Adaptive Under Frequency Load Shedding Scheme Using Genetic Algorithm Based Artificial Neural Network

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Abstract: - This paper presents two schemes of UFLS to keep the system frequency within safe limits. GA-based scheme is introduced as an offline method to get the proper amount of shed load achieving the minimum and steady state frequency within permissible limits. Due to the probability of generation variation and generating units outage during shedding process, ANN-based scheme is presented as an online method to adjust the proper amount of load shedding at any amount of power deficit. Multi scenarios of contingences are carried out on offline mode using GA optimization technique to collect the training patterns for ANN. The ANN-based scheme can consider the generation variations during the load shedding process. Although using this scheme may shed more loads, it maintains the frequency to be within permissible limits at various disturbance scenarios particularly at the absence of secondary control. An analytic system frequency response (SFR) model with no secondary control incorporating UFLS scheme is presented. The proposed method is compared with the classical adaptive method to prove its effectiveness. Results are presented in the form of time domain simulations via MATLAB/SIMULINK.

Key-Words: - Islanding, Blackout, Artificial Neural Network, Genetic Algorithm, Under Frequency Load Shedding, System Frequency Response

1 Introduction

Most of power systems are subjected to thousands of disturbances annually which may take the form of cascading natures

[1]. During cascading failure, a power system may split into isolated sub-systems known as islands [2]. The main function of the control system is to maintain the frequency and voltage at permissible limits. The generation is increased to recover the frequency and the reactive power is adjusted for voltage recovery. However, when sudden power disturbance occurs such as outage of large generating units or islanding of some parts of power system with a shortage of spinning reserve, the system frequency will reduce that lead to generating units outage. Consequently, the outage of some generating units may lead the system frequency to decay to a lower level. Hence, the relays of other generating units might trip and lead to power system blackout [3]. UFLS is considered as the last line of defense for preventing frequency drop in power systems after occurring an imbalance between load and generation.

Underfrequency mainly affects all components of power systems, particularly generators and turbines. Not only it may cause a damage to this equipment, but also the performance of power plant auxiliaries (motor driven) and therefore generation output may be reduced. Thus, the loss of generation (or excess demand) may lead to a cascading loss of generating units due to excess frequency drop [4]. It is usually recognized that for the power frequency of 60 Hz, during generation deficits, sufficient load should be shed to restore system frequency to normal or close to normal (above 59 Hz) and the maximum frequency decay is limited to 57 Hz [4].

Some works on the load shedding set up the swing equation first, and then employ classic control tool, such as transfer function, to find out the amount of load to be shed [5] -[11]. In [5], a classic adaptive scheme to set the UFLS relays was introduced. The power deficit was estimated using the swing equation by measuring the rate of change of frequency (ROCOF). In

[6], the load shedding process consists of two main stages. In the first stage, the frequency and ROCOF are estimated using Newton-type algorithm. In the second stage, by using the swing equation, the magnitude of the disturbance is determined. In [7], a general-order SFR model with load shedding scheme was proposed to produce a closed-form expression of frequency response. In

[8] and [9], some modifications are applied to the classic adaptive scheme to improve its performance. In such schemes, before triggering any load shedding step, a certain measure is carried out to estimate the power provided by primary frequency control to minimize the amount of shed load in each step. In [10], a method to determine the frequency stability limits for UFLS was presented. The minimum average frequency of power system is determined based on SFR model. This minimum frequency for maximum allowable power deficit is defined as the frequency stability border. In [11] and [12], any additional power deficit is considered during load shedding process. As a result, the adaptive scheme could be improved by updating the value of power deficit before each step to avoid under/over shedding due to power deficit change.

In this paper, offline and online schemes of load shedding are implemented based on SFR model. The offline scheme is GA-based scheme which can give the proper amount of load shedding at a certain power deficit to keep the frequency within a safe limit. ANN-based scheme is introduced as an online scheme to adjust the necessary amount of load to be shed and maintain the system frequency in case of change in power generation during the load shedding process.

2 System Modeling

The frequency behavior of large power systems, or islanded portion due to sudden load disturbances can be represented by a low order SFR model. Although SFR model is the simplest model for frequency response, it includes the essential system dynamics. It neglects all nonlinearities in the equations except the largest time constants of the generating units with the assumption that the generation is dominated by reheat steam turbine generators. Accordingly, the inertia and reheat time constants of the generating unit mainly affect the system average frequency response [5].

The basic concept of SFR model is based on the uniform or average frequency of generating units. The SFR model averages the machine dynamic behavior in a large system into an equivalent single machine [13]. Fig. 1 shows the average frequency of three machines after islanding [5].

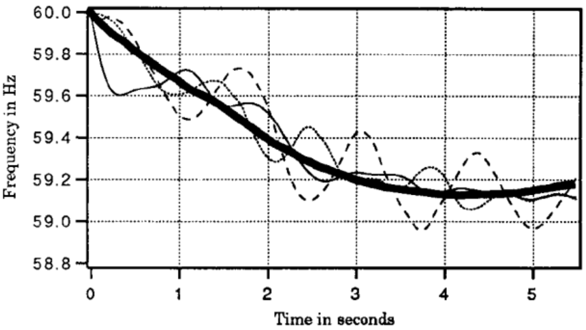


Fig. 1 Average system frequency after islanding [5]

The model behavior depends on six factors; the gain, K_m, the damping factor, D, the regulation constant, R, the inertia constant of the island, H, the average reheat time constant, T_R, and the high-pressure power fraction of the reheat turbines, F_H. All parameters are estimated based on common knowledge of typical system designs. A linear SFR model is shown in Fig. 2. [5].

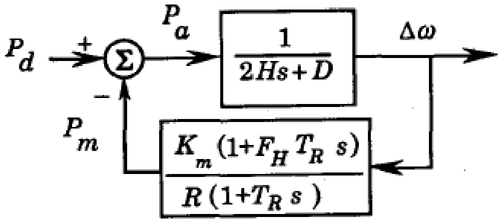


Fig. 2 First order SFR model [5]

The typical parameters of the proposed SFR model are as follow:

$H = 3.5$ $D = 1.0$ $R = 0.06$

$K_m = 0.85$ $F_H = 0.3$ $T_R = 8.0$

3 Classical Adaptive Scheme

In [5], for the classical adaptive setting of UFLS relays, it selects a goal of 57 Hz as the minimum allowable frequency. It performs several disturbances to estimate the maximum disturbance allowed to keep the frequency within a permissible limit. Fig. 3 shows the system frequency at different power deficit without load shedding. It indicates that, with load disturbances greater than about 0.4 pu the frequency deviation drops below 57 Hz.

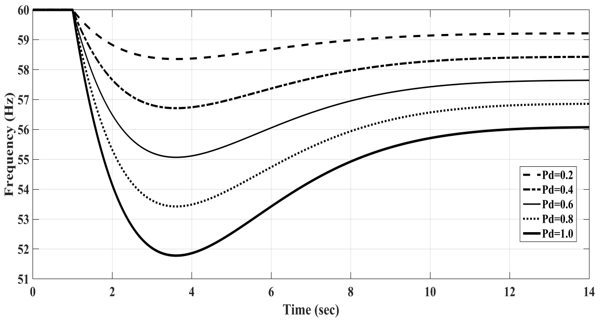


Fig. 3 Frequency response at different disturbances without load shedding

The amount of shed load and the time of triggering for each step of load shedding must be determined. If the load shedding is delayed too long, there is a danger of exceeding the minimum frequency below 57 Hz. This is especially for the larger disturbances, which cause the frequency to decay rapidly as shown in Fig. 3. Therefore, as the size of the disturbance increases, there is more need for a rapid action of load shedding. One way of accomplishing this is to trigger the first load shedding step at 59 Hz which is high enough to assure quick removal of the first step of load [5]. Clearly, the only observed quantity that gives a guide to the size of the disturbance is the initial slope of frequency decline.

This slope is equal to:

$$m_o = \left.\frac{df}{dt}\right|_{t=0} = \frac{P_d}{2H} \qquad pu/s \qquad (1)$$

Where m_o is the initial slope in pu/s, df/dt is the frequency derivative in Hz/s, and P_d is the size of disturbance in pu. Suppose that this slope is observed continuously, so that load shedding can be triggered when the slope exceeds some critical value. The size of the disturbance can be calculated as:

$$P_d = 2H \left.\frac{df}{dt}\right|_{t=0} \qquad pu \qquad (2)$$

If the initial slope is used to estimate the magnitude of the disturbance, every substation in the island will observe slightly different slopes and will therefore shed load based on different estimates of the disturbance. To determine the critical point at which the load shedding should be started, firstly, get the maximum step change of load $P_{d\text{-}max}$ that can be permitted to keep the frequency not to decline below 57 Hz. The slope at this maximum permissible value is called the critical slope m_{oc}. When the magnitude of the observed initial slope is greater than m_{oc}, load shedding must be triggered. The load that must be shed is estimated by subtracting m_{oc} from the computed slope for any disturbance. Therefore, the incremental load shed should be equal to the following:

$$\frac{P_{shed}}{2H} = \frac{P_d}{2H} - m_{oc} \qquad pu/sec \qquad (3)$$

$$P_{shed} = P_d - 2Hm_{oc} \qquad pu \qquad (4)$$

From Eq. 4, we may compute the incremental step function of load to be shed for various sizes of the initial disturbance. The incremental amount of load shed is a linear function of the initial disturbance and is therefore a linear function of the initial slope.

For implementation of the above method of load shedding, first order SFR model with UFLS scheme is assumed without any secondary control as shown in Fig. 4.

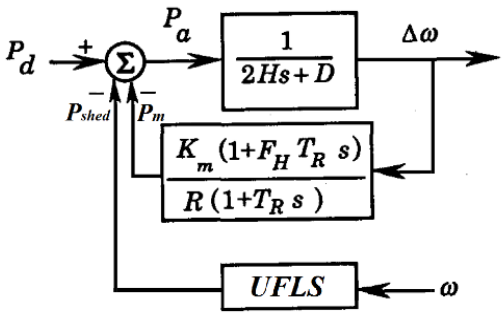


Fig. 4 Implementation of UFLS to SFR model

The maximum disturbance which make the minimum frequency to be equal to 57 Hz can be estimated by trial and error or by using GA optimization technique to find that m_{oc} = 0.0521 pu/s. The amount of load shedding at different disturbances can be calculated from Eq. 4, at H=3.5, to be equal to:

$$P_{shed} = P_d - 0.3647 \qquad pu \qquad (5)$$

Eq. 5 is applied to the SFR model and take a protection plan of four steps. Table 1 shows the size of each step at different frequencies of load shedding.

Table 1 Frequency setting of four steps plan

Threshold frequencies (Hz)	Amount of load shedding (%)
59	35
58.8	30
58.6	20
58.4	15

The minimum frequency (f_{min}) and the steady state frequency (f_{ss}) due to different disturbances are shown in Table 2.

Table 2 Load shedding at different disturbances

P_d (pu)	P_{shed} (pu)	f_{min} (Hz)	f_{ss} (Hz)
0.1	-	59.1781	59.6047
0.2	-	58.3562	59.2094
0.3	-	57.5343	58.8140
0.4	0.0353	57	58.5583
0.5	0.1353	57	58.5583
0.6	0.2353	57	58.5583
0.7	0.3353	57	58.5583
0.8	0.4353	57	58.5583
0.9	0.5353	57	58.5583
1.0	0.6353	57	58.5583

The classical adaptive method introduced in [5] can maintain f_{min} to be above 57 Hz but it fails in maintaining f_{ss} to be within the permissible limit particularly at the absence of secondary control.

4 Novel Adaptive Scheme

The following sections explain the proposed novel adaptive UFLS scheme. It is classified into GA-based scheme which has a fixed setting of relays and ANN-based scheme which has an online relay setting. The comparisons between schemes are carried out with the aid of several simulation studies which may affect the effectiveness of UFLS schemes.

4.1 GA-based adaptive UFLS

The aim of the proposed load shedding scheme is to maintain f_{min} and f_{ss} to be within the safe limits. To provide some margin, f_{ss} is selected to be 59.2 Hz and f_{min} is limited to 57 Hz.

The amount of load shedding is selected as the parameter to be optimized which will be obtained by applying GA optimization technique to achieve the minimum fitness. The fitness function is given by:

$$fitness = abs(\max(f)\ -\ 59.2) \quad (6)$$

Where f is the system frequency. During achieving the fitness, f_{min} should be observed and must be greater than 57 Hz. If f_{min} is below 57 Hz at any cases, the fitness function must be changed to be as the following:

$$fitness = abs(\min(f)\ -\ 57) \quad (7)$$

Table 3 gives the amount of load shedding at different disturbances to achieve f_{min} and f_{ss} above 57 and 59.2 Hz, respectively.

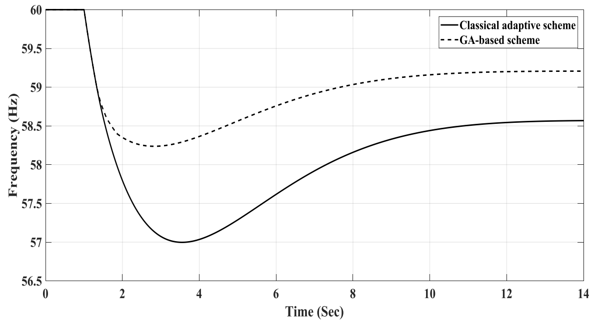
Table 3 Load shedding at different disturbances using GA

P_d (pu)	P_{shed} (pu)	f_{min} (Hz)	f_{ss} (Hz)
0.1	-	59.1781	59.6047
0.2	-	58.3562	59.2094
0.3	0.09778	58.2685	59.2000
0.4	0.19778	58.2378	59.2000
0.5	0.29778	58.2197	59.2000
0.6	0.39778	58.2074	59.2000
0.7	0.49778	58.1986	59.2000
0.8	0.59778	58.1917	59.2000
0.9	0.69778	58.1864	59.2000
1.0	0.79778	58.1818	59.2000

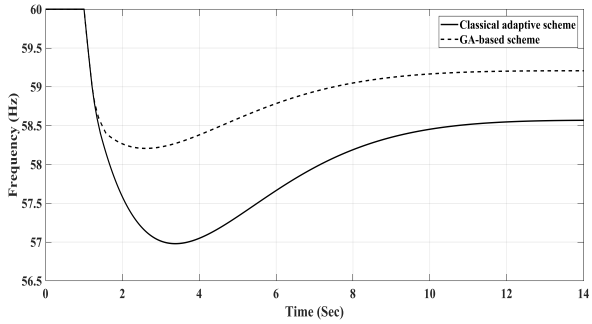
From the results of GA, the equation that relate the amount of load shedding with the power disturbance can be deduced to be a linear equation due to this linear system.

$$P_{shed} = P_d - 0.20233 \qquad pu \quad (8)$$

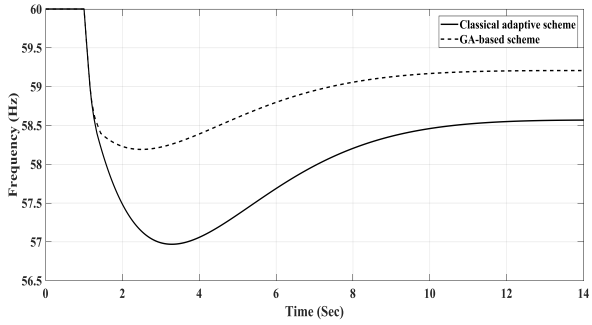
Fig. 5 shows the system frequency due to different disturbances by applying the scheme in [5] (Classic adaptive scheme) and comparing it with GA-based scheme. It shows that for the proposed scheme, although the amount of load shedding increased by 0.16237 pu compared with the other scheme, but f_{min} and f_{ss} are maintained above 57 and 59.2 Hz, respectively.



(a) $P_d = 0.4$ pu



(b) Pd = 0.6 pu



(c) Pd = 0.8 pu

Fig. 5 System frequency at different power deficits

The outage of any of generating units may occur during the load shedding process due to a fault or malfunction of generators underfrequency relays [3]. So, for maintaining the system frequency within the permissible limits, the load shedding schemes must consider this additional power deficit in the consequent steps of load shedding.

The main drawback of GA-based scheme which restricts its implementation in real-time application is its slow response where the computation time of GA to determine the amount of load shedding is very large [14]. As a result, the slowness of GA limits their usage for online application. Consequently, a scheme that has the ability of online ensuring an optimum amount of load shedding is required.

4.2 ANN-based adaptive UFLS

An ANN is a mathematical model based on human neural systems. It has been widely used in power system problems. ANN can be utilized to fine online set the UFLS relays to ensure the frequency stability at any amount of power deficit.

In this study, the ANN training process is organized by considering one input – power deficit – and one output – amount of load shedding. Multi scenarios of contingences are performed off-line on the proposed system by using GA optimization technique to collect the training patterns for ANN. The contingences considered are in the form of power deficit from 5% to 100% with a step of 5% (i.e. 20 points). Several tests were performed on ANN by varying number of hidden layers as well as the number of neurons in each hidden layer. ANN feed forward Multi-Layer Perception (MLP) architecture is considered. One hidden layer with 5 neurons is used with a tansigmoidal activation function and supervised training via a back-propagation technique.

Fig. 6 shows the implementation of ANN with the proposed SFR model. The ANN uses the power deficit to determine the desired amount of load shedding and any change in power deficit is detected from a step decrease in frequency derivative. Hence, ANN can consider this change and compensate the load shedding steps to keep the frequency within permissible limits.

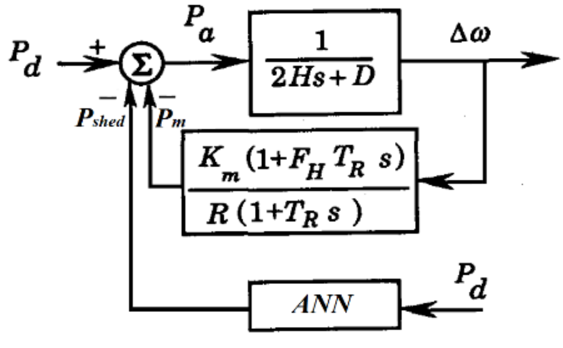


Fig. 6 ANN-based adaptive UFLS

In this case study, to prove the effectiveness of the proposed scheme, initial 0.6 pu power deficit at 1 sec with additional 0.2 pu power deficit at 1.3 sec is considered. For the classical adaptive scheme and GA-based scheme, the power deficit is calculated just after occurrence of the initial power deficit.

Therefore, they are not able to recognize the additional power deficit. Consequently, the additional power deficit is not compensated by these schemes which result the frequency to decline more and more. On the other hand, the ANN-based scheme estimates the power deficit online during the shedding process. Therefore, it can recognize the additional power deficit immediately and in the consequent load shedding steps.

Fig. 7 and Fig. 8 certifies the performance of the proposed scheme in case of occuring an additional power deficit during the load shedding process.

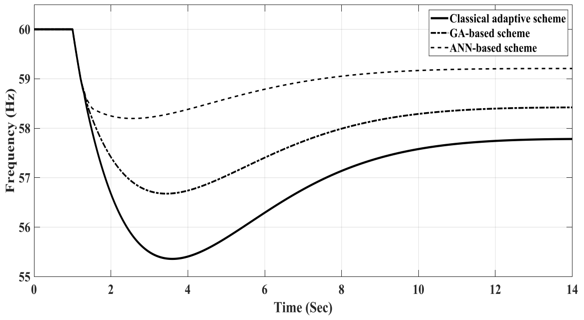


Fig. 7 System frequency with additional power deficit during the load shedding process

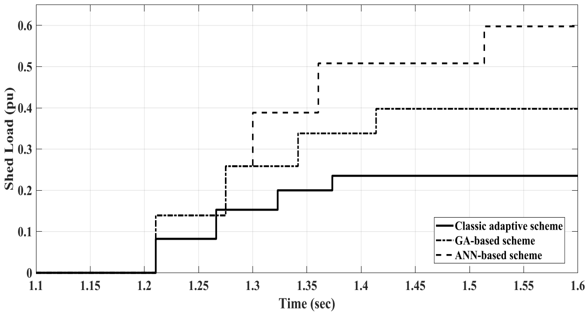


Fig. 8 Load shedding amount with additional power deficit during the load shedding process

From Fig. 7 and Fig. 8 it can be shown that, with additional power deficit at 1.3 sec, ANN-based scheme can consider the power change and it immediately compensate the amount of load shedding at this time and consider this change in the next steps. On the other hand, the classic adaptive scheme and GA-based scheme which have a fixed relay setting fail in recognizing the power deficit change. Consequently, the frequency decays to a lower value exceeding the minimum permissible limit.

5 Conclusion

The frequency behavior of a large power system can be estimated by a low-order SFR model. The system frequency will decrease during a large disturbance such as a sudden outage of a large generation in case of a shortage of spinning reserve. Consequently, the load shedding is the only solution to regain the system frequency to a permissible limit. This paper presents two schemes of load shedding. GA-based scheme can keep the system frequency at safe limit at a certain value of power deficit. The outage of any of generating units may occur during shedding process which affects the amount of power deficit. As a result, ANN-based scheme is proposed to online adjust the proper amount of load shedding during cascading outage of generating units to maintain the frequency within a permissible limit. An appropriate database of disturbances using GA is obtained for training ANN. It was declared that, when an additional power deficit occurs during the load shedding process, ANN-based scheme scheme can shed the appropriate amount of load according to the updated value of power deficit to prevent the frequency from falling below the minimum permissible value. The simulation results demonstrate the effectiveness of the proposed load shedding scheme at different scenarios.

References:

[1] Y. V. Makarov, V. I. Reshetov, A. Stroevand, and I. Voropai, “Blackout Prevention in the United States, Europe, and Russia”, *IEEE*, Vol. 93, No. 11, Nov. 2005, pp. 1942-1955.

[2] E. Theodoro, R. Benedito, J. J. London, and L. Alberto, “Algebraic-graph method for identification of islanding in power system grids”, *Electr Power Energy Syst.*, 2012, pp. 171–179.

[3] A. Ketabi and M. Hajiakbari Fini “Adaptive underfrequency load shedding using particle swarm optimization algorithm,” *Journal of Applied Research and Technology 15*, 2017, pp. 54–60.

[4] W.C. New, J. Berdy, and P. Brown, “Load Shedding, Load Restoration and Generator Protection Using Solid State and Electromechanical Underfrequency Relays”, *General Electric: Philadelphia*, 1983.

[5] P. M. Anderson and M. Mirheydar, “An adaptive method for setting underfrequency load shedding relays,” *IEEE Trans. Power Syst.*, Vol. 7, No. 2, May 1992, pp. 647–655.

[6] V. V. Terzija, “Adaptive underfrequency load shedding based on the magnitude of the disturbance estimation,” *IEEE Trans. Power*

Syst., Vol. 21, No. 3, Aug. 2006, pp. 1260–1266.

[7] DU. Hau Aik, “A general-order system frequency response model incorporating load shedding, analytic modeling and applications,” *IEEE Trans Power Syst*, 2006, pp. 709–717.

[8] U. Rudez, and R. Mihalic, "Monitoring the first frequency derivative to improve adaptive underfrequency load-shedding schemes", *IEEE Trans. Power Syst*., Vol. 26, No. 2, 2011, pp. 839-846.

[9] U. Rudez, and R. Mihalic, "Analysis of underfrequency load shedding using a frequency gradient", *IEEE Trans. Power Del.*, Vol. 26, No.2, 2011, pp. 565-575.

[10] M. Giroletti, M. Farina, and R. Scattolini , “ A hybrid frequency/power based method for industrial load shedding,” *Electr Power Energy Syst*., 2012, pp. 194–200.

[11] A. Ketabi, and M. H. Fini, "An underfrequency load shedding scheme for islanded microgrids", *Int. J. Elec. Power*, Vol. 62, 2014, pp. 599-607.

[12] A. Ketabi, and M. H. Fini, "An underfrequency load shedding scheme for hybrid and multiarea power systems", *IEEE Trans. Smart Grid*, Vol. 6, No.1, 2015, pp. 82-91.

[13] Q. Zhao and Ch. Chen, “Study on a system frequency response model for a large industrial area load shedding,” *International Journal of Electrical Power and Energy Systems, Elsevier*, Vol. 27, 2005, pp. 233-237.

[14] J. A. Laghari, H. Mokhlis, A. H. A. Bakar, and Hasmaini Mohamad. “Application of computational intelligence techniques for load shedding in power systems: A review”, *Energy Conv. and Man. 75*, 2013, pp. 130-140.