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Optimal Load Shedding Planning with Genetic Algorithm

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Abstract – **This paper proposes a novel planning method using genetic algorithm (GA) to achieve minimization of load shedding. The frequency of a power system declines rapidly when generator outage occurs. The general solution is to install sufficient under-frequency relay to pull frequency back to normal range. In this study, a single machine infinite bus (SMIB) is utilized to simulate system load with genetic algorithm for estimating the optimal load shedding and shedding ratio in each stage. Simulated results indicate that the proposed GA-based method is both feasible and effective to facilitate optimal load shedding planning.**

Keywords—**Underfrequency load shedding** (UFLS), **Single machine Infinite Bus** (SMIB), **Genetic algorithm** (GA), **Protection relay.**

I. INTRODUCTION

The world has experienced in recent years several large-scale power system blackouts [1]-[3]. One of the main causes leading to those blackouts is the insufficient amount of under frequency load shedding (UFLS). This paper presents a novel planning method for estimating the optimal load shedding to help keep a power system stable with a minimum load shedding amount.

The frequency of a power system is usually set at a base standard in normal operation to keep the demand and supply of total electricity in equilibrium. The system's frequency starts to fluctuate if the equilibrium is upset by tripped transmission lines or generators. Frequency will drop as electricity demand exceeds supply in the case of tripped generators or transmission lines. The frequency needs to be pulled back to equilibrium, and shedding adaptive load immediately is one of the best ways to restore the frequency to stability. When major generators or vital EHV transmission lines encounter major disturbances, frequency starts to fluctuate dramatically, the system operator must take immediate and effective action; otherwise, there can be a cascading event leading to the system's separation into several islands or collapse into total breakdown. Therefore, most power companies have developed and implemented a UFLS scheme to prevent widespread power system blackout. Simple, fast, and highly reliable, UFLS has been the most important measure against frequency collapse in the recent half century. UFLS has also been used as a popular tool to pull system frequency. Nearly all power companies are equipped with a UFLS program to maintain stable operation by arresting frequency decline [4]. Setting the stages of UFLS is an art since too few and too many stages can result in different problems, such as over-shedding or slow response. In previous studies, Halevi and Kottick used optimal algorithm to process 100 records of generator tripping for obtaining the optimal amount of load shedding in each stage [5]. The basic UFLS principle and guidelines for a small isolated power system were elaborated by Concordia, et al [6]. Huang and Huang proposed a UFLS planning method for application to a real power system but did not address the issue about the importance of spinning reserve capacity [7].

Existing power systems also use the UFLS scheme to prevent loss of electricity. Power companies usually adopt the heuristic method to plan the UFLS scheme to meet the specific needs of their power systems. UFLS, however, may result in either over-shedding that can affect the power quality or under-shedding that can stop the electricity service. How to set UFLS properly so as to avoid over- and under-shedding is therefore very important. In this paper, we utilize GA with the feature of global solution as a planning strategy to simulate every load demand situation to obtain optimal load shedding that includes UFLS stage setting and shedding ratio for each stage. There are two approaches for frequency control. The primary approach mainly evolves around the governor free function while the secondary approaches incorporate automatic frequency control (AFC), automatic generation control (AGC), and emergency generation control (EGC).

With the above functions, the frequency of power system will be pull back to safe range in case of severe disturbance, if not; the UFLS will be initiated such that the frequency is forced to rise. In this study, we use the single machine infinite bus (SMIB) model to simulate the minimal load shedding for both traditional and GA-based methods in an intensive and isolated power system. The load demand range of simulation is from the real record of the previous twelve months such that we can obtain the practical and accurate results.

II. LOAD SHEDDING FREQUENCY SIMULATION

A Power system composed of numerous transmission elements and generators, and they have their own models in power flow and transient stability. The power system is very complicated status. In this study, we use an intensive and isolated power system to simulate when the power system encounters disturbance and utilizes the under frequency load shedding strategy to deal with the power system event.

The 345kV one-line diagram is shown in figure 1, and it has many EHV transmission lines and plans. The most frequently adopted models for analyzing a power system is the single machine infinite bus (SMIB) model with 3-phase balance and synchronism. We accordingly use the SMIB model to replace the complicated power grid system in this paper. The SMIB model simulates load shedding condition when the power system occurs unbalance between supply (system's generation) and demand (system's load). The SMIB is illustrated in Figure 2 [8].

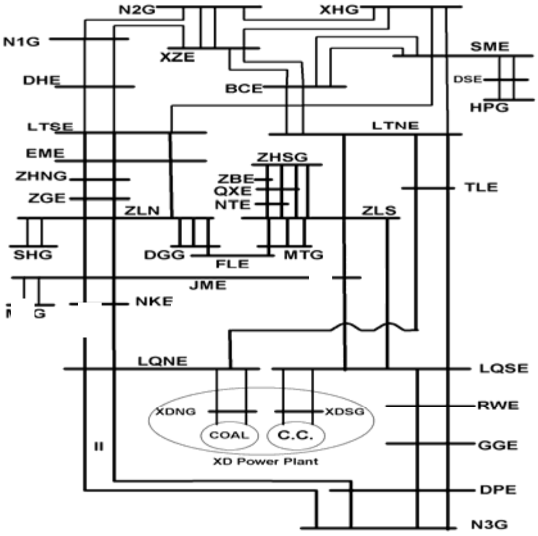

Figure 1. one-line diagram of the power system

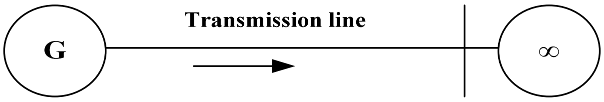

Figure 2. Single machine infinite bus model.

The flow chart for frequency analysis of UFLS is presented in Fig. 2 and described as follows [9]:

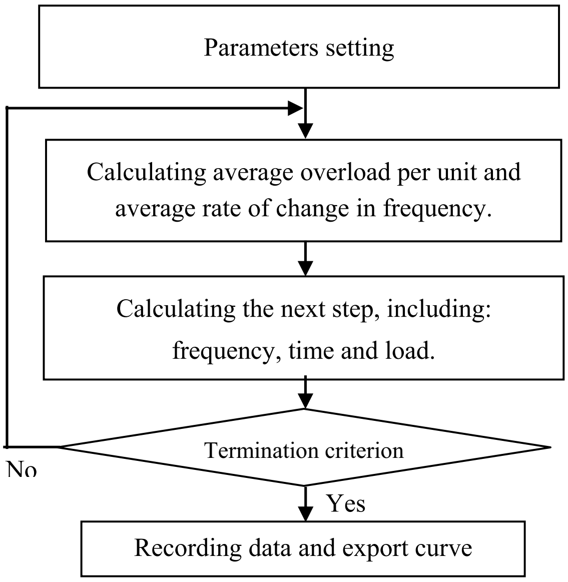

Figure 3. The flow chart of UFLS frequency analysis with SMIB model.

Step 1: *Parameters setting*

To set UFLS input data, including the initial frequency f_1 = 60 Hz, frequency step = 0.01 Hz, inertia constant H = 4.6, power factor Q = 0.9, simulation time = 10 sec., the load reduction factor D =7%MW/HZ, and initial time t = 0.

Step 2: *Calculating* ΔL *and* ΔR

To compute average overload L and the rate of change in frequency R, using equations (1) and (2).

$$L = \frac{(Load - Gen)}{Gen} Q \tag{1}$$

$$R = -\frac{L}{2H} f_1 \tag{2}$$

Step 3: *Calculating the next frequency, time and load*

If the system frequency jumps down to any of the preset frequency of relay, the next frequency and time are computed by equations (3) and (4), and the next load at that time is estimated using equation (5). Otherwise, calculation of the next frequency and time should follow equations (6) and (7). Proceed to calculate the new load with reduction factor based on equation (8).

$$t_2 = t_1 + \mathrm{RF_T} + \mathrm{CB_T} \tag{3}$$

$$f_2 = f_1 + R * (\mathrm{RF_T} + \mathrm{CB_T}) \tag{4}$$

$$\mathrm{Load} = \mathrm{Load} - \mathrm{LSD} \tag{5}$$

$$f_2 = f_1 + 0.01 * \mathrm{sgn}(R) \tag{6}$$

$$t = t + 0.01 / |R| \tag{7}$$

$$\mathrm{Load} = \mathrm{Load} * [1 - \mathrm{D} * (f_2 - f_1)] \tag{8}$$

where:
LSD : Refers to the relay's load shedding amount of relay
sgn(R) : The sign of R
$\mathrm{RF_T}$: The detected time for under frequency relay
$\mathrm{CB_T}$: The active time for circuit breaker

Step 4: *Examining if the termination criterion is met*

If the results meet the termination criterion, then data are recorded and output curve exported. Otherwise, assign $f_2 = f_1$, $t_1 = t_2$ and go back to Step 2 to run the procedures again.

IV. GENETIC ALGORITHM

Genetic algorithm as an optimal method was first proposed by John Holland at the University of Michigan in 1975 [10]. Inspired by the Darwinian evolutionary principles of natural selection and survival of the fittest, GA has been applied to different fields like engineering, computer science, chemistry, and manufacturing In electricity management, GA has been adopted to solve problems like optimal reactive power dispatch, on-line optimal shunt capacitor dispatch, the longest non-intersection route, and over-current relay coordination [11]-[15].

In GA, each phenotype is called a chromosome, and the value for each chromosome is generated randomly. The set of chromosome within a gene is called the "population." The chromosomes in the same generation compete to each other for a better fitness value so that the one with a higher fitness value is more likely to produce children with even higher fitness values through crossover. Moreover, the genetic operator of mutation is applied to prevent the loss of some important genes, though the mutation rate is rather low.

The chromosome with the highest fitness value, i.e., the solution we are looking for, is then generated after several evolutions. What genetic algorithm aims to achieve is not the best solution but the one which is closed to the best solution. Thus, for cases which the best solution could not be detected, genetic algorithm can be used to find the solution closed to the best one effectively and efficiently.

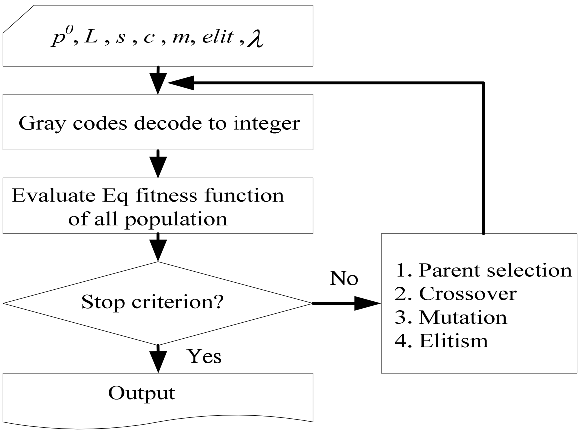

Figure 4. The GA flow chart

The major components of GA include decoding, fitness evaluation, reproduction, crossover, and mutation operators. The core of genetic algorithm lies in the eleven-item entity outlined as follows:

$$GA = (p^0, I, \lambda, L, f, s, c, m, elit, gray, T) \tag{9}$$

where :

p^0 : initial population
I : encoding of chromosomes
λ : population size
L : length of chromosomes
F : fitness function
s : parent-selection operation
c : crossover operation and rate
m : mutation operation and rate
elit : elitism preserving rate
gray : gray code, the better one of the coding method
T : termination criterion

The GA flow chart is shown as Fig.4, and the parameters of GA are summarized as follows: population size is 200, the ratio of elitism is 30%, the crossover rate is 1, the mutation rate is 0.001, and the termination criterion is 250 generations.

V. CASE STUDY

This paper aims at minimizing the average load shedding ratio (LSR) as (10) and assigns it as a fitness function.

$$LSR = \frac{1}{n}\sum_{i=1}^{n} LSR_i = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{load\ shedding}{generation\ tripping}\right)_i \tag{10}$$

where: n : combinations for total load and generation tripping amounts
i : each simulation case

The constraints of this problem include the following items: (10). The lowest frequency is 58.3 Hz because of the turbine life limitation; and (11). The percentage of frequency below 59 Hz at the tenth second must be lower than 2%, i.e.

$$Ne = \frac{No.\ of\ case\ below\ 59Hz}{total\ cases} \times 100\% < 2\% \tag{11}$$

In order to estimate the number of stages for optimal setting, the frequency rate and load shedding ratio for our simulation are set in the range of 58.3 Hz to 59.8 Hz and that of 0.1% to 6.4%, respectively. The simulated amount for generator tripping falls in the range of 700 MW to 2600 MW. The detecting time of frequency relay RF_T is set at 0.167 second (10 cycles). All the circuit breakers' acting time CB_T is set at 0.033 second (2 cycles). For both the GA-based method and the traditional model, the load demands that are taken into consideration are from actual maximum and minimum values in the 12 months of the past year as shown in Table I. The traditional UFLS setting is shown in TABLE II that covers eight stages. Its frequency range is from 58.3 Hz to 59.2 Hz, and the load shedding ratio is from 1.038% to 5.211%.

We obtain Fig. 5 using equation (10) that has fine convergence. Then the results of the simulations by both GA and the traditional model are summarized and in TABLE III. Also indicated in the table are the smallest values of fitness function that suggest fairly satisfactory simulation results. Finally, results of our case study, the 12-month simulation, are illustrated in Table IV and Fig. 5~10 and summarized as follows:

A. The 250 epochs of GA is converged for each case in TABLE IV, indicating that the near-global optimum is obtained. The fitness values of GA appear to be lower than those of the traditional model in all the 12 months as shown in Table III. To compare our GA-based method with the traditional model, it is noted that the load shedding ratios by the GA method are smaller than those by the traditional model; in July, for example, the GA method was able to decrease the load shedding ratio 61.5% more than the tradtional approach, suggesting that using the GA method can help reduce the impacts of the disturbance on both the power system and the customers.

TABLE I. THE MAX. / MIN. LOAD FOR 12 MONTHS

Month / Load	Jan.	Feb.	Mar.	Apr.	May	Jun.
Max (MW)	25,131	25,022	26,404	26,685	31,008	31,102
Min (MW)	16,728	14,148	17,489	17,088	18,797	19,675
Month / Load	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Max (MW)	33,031	32,305	30,554	31,074	26,756	26,406
Min (MW)	21,704	18,816	19,622	17,040	17,649	17,670

TABLE II. THE TRADITIONAL SETTING OF UFLS

UFLS Stages	f(Hz)	Ratio (%)
1st	59.2	4.636
2nd	59.0	4.813
3rd	58.8	5.211
4th	58.7	3.459
5th	58.6	3.630
6th	58.5	3.399
7th	58.4	1.710
8th	58.3	1.038
Total		27.896

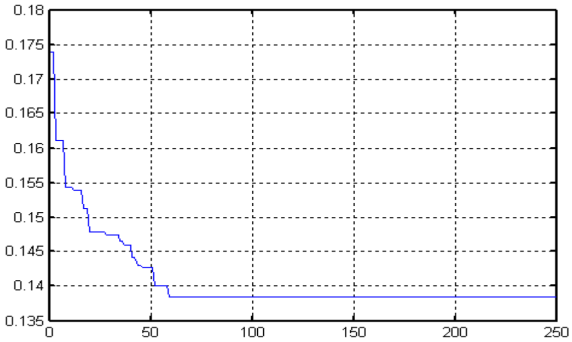

Figure 5. The gragh of UFLS of each epoch in July

TABLE III. THE COMPARISON FITNESS FOR GA AND TRADITIONAL

method month	GA	Traditional	(Tra. – GA)/ Tra. (%)
Jan.	0.3005	0.4614	34.87
Feb.	0.3515	0.4861	27.68
Mar.	0.2681	0.4402	39.09
Apr.	0.2699	0.4442	39.23
May	0.2023	0.3994	49.34
Jun.	0.1830	0.3916	53.26
Jul.	0.1384	0.3595	61.50
Aug.	0.1852	0.3883	52.30
Sep.	0.1919	0.3916	50.99
Oct.	0.2225	0.4144	46.30
Nov.	0.2660	0.4378	39.24
Dec.	0.2672	0.4393	39.17

TABLE IV. THE OPTIMAL PLANNING WITH GA FOR 12 MONTHS

UFLS Stages(Hz)	Load Shedding Ratio (%)					
	Jan.	Feb.	Mar.	Apr.	May	Jun.
59.2	1.3	1.3	0.7	1.0	–	–
59.1	2.0	2.5	1.8	2.0	1.3	1.7
59.0	2.9	3.0	3.1	2.5	3.1	2.4
58.9	2.6	4.1	2.5	2.9	2.7	2.4
58.8	2.6	–	0.1	–	–	–
58.7	–	–	–	–	–	–
58.6	0.1	–	3.1	–	0.1	0.1
58.5	–	3.7	–	–	0.5	–
58.4	–	–	5.5	8.3	–	1.5
58.3	0.4	–	–	3.6	5.0	1.5
Total	11.9	14.6	16.8	20.3	12.7	9.6

UFLS Stages(Hz)	Load Shedding Ratio (%)					
	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
59.2	–	–	–	0.5	0.5	1.0
59.1	1.2	1.7	1.8	1.8	2.4	1.6
59.0	2.3	2.5	2.5	2.8	2.5	3.0
58.9	1.8	2.9	2.2	3.4	2.6	2.3
58.8	–	–	–	–	2.1	–
58.7	6.4	–	0.8	2.6	–	–
58.6	–	–	4.7	1.5	0.1	–
58.5	–	0.3	–	–	–	–
58.4	–	7.3	1.0	4.0	–	0.7
58.3	12.9	0.8	–	–	3.7	6.0
Total	24.6	15.5	13.0	16.6	13.9	14.6

B. In Table III, the average load shedding ratio for Feb. (35.15%) is the highest of the yeear, and the one for July (13.84%) is the lowest. Both remain much lower than the generation tripping amount. GA planning is therefore capable of obtaining better power system reliabiliy.

C. The number of cases of load shedding ratios for GA and the traditional as shown in Fig. 6~7. Thus the loads that need to be shed when a severe fault strikes a power system would be much lesser in the GA case than in the tradtional model.

D. The recovery frequency in the traditional setting is higher than the one in the GA case, as shown in Fig. 8~9. This suggests that the tradtional method tends to shed more load than necessary. Practically, automatic generation control will start to act as the frequency is pulled back to 59Hz. As a result, there is no need to shed extra load. GA method is thus considered to be better than the traditional model.

E. As previously stated, the lowest frequency of the system cannot be lower than 58.3 Hz. As indicated in Fig. 10~11, no matter by the GA or the tradtional method, the lowest frequencies in February and July stay far above 58.3 Hz. Both methods are capable of returning the power system to equilibrium and keep up stable operation.

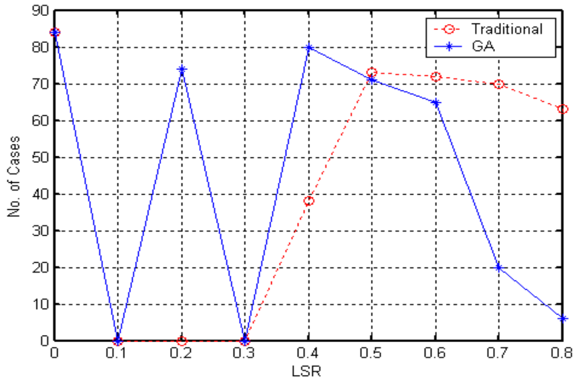

Figure 6. LSR in Feb.

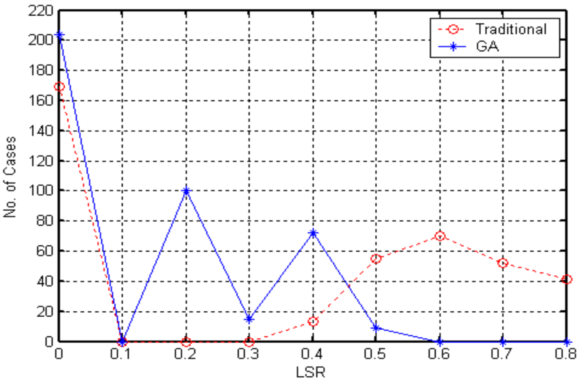

Figure 7. LSR in July

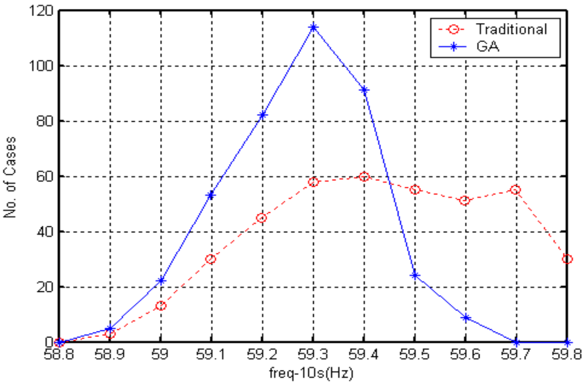

Figure 8. Frequency at 10 sec. in Feb.

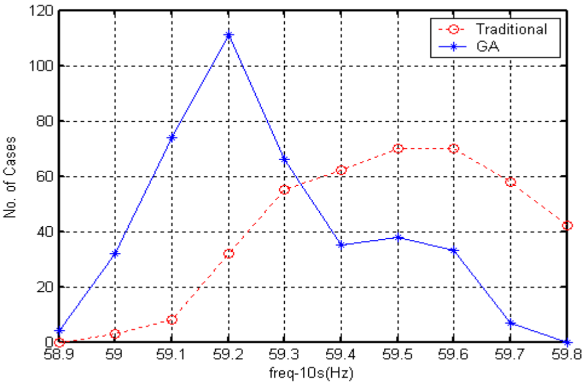

Figure 9. Frequency at 10 sec. in July

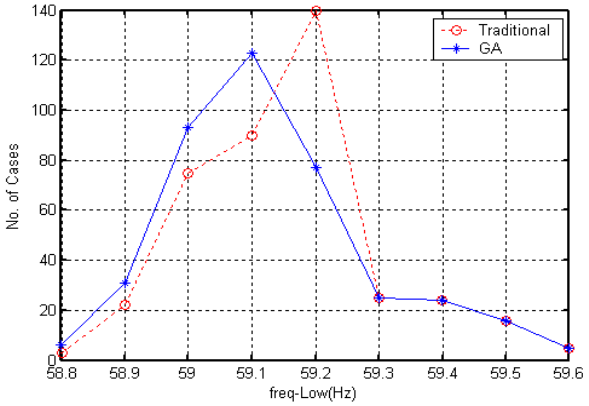

Figure 10. The lowest frequency in Feb.

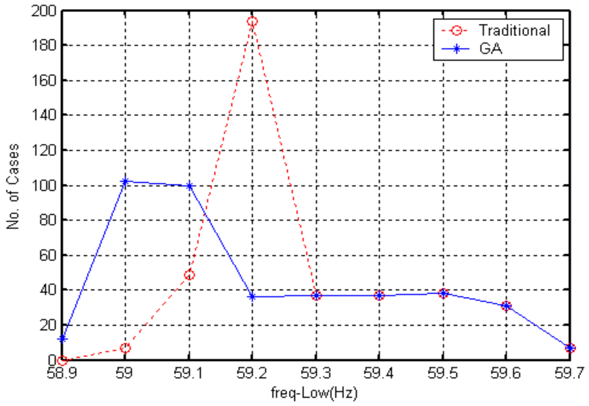

Figure 11. The lowest frequency in July

III. CONCLUSION

The fact that the world's has witnessed several large-scale blackouts in recent years makes UFLS increasingly important because it is the last defensive line to safeguard a power system against blackout. Conventionally, the design of a UFLS scheme is marked by a lack of preciseness as it is based on a tedious heuristic process or personal experiences. In this paper, a GA-based method is developed to obtain optimal UFLS setting by simulating a twelve-month load demand, and the simulation result is compared to those reached by the traditional model. While both methods are found to be able to return the power system to equilibrium and stable operation, the GA-based method helps achieve optimal UFLS planning by keeping the amount of shed load at its minimum and reducing the impacts of the disturbance on the power system and the customers. Our proposed approach can therefore be expected to help power companies plan and practice UFLS in a more effective manner.

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