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Published (to be published) in: ***Energy and Power Engineering***

(Expected) publication date: **2010**

Citation format for published version:

M. A. Anuar, H. Bevrani, T. Hiyama (2010) Regional coordination for under frequency load shedding. Energy and Power Engineering, vol. 2, pp. 148-153, Aug 2010, DOI: 10.4236/epe.2010.23022

Energy and Power Engineering, **2010, 2, 148-153**
doi:10.4236/epe.2010.23022 Published Online August 2010 (http://www.SciRP.org/journal/epe)

Regional Coordination for under Frequency Load Shedding

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Received April 12, 2010; *revised May* 25, 2010; *accepted July* 2, 2010

Abstract

Frequency deviation can be used as an indicator of imbalance between supply and demand. When generation is insufficient, it can cause frequency decline in a power system operation. Implementing under frequency load shedding (UFLS) is one of the common methods to overcome this problem. This paper proposes a novel approach for adaptive load shedding. The concept is an extension of shared and targeted load shedding using reserve margin. The optimal system configuration is then selected from those candidates to fulfill operational objectives. Operational constraints related to system parameters, threshold frequency, total of load shed and control area including line capacity are considered. An example using four sub-areas connected to an external system shows that the proposed regional coordination as an adaptive UFLS is feasible.

Keywords: Load Shedding, Multi-Area Power Systems, Load Frequency Control, Emergency Control

1. Introduction

Frequency deviation can be used as an indicator of imbalance between generation and demand. At the same time, it is needed to make sure that the system frequency is in allowable range. Transmission operator or balancing authority should ensure that the transmission system is operated so that instability, uncontrolled separation or cascading outages will not occur as result of the most severe single contingency and specified multiple contingencies [1]. Practically, transmission operator or balancing authority has the capability and authority to shed load rather than the risk of an uncontrolled failure in the interconnection when generation or transmission capacity is insufficient. The operators of large scale electrical power systems must be constantly alert of possibilities of a system failure. This was one of the reasons of cascading problem which occurred in North America blackout on August 14, 2003 [2]. The system experienced asynchronous oscillation which lasted for about 1 min 40 s, and no out-of-step relays acted to island the asynchronous system and settle the oscillation. When asynchronous oscillation exists for such a long time, surely the power system will experience cascading tripping of generators, and the system blackout will happen because of load-generation imbalance.

Previous studies on the load shedding scheme can be categorized into static and adaptive schemes [3]. In static scheme, a certain amount of load is shed when the system frequency falls below certain threshold. This scheme is the most simple and used by most utilities. Whereas, adaptive methods are used to consider the characteristics of the power system, generator dynamic behavior under large disturbance and nonlinear interacting generators [4-6]. Almost, both above described methods are based on frequency threshold and/or frequency gradient. The under frequency load shedding is triggered/initiated when the frequency drops below the frequency threshold. Frequency gradient provide an important slope as an index to predict the contingency and manage an appropriate emergency control plan.

This paper proposes a method using adaptive under frequency load shedding. The methodology adopted in this method incorporating frequency response analysis, system parameters, frequency threshold**,** total of load shed and control area including line capacity in transmission lines. This paper is organized to describe the methodology in Section 2, a test case in Section 3, results and discussion in Section 4, and finally conclusions in Section 5.

2. Methodology

2.1. Frequency Response Analysis

Figure 1 shows simplified frequency response model where ΔP_L, ΔP_C, R_{sys}, $M_{sys}(s)$ are the system load change, supplementary control, drooping characteristic, and governor-turbine dynamic model, respectively [4]. The system frequency deviation Δf, equivalent inertia H, and equivalent load damping coefficient D are defined as follows:

$$\Delta f = \sum_{i=1}^{N} (H_i \Delta f_i) / \sum_{i=1}^{N} H_i, \quad H = \sum_{i=1}^{N} H_i, \quad D = \sum_{i=1}^{N} D_i, \tag{1}$$

Since, the supplementary control dynamic is usually slower than emergency control dynamics, ΔP_C, can be ignored in an emergency condition analysis. According to **Figure 1**, frequency deviation can be written as

$$\Delta f(s) = \frac{1}{2Hs = D}[\Delta P_m(s) - \Delta P_L(s)] \tag{2}$$

or, taking the inverse Laplace transform,

$$\Delta P_m(t) - \Delta P_L(t) = \Delta P_D(t) = 2H\frac{d\Delta f(t)}{d(t)} + D\Delta f(t) \tag{3}$$

$\Delta P_D(t)$ shows the load-generation imbalance is proportional to the total load change. The magnitude of total load-generation imbalance immediately after the occurrence of disturbance at $t = 0^+$ s can be expressed as follows:

$$\Delta P_D = 2H\frac{d\Delta f(t)}{d(t)} \tag{4}$$

where $d\Delta f / dt$ is the frequency gradient in a power system and is proportional to the magnitude of total load-generation imbalance. For initial rate of frequency change, from (2) with no speed governing, at $t = 0^+$ s and $\Delta P_m = 0$, can be reduced to,

$$\Delta f(s) = \frac{-\Delta P_L(s)}{2Hs + D} \tag{5}$$

for a step change in the load by ΔP_L, the Laplace transform of the load change is

$$\Delta P_L(s) = \Delta P_L / S \tag{6}$$

and rearrange Equation (5),

$$\Delta f(s) = \frac{-\Delta P_L / D}{s[1 + \left(\frac{2H}{D}\right)s]} \tag{7}$$

and taking the inverse Laplace transform,

$$\Delta f(t) = \frac{-\Delta P_L}{D} + (\frac{2H\Delta P_L}{D^2})e^{-\frac{t}{\left(\frac{2H}{D}\right)}} \tag{8}$$

Hence, the initial rate of frequency change at $t = 0^+$ s is proportional to ΔP_L/D,

$$\left.\frac{d\Delta f(t)}{dt}\right|_{t=0^+} \cong -\Delta P_L / D \tag{9}$$

As mentioned before, the main factor and parameters that control the behavior of the frequency are the amount of disturbance, damping D, and inertia H parameters. The effect of the later two parameters should be considered in load shedding planning. From (9) it can be seen that increase in D causes a decrease in frequency gradient. Therefore, higher value of D gives a higher stability and the final system frequency will be stabilized at a higher level. Furthermore, H does not influence the initial amount of frequency gradient, but influences the system dynamics, and higher H may improve the system stability under conditions of disturbance.

2.2. Frequency Threshold and Load Percentages

In normal condition, for most existing networks allowable frequency deviation range can be ± 1% whereas in emergency condition it is ± 4% from nominal frequency. The selection of frequency threshold and the number of load shedding steps depend on the system. In this paper three steps, 1%, 2%, 3% step increment, is considered with the frequency deviation from 59.4 Hz to 58.2 Hz as shown in **Figure 2**. The amount of load to be shed in each step is 10% of total system load. This is because large turbine-generators of the system are not rated for continuous operation below 59.4 Hz. A load shedding program starting at 59.4 Hz would be more effective in minimizing the depth of the under frequency for the large disturbance and the first shedding frequency should not be too close to the normal frequency [6].

If the frequency is still below 59.4 Hz even after the three steps of under frequency load shedding have occurred, all appropriate areas shall coordinate additional manual load shed amounts with their transmission operator or balancing authority. If frequency continues to decline below 58.2 Hz, transmission operator or balancing authority shall take any necessary action to arrest the frequency decline except the opening of transmission tie lines.

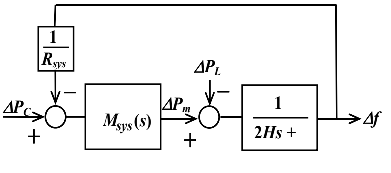

Figure 1. Simplified frequency response model.

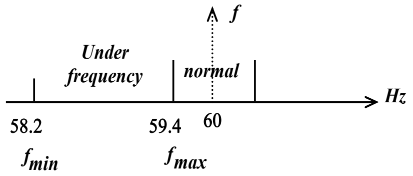

Figure 2. Frequency operating range.

2.3. Total of Load Shed

In a load shedding scheme, total amount of load shed can be considered as

$$P_{LS} = -(\Delta P_D - \Delta P_{L,reserve}) \tag{10}$$

Where, ΔP_D is the load disturbance and $\Delta P_{L,reserve}$ is the reserve (secondary control reserve) capacity of the system with maximum allowable change of frequency 0.6 Hz as mentioned in Subsection 2.2 [7].

From (8), the relation between $\Delta f(t)$ and ΔP_L can be represented as

$$\Delta f(t) = \left[\frac{-1}{D} + \left(\frac{2H}{D^2} \right) e^{-\frac{t}{\left(\frac{2H}{D}\right)}} \right] \times \Delta P_L \tag{11}$$

2.4. Control Area Load Shedding

A control area is an electrical system bounded by interconnected (tie-line) to control generation for maintaining power interchange schedule and contributing to frequency regulation [8]. A significant decline in frequency may require the shedding of load in order to avoid widespread system outages and to minimize the risk of damage to equipment.

The three frequency threshold values (59.4 Hz, 58.8 Hz, and 58.2 Hz) are the same for all the sub-areas so that all entities would participate during a region-wide or multi-region load shedding. During planning we can determine the generation reliability of the power system. One of parameters for generation reliability is reserve margin (RM) which is defined as [9]

$$RM_N\% = \frac{Installed\ Capacity - Load}{Load} \tag{12}$$

where N is the number of sub-areas. The weight or contribution factor for the RM for each area can be obtained using (12). A new sequence for load shedding can be created by ranking the RM from the smallest to the largest.

$$\{RM_1, RM_2, \ldots, RM_N\} \tag{13}$$

The sub-area with RM_1 contributes the most to the system unreliability because of less RM. Negative value of the RM indicates negative reserve, or in other word. The load is greater than generation in that particular sub-area. For system stability the load shedding operation can be targeted, sequentially, starting from the sub-area with the least RM until the system frequency is stabilized to a new steady state condition.

3. Test Case

The study system is composed of four sub-areas connected to an external system. The configuration of the study system is shown in **Figure 3**. Area I and II are interconnected through a 500 kV tie-line. Area I consists of four sub-areas A–D. The sub-areas A–D have eight, five, seven, and three thermal units, respectively. So, external system is considered as Area II. The power system parameters are considered similar to the practical system, which is described in detail in [10-12].

4. Results and Discussion

Table 1 shows the system parameters for four sub-areas connected to an external system. It is observed that sub-area C has the highest value of D and H (*i.e.* $D = 0.0576$ and $H = 0.384$ respectively) which implies that it has the highest stability margin in comparison to other sub-areas.

With the given parameters of generation and load, the RM for all the sub-areas can be calculated by using Equation (12) and displayed in **Table 2**. As seen in the table, sub-areas A and C have the lowest (RM = –42) and the highest (RM = 284.85) RM value respectively.

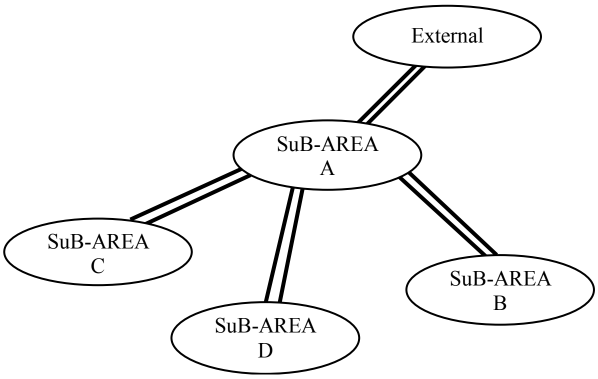

Figure 3. Two control area power system.

Table 1. System parameters.

System Parameter	Sub-area A	Sub-area B	Sub-area C	Sub-area D
D (Load Damping factor)	0.0352	0.02	0.0576	0.0352
H (System Inertia)	0.2347	0.133	0.384	0.2347

Table 2. Generation and load parameters.

	Sub-area A	Sub-area B	Sub-area C	Sub-area D
Load (pu)	0.6269	0.2388	0.1492	0.4776
Generation(pu)	0.362	0.2537	0.5742	0.3026
Reserve margin (%)	–42	6.24	284.85	–36.64

The maximum reserved power available in Area I is 1500 MW (10% of peak load demand). For load shedding scheme we consider two cases of extreme test scenarios *i.e.* a large load disturbance of 3000 MW in sub-area A and C. The total area load demand is much higher than the reserved power, whilst the primary and supplementary controls cannot maintain the frequency at the nominal value. Under this condition the system is under emergency condition and the UFLS scheme should be implemented to recover the system frequency.

4.1. Disturbance at Sub-Area A

As seen in **Table 2**, sub-area A has the least RM and therefore a large load disturbance of 0.3 pu occurred and the implementations of UFLS are considered in the same area. **Figure 4** shows the amount of load shed, the frequency deviation and frequency gradient in all the sub-areas. In the **Figure 4(a)**, only one step load shedding (10% of the load) was implemented. It is sufficient enough to bring the system frequency back to the near normal allowable region as in **Figure 4(b)**. **Figure 4(c)** shows the detection of frequency gradient in emergency condition.

Figure 5 shows the tie line and trunk line power flows under the test condition. Furthermore, it may also be noted that the trunk line power flows into sub-area A except for sub-area D, which actually imports power from sub-area A.

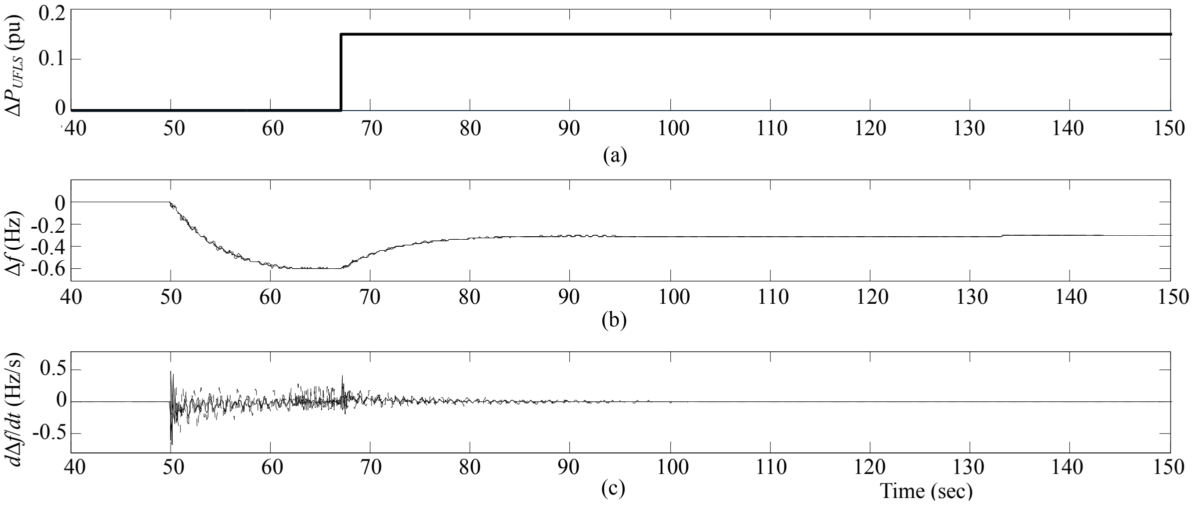

Figure 4. Load shedding plan in sub-area A, frequency deviation and frequency gradient in all sub-areas of Area I respectively.

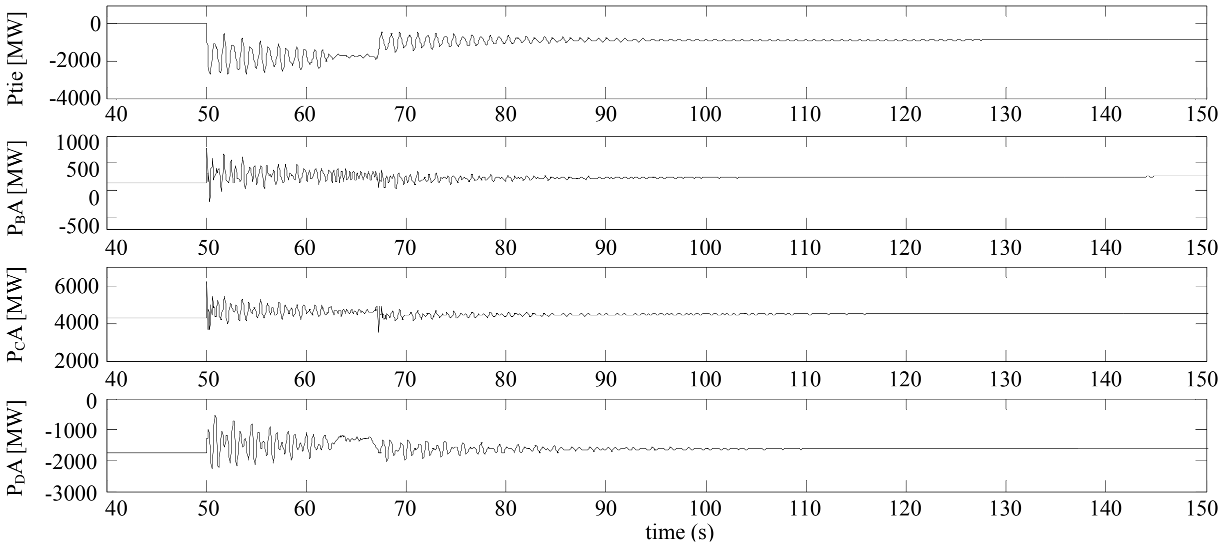

Figure 5. Tie line and trunk power fluctuation load change in sub-area A.

4.2. Disturbance at Sub-Area C

A large load disturbance of 0.3 pu is considered. Since sub-area C has the highest system parameters and RM, the load shedding does not implement in the same area. Instead, load shedding was implemented in some other area. Due to low RMs and identical system parameters, load could be shed in either sub-area A or D. **Figure 6** shows the amount of load shed, the frequency deviation and frequency gradient in all the sub-areas. As seen in **Figure 6(a)**, one step load shedding is implemented at sub-area D. Since sub-area D imports power from A, it is better to shed load in D. It is sufficient enough to bring the system frequency back to the near normal allowable region in **Figure 6(b)**. The detection of frequency gradient in emergency condition is shown in **Figure 6(c)**.

Figure 7 shows the tie line and trunk line power flows under the test condition to support **Figure 6**. Usually

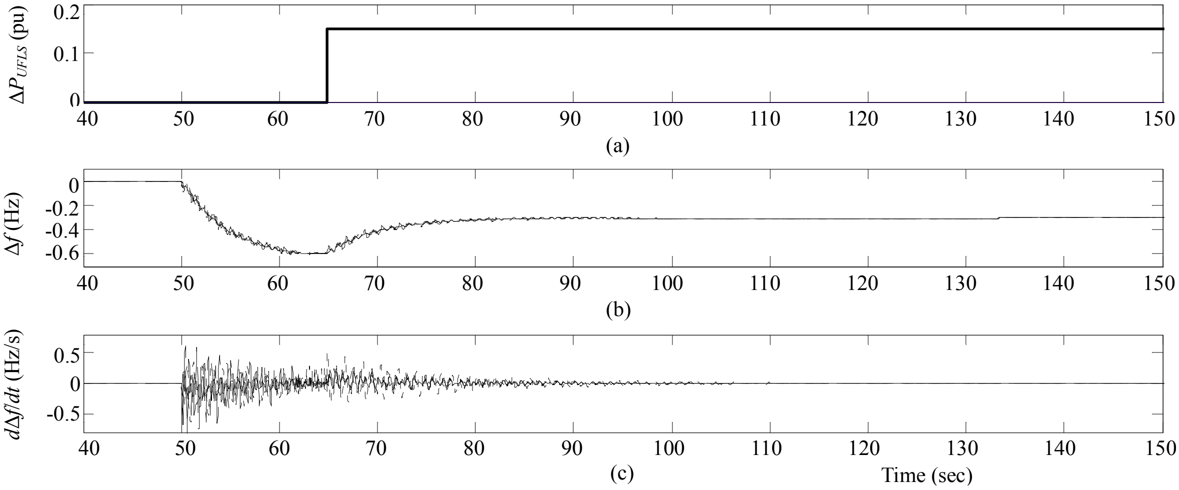

Figure 6. Load shedding plan in sub-area D, frequency deviation and frequency gradient in all sub-areas of Area I respectively.

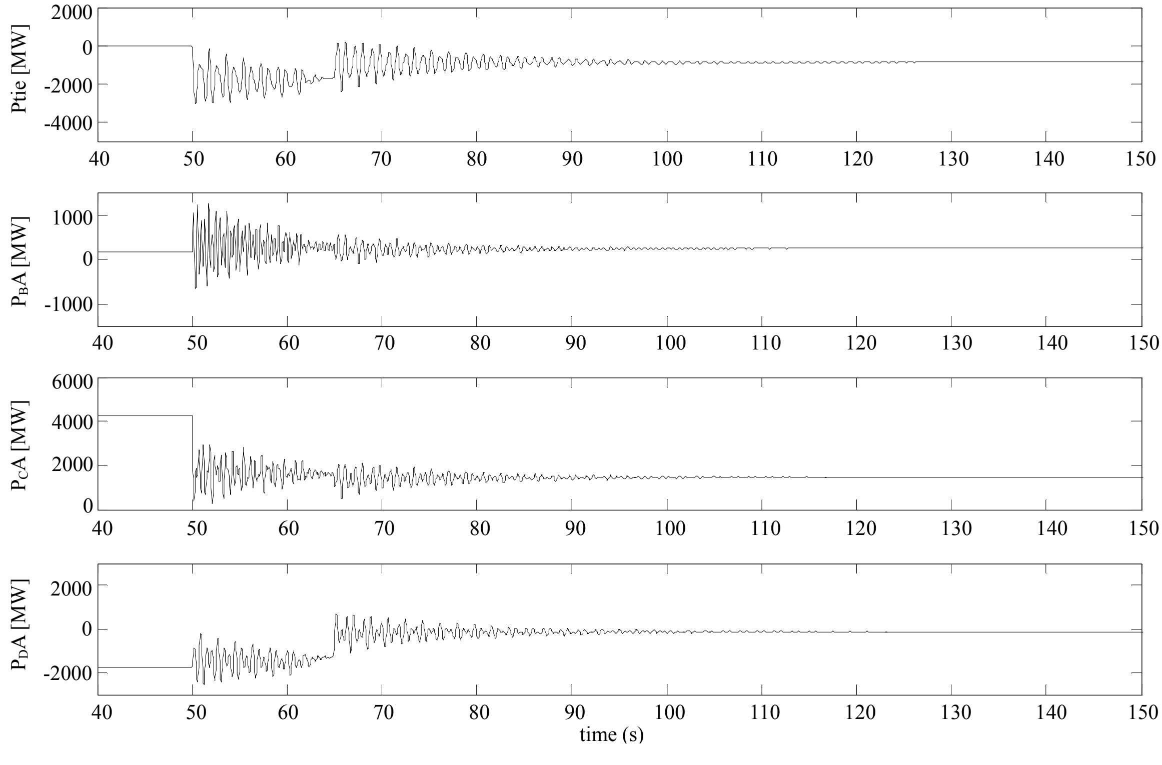

Figure 7. Tie line and trunk power fluctuation load change in sub-area C.

sub-area C will transfer power to sub-area A before the disturbance took place. But, in this case, 0.3 pu disturbance is manageable to load-generation imbalance (generation is greater than load) as discussed in **Table 2**. So, sub-area C reduced power transfer to sub-area A after the disturbance. Consequently sub-area A reduced power transfer to sub-area D. Hence, **Figure 7** is the evidence of the amounts of power transfer from sub-area C to A and sub-area A to D in a drastic reduction manner.

5. Conclusions

Regional coordination in emergency conditions is very important for power system operation and security. These regions are interconnected to each other for improving reliability and reducing cost. Practically, each region has different generation and load. This condition will affect reserve margin. The reserve margin is used to identify a sequential load shedding. This paper shows that regional coordination for four sub-areas connected to an external system using adaptive under frequency load shedding is feasible.

6. Acknowledgements

The authors would like to thank Graduate School of Science and Technology (GSST), Kumamoto University, Japan and MARA University of Technology (UiTM), Malaysia for continuous support of this research.

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