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Load Shedding based on Fuzzy Logic and AHP Algorithm

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***Abstract* - Operation power system stability is always one of the key benefits relating to economic indicators - techniques. When all the available controls cannot maintain the stable frequency of electrical systems, load shedding will be used as a last resort to restore the limited frequency norms and minimize the loss of power and load. This paper proposed the Analytic Hierarchy Process algorithm (AHP) and fuzzy logic algorithm to determine the weight of the load in the system and select appropriate control strategy corresponding to the load levels and different frequencies. The weights of the load nodes were calculated by AHP algorithm to determine the priority order of the load nodes in the system, the low weighted loads will be shed before. The load profile fuzzy and frequency fuzzy help the system reduce the number of control strategy when the problem occurs corresponding to the load levels and different frequencies. It contributes to simplifying the operation, reducing power to shed and the recovery time of the system more quickly when the problem occurs. The effectiveness of the proposed method was demonstrated through the experiment of load shedding on the IEEE 37-bus system by software PowerWorld and simulation results proved the effectiveness of the proposed method.**

Key words: Power system stability, Load shedding, AHP, Fuzzy logic.

I. INTRODUCTION

Criterions for assessing the quality stable power system are frequency and voltage. If one of them changes, it will lead to the power imbalance in the system and causing disturbances. The load shedding is one of the methods selected for frequency and voltage quickly be put on the original parameters of the system or bring new stability point in order to minimize the system black out. However, the number of loads and the time to interrupt is also considered an important factor to determine the stability of the system.

There are many different methods to load shedding and system recovery that has been developed by researchers and has been used in the power company on the world. Most of these are based on the decline in the frequency of the system [1]. The main disadvantage of this method is that it does not estimate the amount of power imbalance in the system. The result caused too much load shedding, affected power quality, or leaded to stop providing electricity services, causing much damage to the economy.

The load shedding too much was not desirable because it causes inconvenience to customers. The improvement on traditional methods has led to the development of load shedding techniques based on frequency as well as the rate of change of frequency. It leads to better predictions of the load will have to be shed, and improve accuracy. Load shedding based on a standard priority, which means the least important loads will be shed before, the industrial load was still maintained. Therefore, in terms of economy also plays an important part in the load shedding plan.

The techniques to solve problems called intelligent load shedding method (ILS), it is a set of techniques applied to mimic human intelligence. These techniques include Artificial Neural Networks (ANN) [2], Adaptive neuro fuzzy inference system (ANFIS) [3], fuzzy logic controller (FLC) [4], Genetic algorithm (GA) [5] and Particle swarm optimization algorithm (PSO) [6]. These techniques can easily solve nonlinear problems, multi goals in the electricity system that the conventional methods cannot be solved with the desired speed and accuracy acceptable.

The load shedding method proposed following to reduce the number of control strategies when the problem occurs corresponding to the load levels and different frequencies through the load profile fuzzy and frequency fuzzy. The order load shedding was predefined corresponding to the load at different frequencies and the load level when the problem occurs. It contributed to simplifying the operation and recovery time of the system faster when the problem occurred.

II. APPROACH METHODS

II.1. Fuzzy Logic Algorithm

Fuzzy logic was developed from fuzzy set theory to perform an approximation argument instead argued exactly the classical predicate logic. Fuzzy logic can be regarded as the application of fuzzy set theory to handle the real-world value to a complex problem.

The membership function $\tilde{M}(\mathrm{x}): R \rightarrow [0,1]$ of the triangle fuzzy numbers $\tilde{M}(\mathrm{x}) = [\mathrm{l}, \mathrm{m}, \mathrm{u}]$ defined on R is equal to

$$\tilde{M}(x) = \begin{cases} \dfrac{x}{m-l} - \dfrac{l}{m-l}, x \in [l,m] \\ \dfrac{x}{m-u} - \dfrac{u}{m-u}, x \in [m,u] \\ 0, \quad \text{otherwise} \end{cases} \tag{1}$$

Where: l and m is the best value of the fuzzy number M, l and u are respectively lower and bound values of the support of M. According to Zadeh's extension principle given

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two triangles fuzzy number $\tilde{M}_1 = [l_1, m_1, u_1]$ and $\tilde{M}_2 = [l_2, m_2, u_2]$ (l_1 *and* $l_2 \geq 0$)

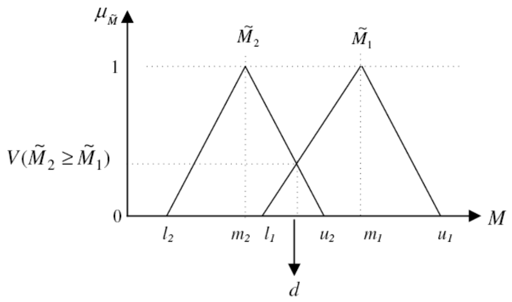

Fig 1: The comparison of two fuzzy numbers $\tilde{M}_1$ and $\tilde{M}_2$

1. Addition of expansion is defined as follows:

$$\tilde{M}_1 \oplus \tilde{M}_2 = (l_1 + l_2, m_1 + m_2, u_1 + u_2) \qquad (2)$$

2. Multiplication expansion is defined as follows:

$$\tilde{M}_1 \otimes \tilde{M}_2 = (l_1 l_2, m_1 m_2, u_1 u_2). \qquad (3)$$

3. Inverse of triangular fuzzy number M_1 is defined as follows:

$$\tilde{M}_1^{-1} \approx \left(\frac{1}{u_1}, \frac{1}{m_1}, \frac{1}{l_1}\right) \qquad (4)$$

II.2 Algorithm AHP (Analytic Hierarchy Process)

AHP algorithm [1] is presented in the following steps (see Figure 3):

Step 1: Set up a decision hierarchy model

Step 2: Build judgment matrix.

The value of the components in the judgment matrix reflects the user's knowledge about the importance the relationship between pairs of factors.

The matrix can be judged based on the ratio method as the *"method rate of* 9". In performing the indices A and B, the relationship between them can be expressed as follows if the *"ratio method"* is used:

+ If both A and B index equal importance, the coefficient will be "1".
+ If performance index A is slightly more important than index B, the coefficient will be "3".
+ If performance index A is more important than index B, the coefficient will be "5".
+ If performance index A is far more important than index B, the coefficient will be "7".
+ If performance index A is extremely important compared with index B, the coefficient will be "9".
+ In a similar "2", "4", "6", "8" is the average value of the judgment neighboring respectively.

Step 3: Calculate the largest eigenvalue and corresponding eigenvectors of judgment matrix.

To calculate the eigenvalue of matrix largest judgment, can use the root methods.

(1) Multiply all the components in each row of the judgment matrix

$$M_i = \prod_i X_{ij} \text{ ,i = 1, ..., n; j = 1, ..., n} \qquad (5)$$

n is the dimension of the matrix A, X_{ij} is the element of the matrix A.

(2) Calculate the n th root of M_i

$$W_i^* = \sqrt[n]{M_i} \qquad i = 1, ..., n \qquad (6)$$

Vector W*:

$$W^* = \left[W_1^*, W_2^*, ..., W_n^*\right]^T \qquad (7)$$

(3) Standardization of vector W^*,

$$W_i = \frac{W_i^*}{\sum_{j=1}^{n} W_j^*} \qquad i = 1, ..., n \qquad (8)$$

In this way, there are eigenvectors of matrix A,

$$W = \left[W_1, W_2, ..., W_n\right]^T \qquad (9)$$

(4) Calculation of the largest eigenvalues λ_{max} of matrix

$$\lambda_{max} = \sum_{i=1}^{n} \frac{(AW)_j}{nW_i} \qquad j = 1, ..., n \qquad (10)$$

where AW_i represents the i-th component of the vector AW.

Step 4: Hierarchy ranking and check the consistency of the results.

II.3 Applications of AHP and Fuzzy logic algorithms for load shedding

II.3.1 Load shedding based on AHP algorithm

AHP method determines the importance of the units of the load in the system, thus the basis for dismissing the load with low importance will be shed before or reduced the damage.

The steps for an IEEE 37bus typical power system:

Step 1: Identify the load centers and load units at the load center.

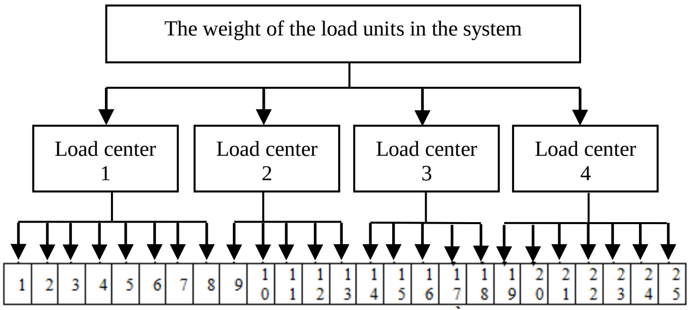

Fig 2: AHP model includes load centers and load units

In this model, the system has 4 load centers and 25 load units.

Step 2: Construction AHP hierarchical model based on load centers and load units determined in Step 1.

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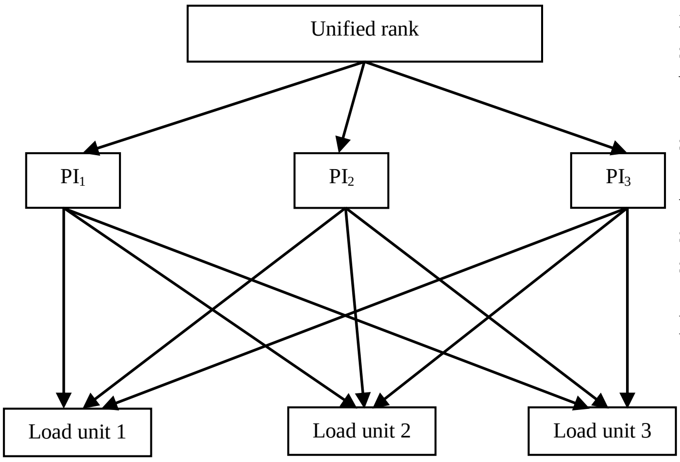

Fig 3: Model of AHP hierarchy

Step 3: Determine the weighting coefficients importance of the load centers and load units using judgment matrix.

Build judgment matrix LC and LU that show the important factor between load centers (LC) and load units (LU) each other of the power system. The value of elements in the judgment matrix reflects the user's knowledge about the relative importance between every pair of factors.

The LC matrix judgment:

$$LC = \begin{bmatrix} w_{D1}/w_{D1} \; w_{D1}/w_{D2} \; ..... \; w_{D1}/w_{Dn} \\ w_{D2}/w_{D1} \; w_{D2}/w_{D2} \; ..... \; w_{D2}/w_{Dn} \\ . \qquad\qquad . \\ . \qquad\qquad . \\ . \qquad\qquad . \\ w_{Dn}/w_{D1} \; w_{Dn}/w_{D2} \; ..... \; w_{Dn}/w_{Dn} \end{bmatrix} \quad (11)$$

The LU matrix judgment:

$$LN = \begin{bmatrix} w_{K1}/w_{K1} \; w_{K1}/w_{K2} \; ..... \; w_{K1}/w_{Kn} \\ w_{K2}/w_{K1} \; w_{K2}/w_{K2} \; ..... \; w_{K2}/w_{Dn} \\ . \qquad\qquad . \\ . \qquad\qquad . \\ . \qquad\qquad . \\ w_{Kn}/w_{K1} \; w_{Kn}/w_{K2} \; ..... \; w_{Kn}/w_{Kn} \end{bmatrix} \quad (12)$$

where, WDi/WDj is the relative importance of the ith load unit compared with the jth load unit; wki /wkj is the relative importance of the ith load center compared with the jth load center.

It is difficult to accurately calculate critical coefficients of each load. The reason is the relative importance of this type of load is not the same.

According to the principle of AHP, the weighting factors of the loads can be determined through the ranking computation of a judgment matrix, which reflects the judgment and comparison of a series of pair of factors. Therefore, the unified weighting factor of the load units of the power system can be obtained from the following equation:

$$w_{ij} = w_{Kj} \times w_{Di} \qquad D_i \in K_j \qquad (13)$$

where, $D_i \in K_j$ means load unit D_i is located in load center K_j.

After calculating the load important factor and the important center of the load factor, the optimization load shedding plan and achieve maximum benefits are calculated with the approach proposed method.

Step 4: Calculate the weights of the load units to the entire system.

Step 5: Sort by descending order of importance of the load units. In the load unit's arrangement table, the load that has smaller weighted priority will be shed before in the control strategies.

Flowchart of the steps load shedding based on Fuzzy logic and AHP algorithm is shown in Figure 4:

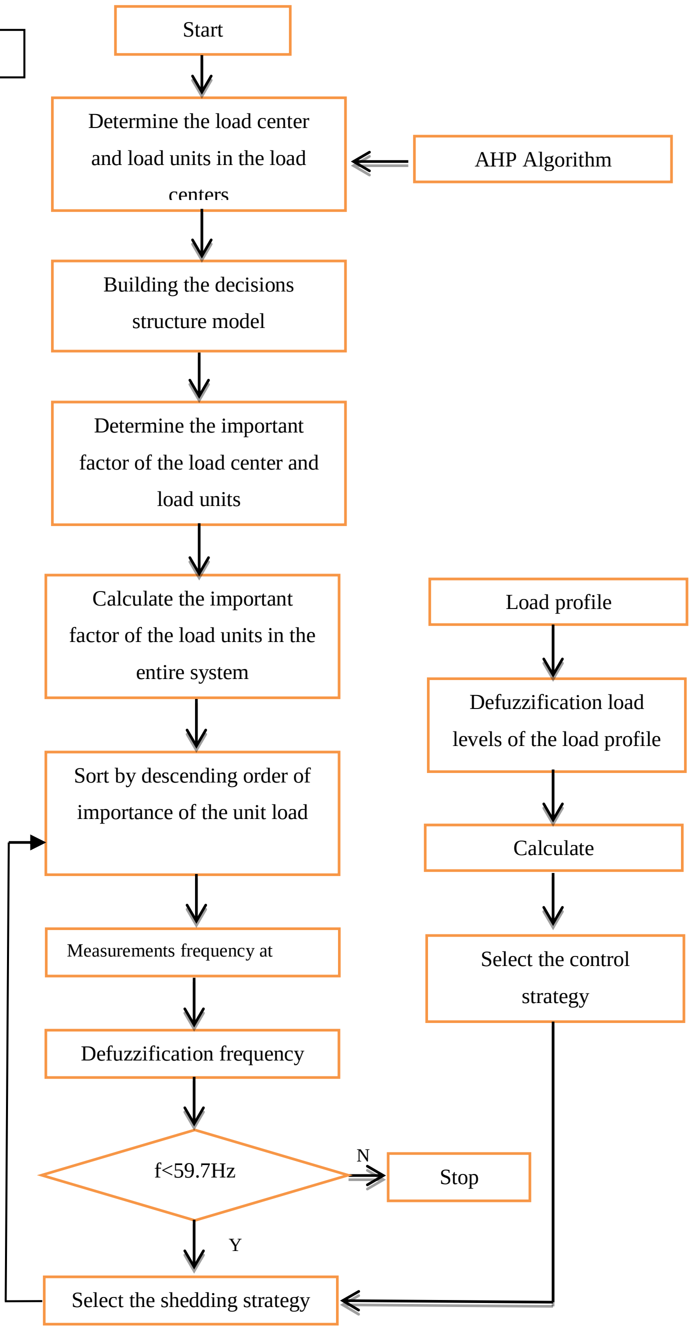

Fig 4: Flowchart of steps using fuzzy logic and AHP algorithm to load shedding

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II.3.2 Fuzzy techniques for frequency and load profile

Technical fuzzy frequency

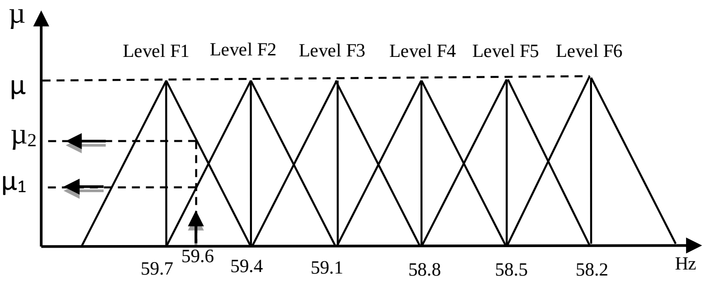

Fig 5: Technical fuzzy frequency

Assuming case the load is operating at 59.6 Hz frequency, the result shows the value $\mu_2 > \mu_1$ therefore choose the frequency level 1. Results calculated sum defuzzification frequencies are shown in Table 1.

Table 1: Results calculated sum of the defuzzification frequencies system

Frequency	Frequency level
59.7 - 59.55	Frequency level 1
59.55-59.25	Frequency level 2
59.25-58.95	Frequency level 3
58.95-58.65	Frequency level 4
58.65-58.35	Frequency level 5
Under 58.35	Frequency level 6

Technical fuzzy load profile

Similar technical fuzzy frequency, with peak values of 70%, 80%, 90% and 100% of the maximum power load.

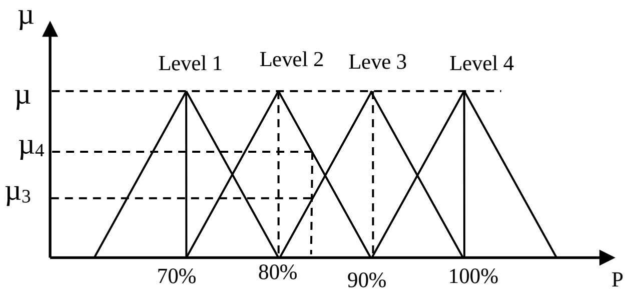

Fig 6: Technical fuzzy load profile

Assuming the case load is operating at 83% of maximum load, the results show the value of $\mu_4 > \mu_3$ so select the load level 2. Calculation results of the defuzzification load profile are shown in Table 2.

Table 2: Results calculated synthetic fuzzy case load graph

Value percent of maximum load power	Load level
of 70% -75%	Level 1
75% -85%	Level 2
85% -95%	Level 3
Over 95%	Level 4

Table 3: Control Strategy respectively to load and frequencies levels

f (Hz) / Level load	Level frequency 1	Level frequency 2	Level frequency 3	Level frequency 4	Level frequency 5	Level frequency 6
Level 1	CLDK 1	CLDK2	CLDK3	CLDK4	5CLDK	CLDK6
Level 2	CLDK7	8CLDK	CLDK9	CLDK 10	CLDK 11	CLDK 12
Level 3	CLDK 13	CLDK 14	CLDK 15	CLDK 16	CLDK 17	CLDK 18
Level 4	CLDK 19	CLDK 20	CLDK 21	CLDK 22	CLDK 23	CLDK 24

III. CALCULATION, TEST, SIMULATION ON SYSTEM

We conducted experiments and simulations proposed algorithm on example model from PowerWorld that was shown in Fig. 7. The model consists of 9 generators and 25 load buses out of totally 37 buses. Consider the case study of problem generator, and bus problem respectively system was operating in the state to 70%, 80%, 90% and 100% of maximum capacity load. Corresponding to each case would build "strategic control" of the load shedding to restore the parameters return to the approximate original steady state.

Consider the case of loss of a SLACK345 generator when the system is operating 80% of maximum capacity. Simulation used software PowerWorld and observed the results when applied the traditional load shedding program and load shedding algorithm proposed.

Results of the change frequency profile after applying the traditional load shedding program is shown in Figure 8.

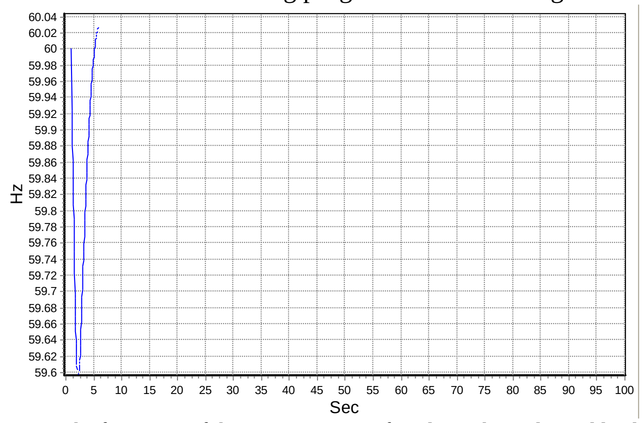

Fig 8: The frequency of the system in case of applying the traditional load shedding program

Frequency profile after applying the load shedding programs proposed is shown in Figure 9.

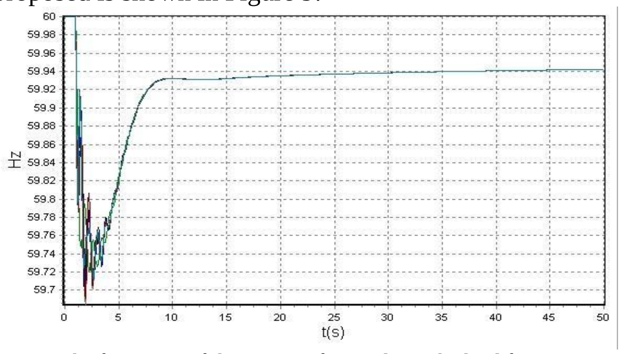

Fig 9: The frequency of the system after applying the load firing programs based on algorithm Fuzzy Logic and AHP

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The frequency before the load shedding was 59.6 Hz. The results from Fig. 9 showed that after applying load shedding program based on Fuzzy logic and AHP algorithm, the frequency was improved to a stable value of nearly 59.94 Hz within 20 seconds.

Assuming, the load was operating at 83% of maximum load capacity, the LAUF69 generator incidents. Application the proposed load shedding program, the results presented in Figure 10.

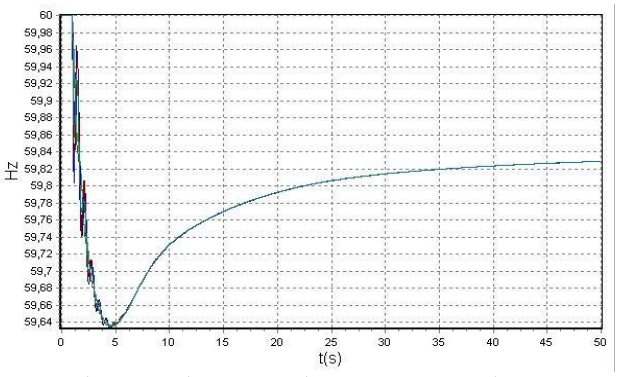

Fig 10: The frequency of the system after applying the load firing programs based on Fuzzy Logic and AHP algorithm at 83% load

Obtained results, the frequency is 59.6 Hz when the generator incident occurred, after applying the proposed load shedding program, the frequency improved to a stable value close to 59.82 Hz in 37 seconds.

In comparison with the case of traditional load shedding programs: load shedding base on the smallest load and ascending order, load shedding base on frequency and voltage sensitivity, load shedding base on the steps based on rate of change of frequency, comparing results are shown in Table 4.

Table 4: Results compared load shedding methods in case of generator incidents

Load shedding methods	Recovery Frequency (Hz)	Shed capacity (MW)	Recovery time (s)
Load shedding based on Fuzzy Logic and AHP algorithm	59.84	102.85	25
Load shedding based on frequency, in order of dV/dt and voltage sensitivity	59.99	185	32
Load shedding based on frequency, not in order of dV / dt and voltage sensitivity	59.87	185	50
Load shedding based on the rate of change of frequency	59.901	206.58	55

Consider the case of the incident at the JO345 bus while the system is operating 80% of maximum capacity. Simulation use software PowerWorld and observe the results when applying the proposed load shedding program.

The frequency profile when we don't load shedding is shown in Fig 11.

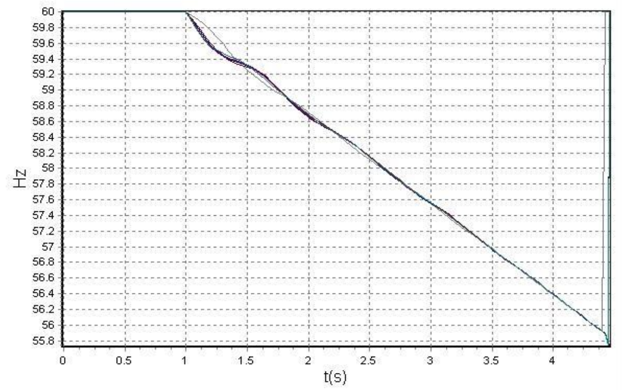

Fig 11: The frequency of the system in case of incidents at the JO345 bus

The system frequency after we apply the load shedding program according to Fuzzy Logic and AHP algorithm is shown in Figure 12.

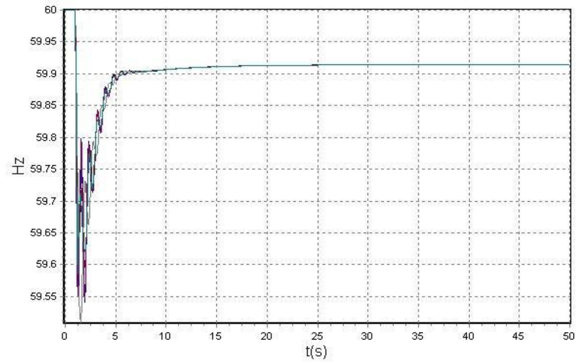

Fig 12: The frequency of the system after applying the load firing programs according to plan design.

According the received results, before the implementation of the proposed load shedding program, the power system is collapsed. After applying the proposed load shedding program, the frequency improved to a stable value close to 59.91 Hz in 15 seconds.

The control strategies are presented in Figure 13-18

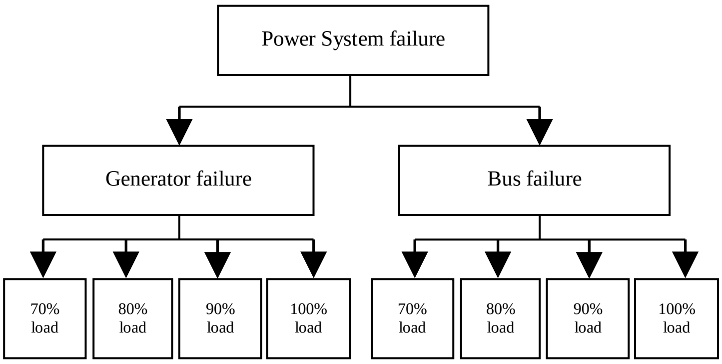

Fig 13: The control strategy when incidents occur on the system

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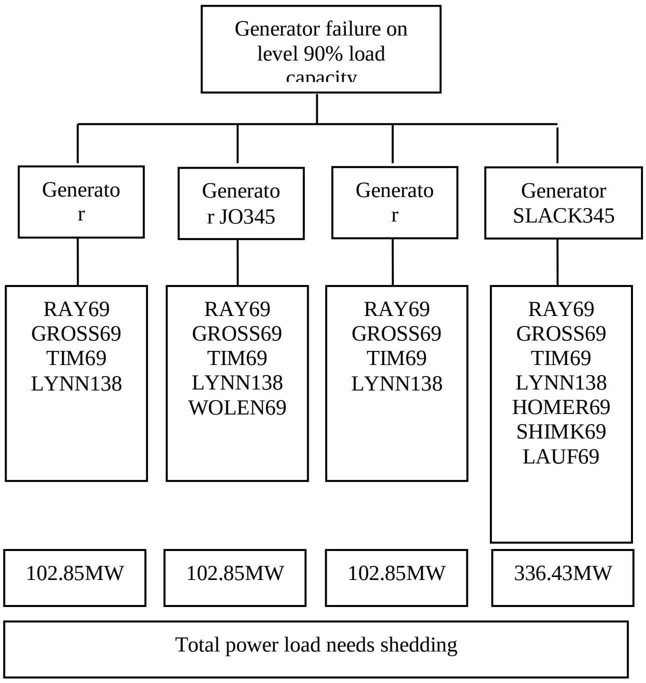

Fig 14: Control strategy when the generator failures and load reaches 70% of maximum capacity

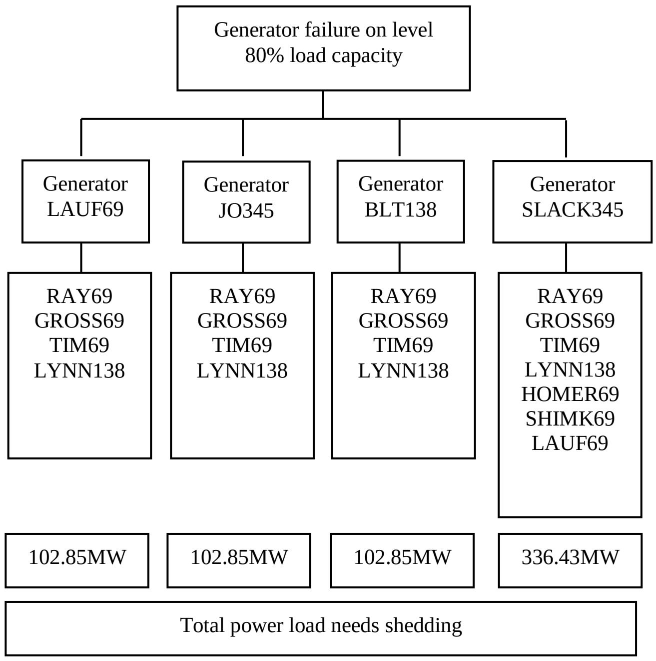

Fig 15: Control strategy when the generator failures and load reaches 80% of maximum capacity

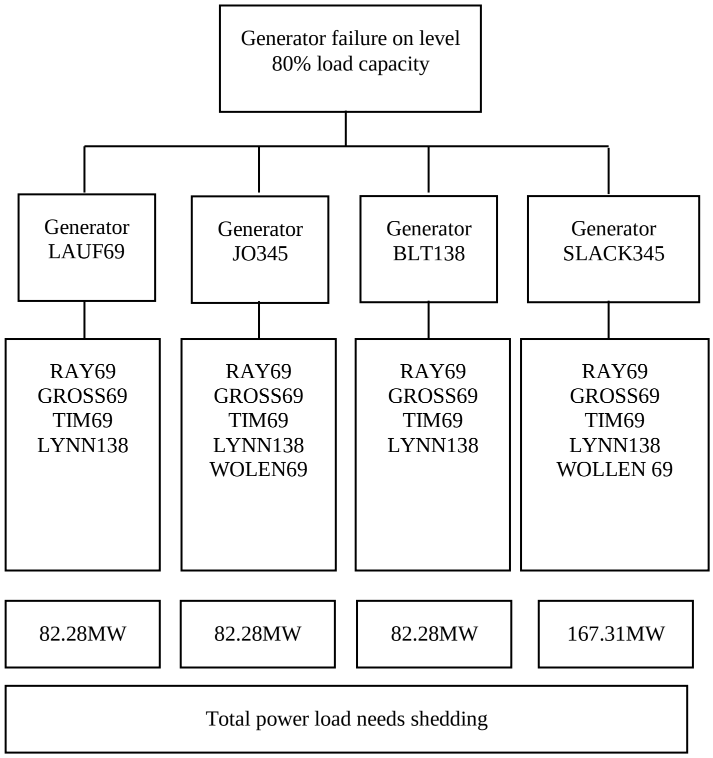

Fig16: Control strategy when the generator failures and load reaches 90% of maximum capacity

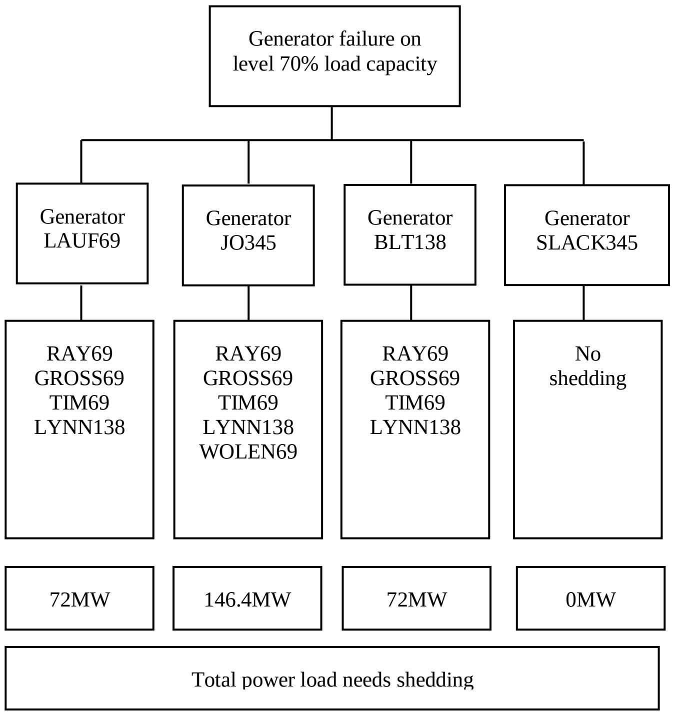

Fig 17: Control strategy when the generator failures and load reaches 100% of rated load maximum

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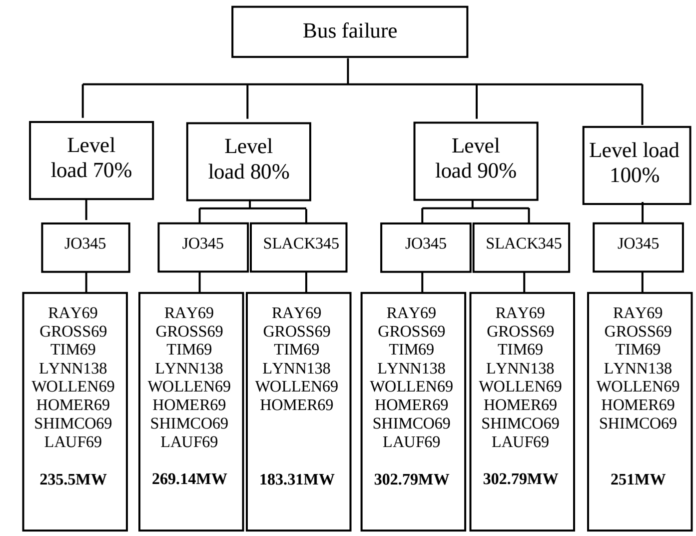

Fig 18: Control strategy in case incidents at the bus

Combined results of the control strategy are presented in table 5.

Table 5: Summary of control strategies when the generator failures

Control strategy	Number of loading and shedding ordinarily
CLDK1	RAY69, GROS69, TIM69, LYNN138
CLDK2	RAY69, GROS69, TIM69, LYNN138, WOLEN69
CLDK3	not happen
CLDK4	not happen
CLDK5	not happen
CLDK6	not happen
CLDK7	RAY69, GROS69, TIM69, LYNN138
CLDK8	(RAY69, GROS69, TIM69, LYNN138 , WOLLEN69) x 50%
CLDK9	(RAY69, GROS69, TIM69, LYNN138, WOLLEN69) x 60%
CLDK10	(RAY69, GROS69, TIM69, LYNN138, WOLLEN69) x 70%
CLDK11	(RAY69, GROS69, TIM69, LYNN138, WOLLEN69) x 80 %
CLDK12	RAY69, GROS69, TIM69, LYNN138, WOLLEN69
CLDK13	(RAY69, GROS69, TIM69, LYNN138, WOLLEN69, HOMER69, SHIMCO69) x 40%
CLDK14	(RAY69, GROS69, TIM69, LYNN138, WOLLEN69, HOMER69, SHIMCO69) x 50%
CLDK15	(RAY69, GROS69, TIM69, LYNN138, WOLLEN69, HOMER69, SHIMCO69) x 60%
CLDK16	(RAY69, GROS69, TIM69, LYNN138, WOLLEN69, HOMER69, SHIMCO69) x 70%
CLDK17	(RAY69, GROS69, TIM69, LYNN138, WOLLEN69, HOMER69 , SHIMCO69) x 80%
CLDK18	RAY69, GROS69, TIM69, LYNN138, WOLLEN69, HOMER69, SHIMCO69
CLDK19	(RAY69, GROS69, TIM69, LYNN138, WOLLEN69, HOMER69, SHIMCO69, LAUF69) x20%
CLDK20	(RAY69, GROS69, TIM69, LYNN138, WOLLEN69, HOMER69, SHIMCO69, LAUF69) x30%
CLDK21	(RAY69, GROS69, TIM69, LYNN138, WOLLEN69, HOMER69, SHIMCO69, LAUF69) X40%
CLDK22	(RAY69, GROS69, TIM69, LYNN138, WOLLEN69, HOMER69, SHIMCO69, LAUF69) X50%
CLDK23	(RAY69, GROS69, TIM69, LYNN138, WOLLEN69, HOMER69, SHIMCO69, LAUF69) x60%
CLDK24	RAY69, GROS69, TIM69, LYNN138, WOLLEN69, HOMER69, SHIMCO69, LAUF69

IV. CONCLUSION

Load shedding based on Fuzzy Logic and AHP algorithm is applied in the emergency situations to maintain stability of the power system. The important feature of this method is load profile and frequency is fuzzy, combining AHP algorithm, which determines the amount of load and load position nedd to be shed, reduce the number of control strategies corresponding to the load levels and different frequencies. The implementation of strategic control with this method contributed to simplifying the operation, reducing the memory and increasing processing speed of the program, helping the system to recover faster in emergency.

The effectiveness of the proposed method is demonstrated by applying the IEEE 37 bus system show that amount of power capacity to shed reduce 44% and the recovery time is faster about 22% than the traditional programs.

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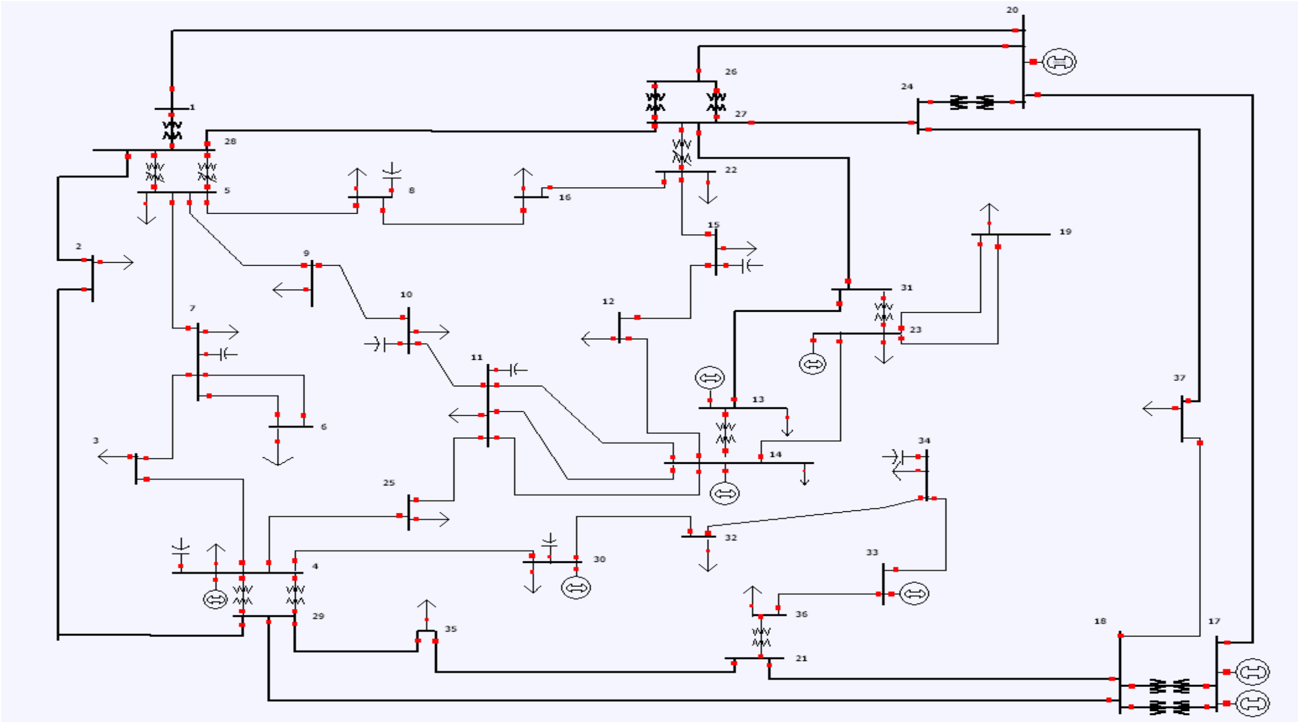

Figure 7: Diagram system 37 bus generator 9

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