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Optimal Setting of Under Frequency Load Shedding Relays in Low Inertia Networks

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***Abstract*—Under Frequency Load Shedding (UFLS) is one of the most important protection schemes against frequency instability. In this paper a multi-stage UFLS plan is developed. The main devices of this scheme are under frequency relays that are tuned offline. The amount of load shedding, frequency threshold and time delay for load shedding are optimized according to the system conditions. Hence, the setting of these relays with regard to the actual operation conditions seems to be a necessity. The focus of this paper is to utilize the UFLS plan in the primary control of the frequency response, which ranges from the beginning of the contingency until tens of seconds later. The dynamics of governors and load damping are also considered. The performance of the multi-stage UFLS plans under the high penetration of non-synchronous renewable generation resources is investigated. The proposed scheme is implemented in IEEE 39-Bus test system using GAMS software.**

***Keywords*— Frequency stability; Primary frequency control; under frequency load shedding; optimization.**

I. NOMENCLATURE

P_{mi}	Input mechanical power of generator *i*
P_{ei}	Electric power output of generator *i*
H_i	Inertia constant of generator i
H	Equivalent inertia constant of the system
f_i	Frequency of bus i
N_g	Number of generators
S_i	Apparent power of generator i
S	Equivalent apparent power of the system
d	Differential operator
t	Subscript of time instant
P_m	Total mechanical power of the system
P_e	Total electrical power of the system
P^{acc}	Accelerating power
P_g	Active generation by governor action
P_c	Generation deficiency caused by unit outage
D	Load damping constant
f_0	System nominal frequency
T	Governor time constant
R	Equivalent speed drop of governors
R_i	Speed drop of governor i
n	Counter of time step
Δt	Time step
$\Delta f_{\min}$	Minimum frequency between two sequential stages
$f_{\min}^{sh}$	Minimum Load shedding frequency
$f_{\max}^{sh}$	Maximum Load shedding frequency
$f_{\min}$	Minimum authorized network frequency
$\Delta f_{\max}^{ss}$	Minimum authorized frequency changes in steady state
$u_{s,n}^{C}$	Axillary binary variable
$v_{s,n}^{C}$	Axillary binary variable

II. INTRODUCTION

Power system stability always has been one of the most important issues for network operators. Nowadays with growing integration of renewable energy sources, the issue of frequency stability will face some new challenges. Renewable energy resources such as wind turbines, beside their many advantages, will decrease the equivalent inertia of the network. In the hours that their penetration is high, if a major generation outage occurs the network may experience severe excursion in frequency response. Therefore, as the penetration of the renewables increases, new protection schemes should be developed.

Authors in [1] present a probabilistic model for Multi-stage UFLS plan. In this method, system parameters by means of discretized dynamic frequency response and with considering uncertainty of contingency are calculated. UFLS design is developed in the form of mixed integer linear programming (MILP) problem that its purpose is to minimize the amount of load shedding in every stage. The problem uncertainty is calculated using point estimate method that is faster, and simpler comparing with the Mont-Carlo simulation method. Also authors in [2] propose a new standard classification of uncertainty modelling techniques for decision making process.

In [3] a UFLS design is proposed for fast frequency restoration based on the minimum permissible frequency and rate of change of frequency (ROCOF). The proposed algorithm contains three stages: 1. Identifying faults (power plant outage) 2. Primary load shedding 3. Fast load shedding. In every stage the amount of load should be shed and its critical time will be calculated.

The proposed algorithm in [4] gives an optimal UFLS design under some uncertainties such as inertia, load damping and generation deficiency. Also this paper considers the operation of ROCOF relays that are used as the islanding detection relays of distributed generators. In this paper, it has been shown that if the operation of such relays be ignored, the UFLS parameters may be set undesirable.

The number of synthetic AC/DC lines and penetration of renewables is increasing. Fluctuations and uncertainty in such sources, exposes the power system to new challenges. Author in [5] suggests an online UFLS method using control of virtual inertia of wind turbines. Virtual inertia control method, for utilizing kinetic energy of wind turbine, is used when a contingency happens.

Authors in [6] present a UFLS method based on a sensitivity analysis. The main purpose of this method is finding the sensitivity level to the center of inertia (COI) frequency in each node by changing in loads. The proposed method is used for locating and calculating of the load to be shed.

With genesis of wide area monitoring systems (WAMS) and technology development in demand response and smart equipment, the implementation of UFLS plans has been facilitated. In [7] a smart method is introduced for UFLS and under voltage load shedding (UVLS) design based on the participation of smart active loads. The proposed method can prevent decreasing and collapsing of voltage and frequency and also reduce the amount of load shedding and economic costs.

The optimization model of UFLS plan can be solved using analytic or intelligent methods. For example [8] uses genetic algorithm for UFLS plan. Also the authors in [9] and [10] have presented an adaptive load shedding plan based on artificial neural network (ANN). The proposed ANN in [9] is used for estimating the amount of power imbalance in the network. This paper has claimed that the ANN method is more accurate comparing with other methods proposed for estimating power imbalance form swing equation.

In [11], a semi-adaptive UFLS plan has been proposed using the Particle Swarm Optimization (PSO) algorithm. In the proposed method, first the amount of generation outage is calculated and then the size of load shedding is computed. This paper also considers the effect of wind turbines.

Authors in [12] and [13] present an adaptive UFLS design. In this method, for large contingencies, first by means of local measurements the points of networks with low voltage magnitudes are identified, then the UFLS is applied exactly in these points. By means of this method, voltage and frequency stability will be improved simultaneously.

The UFLS schemes also can be presented for microgrids exclusively. For example [14] presents a UFLS design for islanded micro grid. In this paper using state estimation, the amount of network load and then the amount of power imbalance are estimated. At the end, the amount of load shedding is calculated.

Among the proposed protection schemes, one of the approach for preventing load shedding is using of energy storage sources. In [15] a control method has been proposed using energy storages for postponing the load shedding. System parameters are estimated by Kalman filter.

The rest of this paper is arranged as follows. In section III, a discrete time model for frequency response and UFLS plan is proposed. In section IV, the simulation results of the developed model will be discussed. All the simulation has been implemented on IEEE 39 bus system using GAMS program. Finally the paper is concluded in section V.

III. PROBLEM FORMULATION

In this section, first the discrete time model is proposed for frequency response and in the second part the UFLS modelling is presented.

A. *Frequency response modelling*

In this section at first the swing equation will be expressed then it will be linearized in the form of discrete time model. Swing equation first is expressed for one generator and then it will be generalized to a multi-machine system based on center of inertia (COI) concept. It is assumed that the network frequency is sampled with step Δt [16]. The swing equation for a synchronous machine is as follow:

$$\frac{2H_i}{f_0}\frac{df_i(t)}{dt} = (P_{mi} - P_{ei}), i = 1, 2, ..., N_g \tag{1}$$

For a multi-machine system based on COI reference, the swing equation can be expressed in a new base as follow [1]:

$$S = \sum_{i=1}^{N_g} S_i \tag{2}$$

And the equivalent inertia of the system and COI frequency are as given in (4) and (5):

$$f = \sum_{i=1}^{N_g} \frac{f_i H_i}{H} \tag{3}$$

$$H = \sum_{i=1}^{N_g} \frac{H_i S_i}{S} \tag{4}$$

The equations related to equivalent electrical power and mechanical power of the system are expressed as follow:

$$P_e = \sum_{i=1}^{N_g} P_{ei} \frac{S_i}{S} \tag{5}$$

$$P_m = \sum_{i=1}^{N_g} P_{mi} \frac{S_i}{S} \tag{6}$$

For developing a discrete time model, with considering the generation outage, the governor dynamic, load damping and load shedding the swing equation is changed as below:

$$\frac{d\Delta f(t)}{dt} = \frac{f_0}{2H} \Delta P^{acc}(t) \tag{7}$$

According to the single bus model, the accelerating power is defined as follows.

$$\Delta P^{acc}(t) = [\Delta P_g(t) - \Delta P_c + \Delta P_{shed}(t) - D\Delta f(t)] \tag{8}$$

Also the governor dynamic is expressed as given in (9).

$$\frac{d\Delta P_g}{dt} = \frac{1}{T}(-\Delta P_g(t) - \frac{\Delta f(t)}{R}) \tag{9}$$

Furthermore the equivalent speed droop is calculated as below:

$$\frac{1}{R} = \sum_{i=1}^{N_g} \frac{S_i}{R_i S} \tag{10}$$

Finally, the discretized frequency response with the time step of Δt is defined as follows [1].

$$\Delta f(n\Delta t) = \Delta f_n \tag{11}$$

$$\Delta P^g(n\Delta t) = \Delta P_n^g \tag{12}$$

$$\Delta P_{shed}(n\Delta t) = \Delta P_{shed,s,n} \tag{13}$$

Using the modified Euler method, the system frequency response is redefined as given below.

$$RHS(t) \triangleq \frac{f_0}{2H} \Delta P^{acc}(t) \tag{14}$$

$$\Delta f_{n+1} = \Delta f_n + \int_{t_n}^{t_{n+1}} RHS(t_n, \Delta f_n) \tag{15}$$

The above integral rewritten using the trapezoidal rule as follows:

$$\Delta f_{n+1} \simeq \Delta f_n + \frac{\Delta t}{2}[RHS(t_n, \Delta f_n) + RHS(t_{n+1}, \Delta f_{n+1})] \tag{16}$$

$$RHS(t_n, \Delta f_n) = \frac{f_0}{2H}(\Delta P_n^g - \Delta P^C + \Delta P_{shed,s,n} - D\Delta f_n) \tag{17}$$

$$\Delta P_{n+1}^g = \Delta P_n^g + \frac{\Delta t}{T}(\frac{-\Delta f_{n+1}}{R} - \Delta P_n^g) \tag{18}$$

Before any contingency the frequency is at its nominal value and there is no change in frequency. Therefore the initial value in frequency change is zero [17].

B. UFLS modelling

Here the mathematical model of the proposed multi-stage UFLS is presented. In this scheme, if the frequency fall below its threshold f_s, more than Δt_s, then the UFLS scheme will be activated and curtail a certain amount of load $(\Delta P_{shed,s})$ since, the UFLS relays are programed as multi-stage plan, there should be a timer for every stage that computes the time delay of Δt_s. A binary variable is defined to model the timer as follows.

$$\frac{f_s - (f_0 + \Delta f_n^C)}{L} \le v_{s,n}^C \le 1 + \frac{f_s - (f_0 + \Delta f_n^C)}{L}, \forall c, s, n \tag{19}$$

In (19), the parameter of L is an arbitrary big number (e.g. 1000). By means of binary variable in (19), the time that frequency is under the frequency threshold can be computed according to (20).

$$\Delta t_{s,n}^C = \Delta t_{s,n-1}^C + v_{s,n}^C \Delta t, \forall c, s, n \tag{20}$$

Additionally, another binary variable is needed to activate the load shedding of a given stage, if $\Delta t_{s,n}^C$ exceeds its threshold (i.e. Δt_s). This binary variable is introduced using (21)-(23).

$$\frac{\Delta t_{s,n}^C - \Delta t_s}{L} \le u_{s,n}^C \le 1 + \frac{\Delta t_{s,n}^C - \Delta t_s}{L}, \forall c, s, n \tag{21}$$

$$\sum_{j=0}^{3} \frac{v_{s,n-j}}{3} - 1 \le u_{s,n} \le v_{s,n-k}, k = 0, \ldots, 3 \tag{22}$$

$$u^c{}_{s,n-1} \le u^c{}_{s,n} \tag{23}$$

Now for consdiering different continmgencies(i.e. generation outages) the frequency response given in (16)-(18) are redefined as follows.

$$\Delta f_{n+1}^{c} \simeq \Delta f_{n}^{c} + \frac{\Delta t}{2}[RHS(t_{n}, \Delta f_{n}^{c}) + RHS(t_{n+1}, \Delta f_{n+1}^{c})], \forall c, n \tag{24}$$

$$RHS(t_n, \Delta f_n^c) = \frac{f_0}{2H}(\Delta P_{g,n}^c - \Delta P^c + \sum_{s} Alarm_{s,n}^c \Delta P_{shed,s,n} - D\Delta f_n^c) \tag{25}$$

$$\Delta P_{g,n+1}^{c} = \Delta P_{g,n}^{c} + \frac{\Delta t}{T}(\frac{-\Delta f_{n+1}^{c}}{R^{c}} - \Delta P_{g,n}^{c}), \forall c, n \tag{26}$$

Also it is needed to have a minimum interval between two subsequent frequency set-points.

$$f_s^{shed} - f_{s+1}^{shed} \succ \Delta f_{\min}, s = 1, 2, \ldots, n_{s-1} \tag{27}$$

According to (28), the frequency thresholds should be in a predetermined range.

$$f_{\min}^{sh} \le f_s^{sh} \le f_{\max}^{sh}, s = 1, 2, \ldots, n_s \tag{28}$$

Based on (29), the network frequency should be greater than a minimum value (e.g. 47Hz-47.5 Hz).

$$f_n = (f_0 + f_0 \Delta f_n) \ge f_{\min} \tag{29}$$

One of the UFLS purposes is to restore the steady state frequency to a normal safe range (e.g. ±0.50Hz to 1 Hz). This issue is fulfilled via (30).

$$-\Delta f_{\max}^{ss} \le \Delta f^{ss} \le \Delta f_{\max}^{ss} \tag{30}$$

Also the steady state frequency is calculated based on (31).

$$\Delta f^{ss} = \frac{(-\Delta P^c + \sum_{s=1}^{n_s} P_s^{sh})}{D + \frac{1}{R}} \tag{31}$$

According to (32), the amount of load shedding at every stage according to the technical issues should be less than a maximum.

$$\Delta P_s^{sh} \le \Delta P_s^{\max} \tag{32}$$

Finally the objective function is defined as below:

$$\min \sum_{s=1}^{n_s} P_{shed,s} \tag{33}$$

IV. SIMULATION RESULTS

A. Study case network

All the simulation in this part has been done on IEEE 39 bus system which its single line diagram has been shown in Fig1. This network has three different islands highlighted by three different colors. Also islanding procedure has been presented in [18]. It is assumed that all the governors in each island are the same and different from other islands. More details about governors have been presented in Table 1.

Table 1 Input Parameters for UFLS design

Parameters			Value
Governor model	North Area	R	0.05 (p.u.)
		T	6.6 (s)
	East Area	R	0.05 (p.u.)
		T	5 (s)
	West Area	R	0.047 (p.u.)
		T	3.5 (s)
f_0			50 (Hz)
H			2 (s)
$\Delta f_{\min}$			0.2 (Hz)
$f_{\min}^{sh}$			48 (Hz)
$f_{\max}^{sh}$			49 (Hz)
$f_{\min}$			47.5 (Hz)
$\Delta f_{\max}^{ss}$			0.5 (Hz)
D			2 (p.u.)

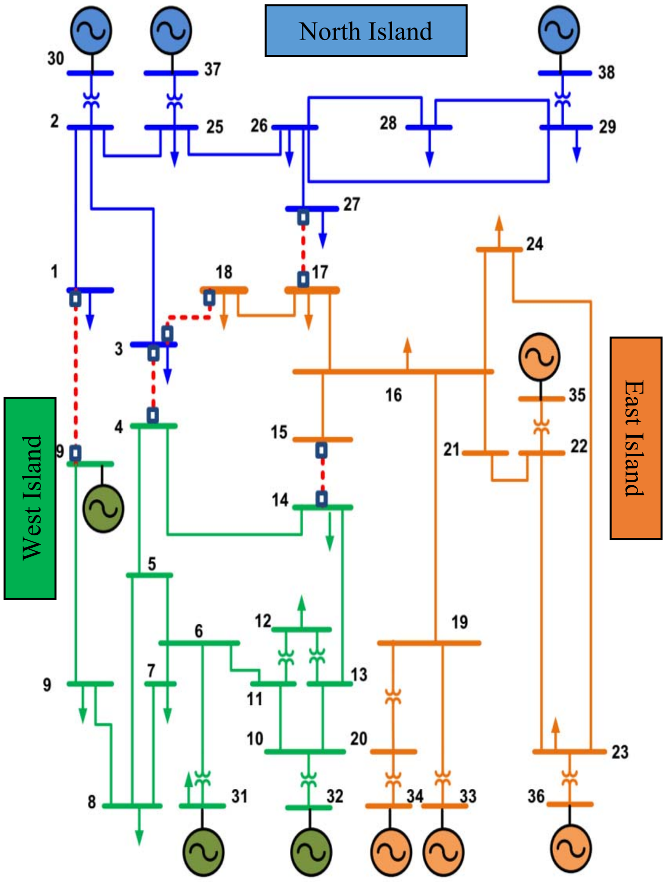

Figure 1. Single Line Diagram of the IEEE 39-bus system

B. *Case Studies*

In this section simulation results under different case studies is presented with the optimized UFLS scheme. Considering assumptions in Table 1, under generation outages less than 0.2 p.u., the network frequency will not violate the constraints, so the proposed UFLS scheme will be activated for contingencies with the outages greater than 0.2 p.u. The optimal UFLS plan including the frequency thresholds and load blocks is obtained and the results have been reported in Table 2. It is noted that the UFLS plan is obtained and optimized for three different schemes including decreasing, increasing and equal blocks. Therefore the problem will find the minimum total load shedding under the given outage scenarios. All double generation outages, the largest triple generation outages and islanding scenarios have been considered as outage scenarios.

Table 2 Optimal setting of UFLS schemes

UFLS Plan		Eq.	Dec.	Inc.	Time delay(s)
Load shedding stages	f_s	P_{shed}	P_{shed}	P_{shed}	
1	48.6	4.1%	6.5%	2%	0.2
2	48.4	4.1%	4.3%	3%	0.2
3	48.2	4.1%	3.3%	4%	0.2
4	48	4.1%	2.3%	7.5%	0.2

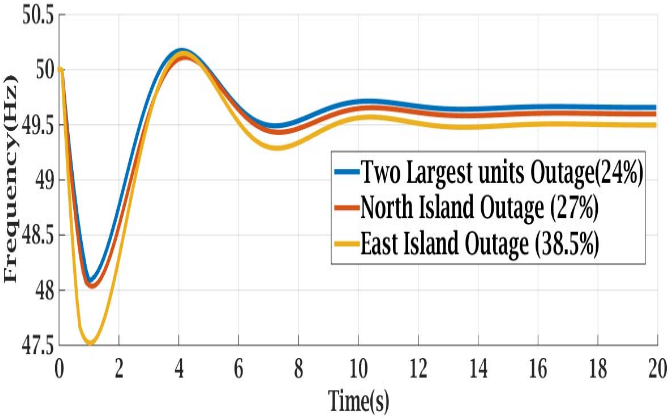

Figure 2 Frequency response for some contingencies using the proposed Increasing UFLS plan

Fig 2 shows the frequency responses under three outage scenarios using increasing UFLS plan. For example, the East Island outage is one of the most sever contingencies that results in 38.5% generation loss but, as shown in Fig 2, using the proposed UFLS plan, the network frequency will be restored to a safe range.

Fig 3 indicates the frequency responses under the same scenarios using decreasing UFLS plan.

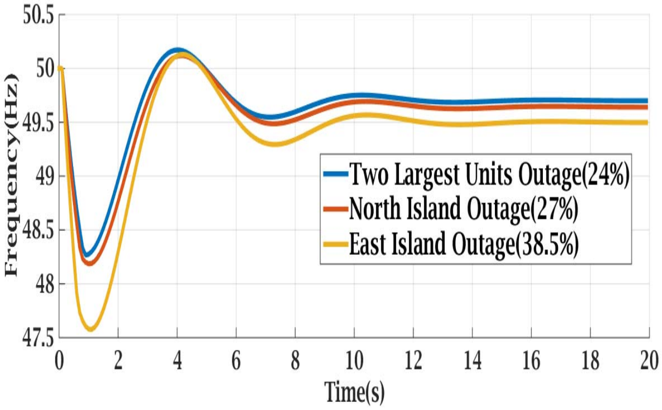

Figure 3 Frequency response for some contingencies using the proposed Decreasing UFLS plan

In the following, different UFLS plans will be compared. As shown in Fig 4 decreasing UFLS plan is more suitable for low inertia network with high penetration of renewables. As show below, frequency nadir is higher when decreasing UFLS scheme is used also steady state frequency in this scheme can be restored better comparing with other plans. But one of the most important issues about decreasing UFLS plan is frequency overshoot. In this paper upper limit for frequency is assumed 50.5 Hz.

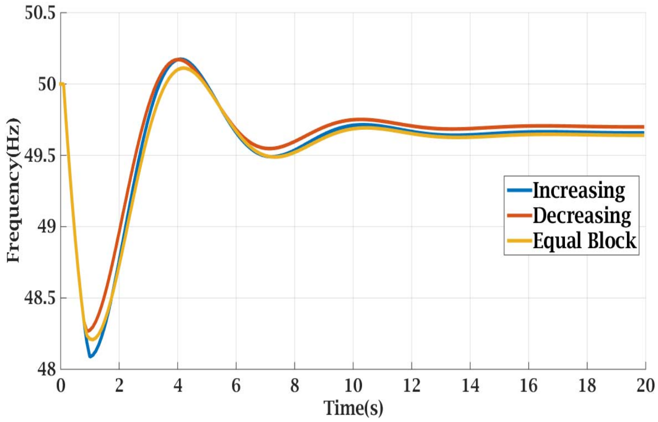

Figure 4 Comparison between proposed UFLS plans under 0.24 p.u. outage

Networks with high penetration of renewables are not robust enough and when the system faces different contingencies it will be in danger of instability. One of the approach for stabilizing these networks against such conditions is the application of UFLS scheme.

Also in Fig 5 the deviation between the frequency nadir and the nominal frequency is increased by increasing the penetration level of non-synchronous generators under a generation outage of 0.385 p.u. and without activation of UFLS relays. The same results but assuming the activation of UFLS relays has been illustrated in Fig. 6.

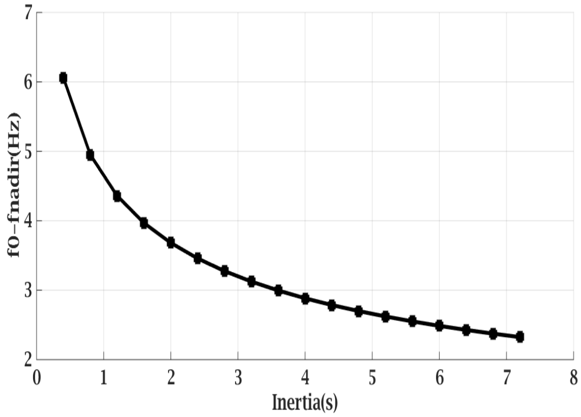

Figure 5 The effect of inertia reduction on frequency nadir without load shedding

Fig 5 shows that in low inertia networks without load shedding the frequency nadir drops rapidly and network will be in danger of blackout. As shown in the figure if a contingency occurs, when DG penetration is too high, then the frequency drops under 44 Hz.

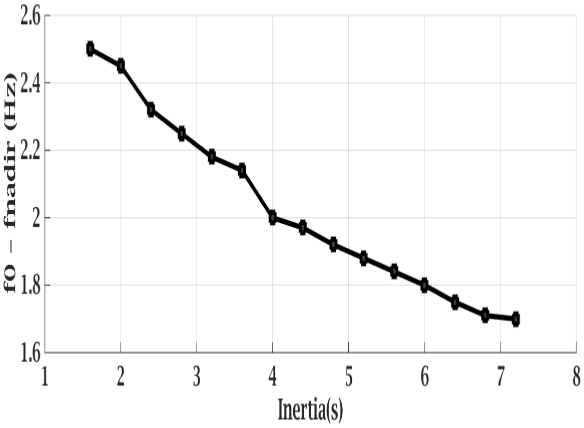

Figure 6 The effect of inertia reduction on frequency nadir with load shedding

V. CONCLUSION

In this paper a MIP model for UFLS scheme was presented. Three different UFLS plans were optimized for the network considering different outage scenarios. The efficiency of any UFLS plan depends on the system parameters such as total inertia constants. The penetration of non-synchronous generation resources causes the reduction of total inertia time constant. It was shown that by means of a robust UFLS design, the network frequency stability is achieved even with high penetration levels of non-synchronous generation resources. The consideration of uncertainties in system parameters due to the penetration of low inertia technologies is an open question for future researches.

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