) with a total load of 315 MW. The variable (P_{ij}) is set to be less than 120% for each line rather than its normal operation. As shown in figure 2, there are 6-lines in the system with different percentages of loading. The variable α is set to be within [0.01 0.9] with a discrete step 0.5%. The number of load shedding stages s can be represented by [1:20] stages. The delaying time is in the range from 0 to 0.2s. The updating values of PSO and population size are performed for velocity and position vectors for each particle in PSO to reach the global optimal position. The population size, P_{best} and neighbourhood best attraction [local b_{est}] are 20, 0.9, and 0.01 respectively in the proposed PSO. The proposed PSO takes 200 iterations to get a set of degenerated optimal solutions, implying exactly similar amount of load shedding at each stage (s) with different delayed times (d). Different percentages of α are obtained for all 200 individuals. Table II illustrates the results of this scenario for different loss of generations.

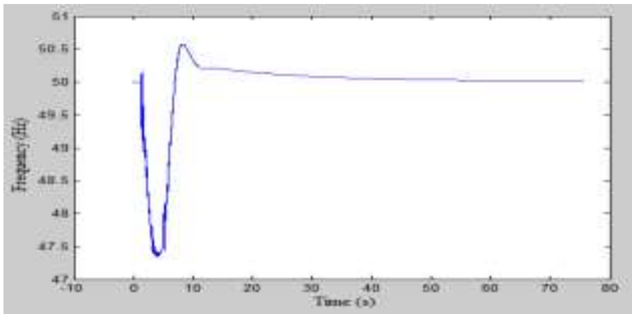
TABLE II
RESULTS OF SCENARIO 2 FOR DIFFERENT LOSS OF GENERATIONS.

Case	proposed method (α [%])	Conventional method (α [%])	s	d
G1	31.3	42.5	5	0.01
G2	32	42.5	6	0.02
G3	30	42.5	7	0.03
G1&G2	52.747	62.871	8	0.05
G1&G3	49.233	60.004	9	0.08
G2&G3	59.257	68.1098	10	0.08
Load Increase	76.454	87.693	10	0.1

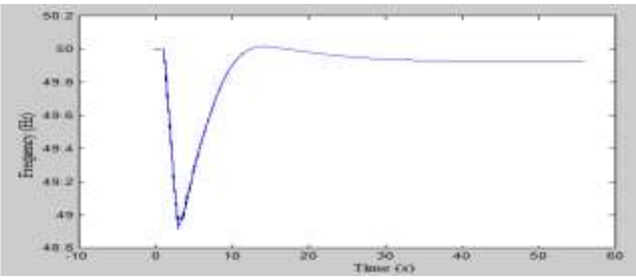
From the above table, it can be observed that, the proposed technique is better than the conventional one. A large difference can be observed in the value of α between both conventional and the proposed technique. Figure 4 shows the frequency responses for the different cases of the outage of the generators.



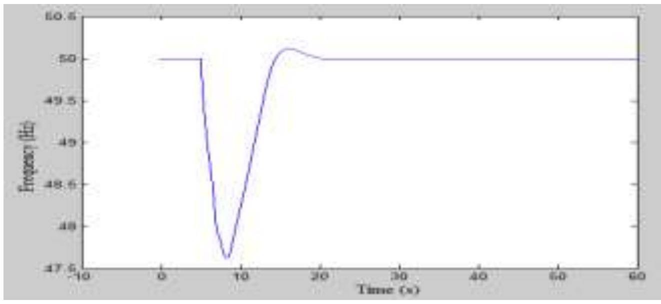
(a) Frequency response when G1 outage



(b) Frequency response when G2 outage



(c) Frequency response when G3 outage



(d) Frequency response when G1and G2 outage

Fig. 4.(a,b,c & d) The frequency responses for different cases of outage of the generators.

The proposed SOPSO method limits the size of load shedding block so reducing or preventing the unnecessary disconnecting of loads. Moreover, the power system will be more sensitive and secure.

B. *Result of IEEE 39-bus test system*

Case 1: Traditional UFLS without optimization

The IEEE-39 bus system is simulated using system dynamic equations in DigSilent software package. The simulation duration is 70 seconds, the generators trip after 5s and the load shedding signals are generated at 6 s. In this case G1 and G2 will be out of service that means about 24.77% of total generation will be lost. Multi-stages of load shedding are implemented in this case. Table III shows the amount of load shedding for different stages and the frequency limits in each stage.

TABLE III

RESULTS OF SCENARIO 1 FOR DIFFERENT LOSS OF GENERATIONS.

Amount of LS [%]	No. of LS stages	Frequency stage limit
34.7	2	49.2- 48.7
34.33	3	49.2- 48.7- 48.4
33.92	4	49.2- 48.7- 48.4 -48.1

The minimizing of the amount of shed load at 4-stages is better than at 2 and 3 stages but the lowest swing frequency is not the greatest which act as bad factor. So, the UFLS relay parameters requires to be optimized for minimizing the amount of shed load while keeping the lowest swing frequency within its acceptable limits.

Case 2: Optimal UFLS with Considering Minimal amount of load shedding

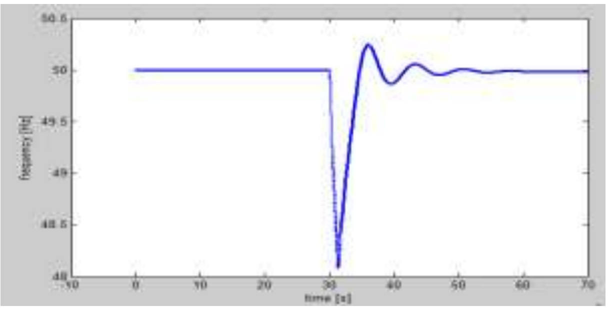
This scenario will be applied for different loss of generations at different times (30, 1.2 and 5 seconds) with a total load of 6097.1 MW. The variable (P_{ij}) is set to be less than 120% for each line rather than its normal operation. As shown in the figure 3, there are 46-lines in the system with different percentages of loading. The variable α is set to be within [0.01 0.9] with a discrete step 0.5%. The number of load shedding stages s can be represented by [1:20] stages. The delaying time, in seconds, is in the range from 0 to 0.2s. The updating values of PSO and population size are performed for velocity and position vectors for each particle in PSO to reach the global optimal position. The population size, P_{best} and neighbourhood best attraction [local best] are 20, 0.9, and 0.01 respectively in the proposed PSO. The proposed PSO takes 200 iterations to get a set of degenerated optimal solutions, implying exactly similar amount of load shedding at each stage (s) with different delayed times (d). Different percentages of α are obtained for all 200 individuals. Table III illustrates the results of this scenario for different loss of generations.

From table III, it can be observed that the proposed technique used for UFLS are better than the traditional one. A large difference can be observed in the value of α between both the traditional and the proposed technique. Figure 5 shows the frequency response of the IEEE 39-bus system under various cases of generation outage.

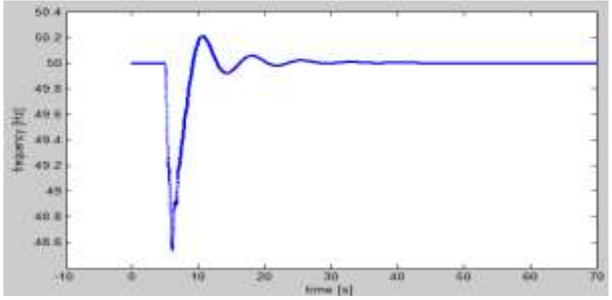
TABLE III

RESULTS OF SCENARIO 2 FOR DIFFERENT LOSS OF GENERATIONS.

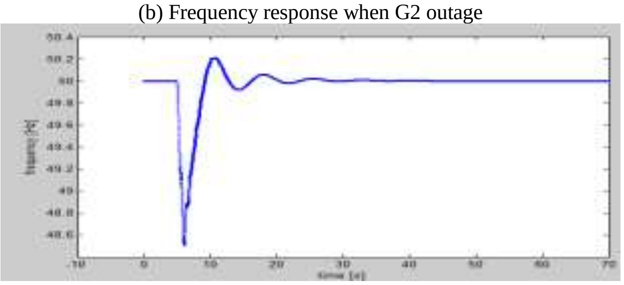
Case	proposed method (α [%])	Conventional method (α [%])	s	d
G1	8.113	16.4	5	0.01
G2	4.071	8.54	6	0.02
G3	6.219	10.7	7	0.03
G1&G2	14.302	24.49	8	0.05
G1&G3	16.958	27.1	9	0.08
G2&G3	12.374	19.2	10	0.08
Load Increase	24.682	34	10	0.1



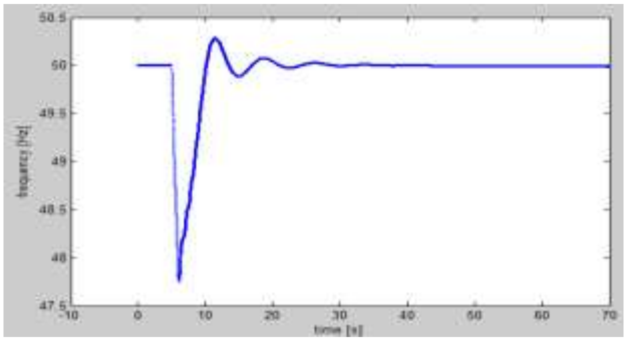
(a) Frequency response when G1 outage



(b) Frequency response when G2 outage



(c) Frequency response when G3outage



(d) Frequency response when G1&G2 outage

The proposed SOPSO continues to prove its effectiveness and applicability for different type of disturbances. It has a considerably less amount of shaded load as compared with conventional method.

VIII. CONCLUSION

A new optimal UFLS scheme has been developed. The Particles Swarm Optimization algorithm was used to minimize the amount of shed load in IEEE 9-bus and 39-bus power systems. The results proved that, the power system stability was increased when applying optimal load shedding technique compared to conventional one. The DigSilent power factory software package is used to make simulations of various studied cases of generation and/or tie-lines losing or loads increasing. A MATLAB software package is used to code the proposed SOPSO algorithm. The proposed SOPSO algorithm can achieve more accurate, and effective load shedding to keep system stability and to prevent excessive loads outage. The algorithm is simple, very fast, and has the ability to find the optimum value. The larger system can take longer time to restore its stability and have some oscillations. The proposed technique can assign some other parameters such as maximizing the number of load shedding stages with fast and dynamic response and minimizing the decaying time between increasing the loads and taking action to shed.

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