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Study on Underfrequency Load Shedding Based on Power Partition

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Abstract: Underfrequency load shedding is the last defensive line to maintain the safe operation of power system. Frequency stability refers to the ability of a power system to maintain frequency stability following a severe system disturbance. This results in a significant power imbalance between generation and load. The new method presented in this paper assumes the application of WAMS(wide area measurement system, WAMS) as a base for this successful implementation. Two-area system's frequency response model is studied. Power partition is significant to load shedding scheme under emergency situation. An adaptive load shedding method is designed based on this idea. This may make new method more suitable to interconnected multi-area power system. The simulation result show the analysis of two-area frequency response model is accurate and new load shedding method is more effective.

Key words: Frequency stability, active power balance, two-area system model, underfrequency load shedding (UFLS), power partition

INTRODUCTION

Intrusion Frequency stability refers to the ability of a power system to maintain steady frequency following a severe system upset resulting in a significant imbalance between generation and load. When a power system encounters a serious disturbance or a large generator unit trip, the balance between power generating and load demand may be broken. If load power consumption is greater than generation power, the system frequency should decrease significantly, even leading to system frequency collapse. Load shedding is an effectively solution to restore system frequency stability.

A tendency exists in maximizing the efficiency of the load shedding control and bringing its operation to the limits. (Anderson and Mirheydar, 1990) try to establish more accurate frequency response model to achieve exact algorithms and want to design the more effective load-shedding scheme, to improve the response speed and accuracy of the control. Aik (2006) adds a load restoration block. The load can repower in a short time after the frequency is normal. (Hirodontis *et al*., 2009) considers the characteristics of micro grid, proposing a scheme adapting to micro grid. (Shokooh *et al*., 2005) defines an intelligent load shedding system, and demonstrates the need for a modern load shedding scheme.

All the mentioned literatures (Chang *et al*., 2010; Grewal *et al*., 1998; He *et al*., 2010; Seyedi and Sanaye-Pasand, 2009; Shen *et al*., 2011) previously based on the single partition system that is equivalent to a single generator system. When the disturbance occurs, the system affected by the load shedding control may be a subsystem consisting of multiple partitions. The load shedding scheme based on single partition is not very appropriate; the load shedding result may not be very satisfactory. More seriously, inappropriate action may cause power flow transfer, leading to further splitting and a large-scale blackout. In this case, multi-area frequency response characteristics are different. The coordination between the various partitions' load shedding control should be considered.

This paper discusses the two-area system's frequency response model. Studies have shown that the frequency has significant spatial distribution characteristic. How to divide power partition is discussed and used. Power correlation degree is advised and analyzed. Load shedding scheme based on this model allows for selecting the suitable location where load to be shed. This advantage makes the control achieve a quick and better effect on recovering system stability.

TWO-AREA INTERCONNECTION MODEL FREQUENCY RESPONSE ANALYSIS

To simplify the analysis, without loss of generality two-area system is equivalent to a two-generator system (Fig.1). Analyzing the frequency dynamics process of the system after power disturbances emerge, establish a two-

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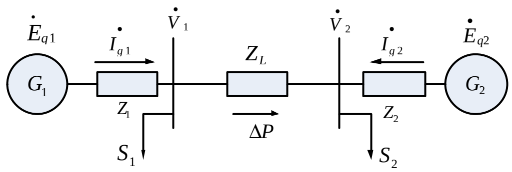

Fig. 1: Two-area equivalent power system model

area system's frequency response model (Wang *et al*., 2010; Zhao *et al*., 2010).

Without considering the governor, the equationof singlegenerator rotor motionas follows:

$$\begin{cases} \dfrac{d\Delta\delta_i}{dt} = \omega_0\Delta\omega_i \\ M_i\dfrac{d\Delta\omega_i}{dt} = \Delta P_{mi0} - \Delta P_{Ei} - K_{Li}\Delta\omega_i \end{cases} \tag{1}$$

Where:

Δp_{mio} : Is the prime mover mechanical power increment;
ΔP_{Ei} : Is the generator electromagnetic power increment;
K_L : Is load frequency regulation coefficient.

The network equation of this system as follow:

$$\begin{bmatrix} \dot{I}_{G1} \\ \dot{I}_{G2} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} Y_1 & 0 & -Y_1 & 0 \\ 0 & Y_2 & 0 & -Y_2 \\ -Y_1 & 0 & Y_1 + Y_L + Y_{D1} & -Y_L \\ 0 & -Y_2 & -Y_L & Y_2 + Y_L + Y_{D2} \end{bmatrix} \begin{bmatrix} \dot{E}_{q1} \\ \dot{E}_{q2} \\ \dot{V}_1 \\ \dot{V}_2 \end{bmatrix} \tag{2}$$

The generator's power output:

$$\begin{aligned} \bar{S}_i = \bar{V}_i \bar{I}_i^* &= E_{qi}\angle\delta_i \sum_{j=1}^{n} Y_{ij}E_{qj}\angle(-\delta_j - \alpha) \\ &= E_{Gi}\left\{\sum_{j=1}^{n}[Y_{ij}E_{Gj}\cos(\delta_{ij} - \alpha) \right. \\ &\quad \left. + jY_{ij}E_{Gj}\sin(\delta_{ij} - \alpha)]\right\} \end{aligned} \tag{3}$$

Eliminate the load nodes:

$$\begin{cases} P_{Gi} = E_{Gi}\sum_{j=1}^{n} Y_{ij}E_{Gj}\cos(\delta_{ij} - \alpha) \\ Q_{Gi} = E_{Gi}\sum_{j=1}^{n} Y_{ij}E_{Gj}\sin(\delta_{ij} - \alpha) \end{cases} \tag{4}$$

$$\begin{cases} P_{G1} = E_{q1}{}^2G_{11} + E_{q1}E_{q2}|Y_{12}|\cos(\delta_{12} - \alpha) \\ Q_{Gi} = -E_{q1}{}^2B_{11} - E_{q1}E_{q2}|Y_{12}|\sin(\delta_{12} - \alpha) \end{cases} \tag{5}$$

$$\begin{cases} P_{G2} = E_{q2}{}^2G_{22} + E_{q1}E_{q2}|Y_{12}|\cos(\delta_{12} + \alpha) \\ Q_{G2} = -E_{q2}{}^2B_{22} - E_{q1}E_{q2}|Y_{12}|\sin(\delta_{12} + \alpha) \end{cases} \tag{6}$$

Where, δ_{12} is the phase angle difference between G_1 and G_2, Y_{12} is the mutual admittance between G_1 and G_2, α is the argument of Y_{12}, $G_{11} + jB_{11}$ is the self-admittance of G_1. $G_{22} + jB_{22}$ is the self-admittance of G_2. With the small signal model, representing the prime mover disturbance:

$$\begin{cases} \Delta P_{G1} = K_{11}\Delta\delta_1 + K_{12}\Delta\delta_2 \\ \Delta P_{G2} = K_{21}\Delta\delta_1 + K_{22}\Delta\delta_2 \end{cases} \tag{7}$$

Where, $K_{11} = \partial P_{G1}/\partial\delta_1$, $K_{12} = \partial P_{G1}/\partial\delta_2$, $K_{21} = \partial PG_2/\partial\delta_1$, $K_{22} = \partial P_{G2}/\partial\delta_2$ and $K_{11} = -K_{12}$, $K_{22} = -K_{21}$. Solving simultaneous equations (1), (5), (6) and (7), eliminate $\Delta\delta_1$ and $\Delta\delta_2$ with Laplace transform:

$$\begin{cases} \Delta w_1(s) = \dfrac{M_{22}\Delta P_{m10} - M_{12}\Delta P_{m20}}{M(s)} \\ \Delta w_2(s) = \dfrac{M_{11}\Delta P_{m20} - M_{21}\Delta P_{m10}}{M(s)} \end{cases} \tag{8}$$

Where, $M_{11} = M_1s^2 + K_{L1}s + \omega_0K_{11}$, $M_{12} = \omega_0K_{12}$, $M_{22} = M_2s^2 + K_{L2}s + \omega_0K_{22}$. $M_{21} = \omega_0K_{21}$, $M(s) = M_{11}M_{22}-M_{12}M_{21}$. The system frequency represent as follow:

$$\begin{aligned} \Delta w_{sys}(s) &= \frac{\sum_{i=1}^{2} M_i\Delta\omega_i(s)}{\sum_{i=1}^{2} M_i} = \frac{M_1\Delta\omega_1(s) + M_2\Delta\omega_2(s)}{M_1 + M_2} \\ &= \frac{(M_1M_{22} - M_2M_{21})\Delta P_{m10} + (M_2M_{11} - M_1M_{12})\Delta P_{m20}}{(M_1 + M_2)M(s)} \end{aligned} \tag{9}$$

The initial change rate of generator frequency and system frequency can be obtained using the Laplace transform and initial value theorem:

$$\begin{cases} \dfrac{d\Delta\omega_1}{dt}\Big|_{t=0} = \lim\limits_{s\to\infty} s^2\Delta\omega_1(s) = \dfrac{\Delta P_{m10}}{M_1} \\ \dfrac{d\Delta\omega_2}{dt}\Big|_{t=0} = \lim\limits_{s\to\infty} s^2\Delta\omega_2(s) = \dfrac{\Delta P_{m20}}{M_2} \\ \dfrac{d\Delta\omega_{sys}}{dt}\Big|_{t=0} = \lim\limits_{s\to\infty} s^2\Delta\omega_{sys}(s) = \dfrac{\Delta P_{m10} + \Delta P_{m20}}{M_1 + M_2} \end{cases} \tag{10}$$

The steady state frequency can be obtained using the Laplace transform final value theorem:

$$\begin{cases} \Delta\omega_1(\infty) = \lim_{s\to 0} s\Delta\omega_1(s) = \dfrac{k_{22}\Delta P_{m10} - k_{12}\Delta P_{m20}}{k_{11}k_{L2} + k_{22}k_{L1}} \\ \Delta\omega_2(\infty) = \lim_{s\to 0} s\Delta\omega_2(s) = \dfrac{k_{11}\Delta P_{m20} - k_{21}\Delta P_{m10}}{k_{11}k_{L2} + k_{22}k_{L1}} \\ \Delta\omega_{sys}(\infty) = \lim_{s\to 0} s\Delta\omega_2(s) = \dfrac{k_{22}\Delta P_{m10} - k_{11}\Delta P_{m20}}{k_{11}k_{L2} + k_{22}k_{L1}} \end{cases} \quad (11)$$

Analyzing those equations, the result can be obtained. Due to $k_{11} = -k_{12}$, $k_{22} = -k_{21}$, all the steady state frequency is equal to $\Delta w_1(\infty) = \Delta w_2(\infty) = \Delta w_{sys}(\infty)$.

- When the generator G_1 encounters power mutation, the magnitude is ΔP, that $\Delta P_{m10} = \Delta P$, $\Delta p_{m20} = 0$. Substituting into the equation, the initial frequency change rate of G_1 is $\Delta P/M_1$ and the frequency change rate of G_2 is 0. And, $\Delta w_1(s) = (M_{22}\ \Delta P_{m10})/M(s)$, $\Delta w_2(s) = (-M_{21}\ \Delta P_{m10})/M(s)$. This shows the differences of frequency change process between two generators. Finally, the two generators frequency will both stabilize to $k_{22}\ \Delta P/(k_{11}k_{L2} + k_{22}K_{L1})$.
- When the generator G_2 encounters power mutation, the magnitude is ΔP, that $\Delta P_{m20} = \Delta P$, $\Delta P_{m10} = 0$. Substituting into the equation, the initial frequency change rate of G_2 is $\Delta P/M_2$ and the frequency change rate of G_1 is 0. And, $\Delta w_1(s) = (-M_{12}\Delta P_{m20})/M(s)$, $\Delta w_2(s) = (M_{11}\Delta P_{m20})/M(s)$. This shows the differences of frequency change process between two generators. Finally, the frequency of two generators will both stabilize to $k_{11}\Delta P / (k_{11}k_{L2} + k_{22}k_{L1})$.
- When the disturbances are occurring simultaneously on two generators, the system dynamic process is single disturbance superposition. Two-area system's conclusion can apply to multiple generators' systems. When units have disturbances, influence only on the initial frequency variation about disturbed generator. Disturbance quantity is proportionate to the rate of frequency; after different frequency variation process, ultimately each unit stabilizes to the same frequency value.

AN NEW ADAPTIVE UFLS SCHEME

Based on the above analysis an adaptive UFLS scheme is advised. It can be divided into preparation stage and action stage.

Preparation stage: Their main task is to determine the division of power associated partition by using network topology analysis and steady state calculation with wide-area real time information.

Power associated partitions include some generator nodes and load nodes, which has direct power relationship. The system is divided into several partitions by power correlation. Once the decision center confirms the location of disturbance, the center can choose the optimal load shedding point of the partition quickly.

The center gets the wide-area information, calculating the frequency (f) and change rate of frequency (df/dt) and upload the local information to decision center. If there is any partition's frequency change rate is greater than setting value, the process enters action stage.

Action stage: When the process enters this stage, it shows that the system has encountered a big disturbance. The system is not inevitable unstable and the system need corresponding control schemes' action. Operating partition is selected according to the initial frequency change rate. The frequency response model shows the relationship between initial frequency change rate and disturbance location. Calculate the frequency and its rate by using rotor motion equation. Determine whether needing neighbor partitions assistance or not. Rank load-shedding node, assigning the amount of load shedding, forming load-shedding plan. If the frequency of the selected partition is lower than the threshold, decision center sends out signal to drop load.

SIMULATION AND VERIFICATION

Kunder's four generators two-area system is used to test and verify theoretical analysis and load shedding scheme is designed in this section.

According to the network topology and the tidal current calculation results, the power associated division search is processed. Generator G_1, G_2 are equivalent to a generator. and G_3, G_4 are equivalent to another generator. Considering G_1, G_2 as starting point and searching all load nodes, L_1's 967 MW active power is all supplied by starting point generator power. So L_1's power correlation degree is 1 with generator G_1 and G_2. Down the tidal current direction, searching in depth, L_2's 1767MW active power of which 413MW is supplied by the starting point equivalent generator. So L_2's power correlation degree is 413/1767(0.234) with generator G_1 and G_2.

Similarly, L_2's power correlation degree is 1354/1767(0.766) with generator G_3 and G_4. Search ends when the trend of the path is opposite to the direction of the search direction.

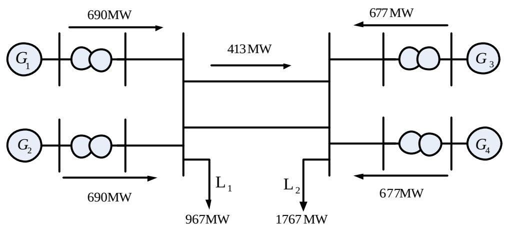

Fig. 2: Four generators two-area power system

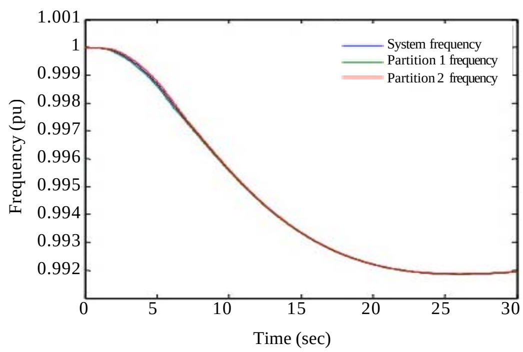

Fig. 3: All partition's generators system frequency response

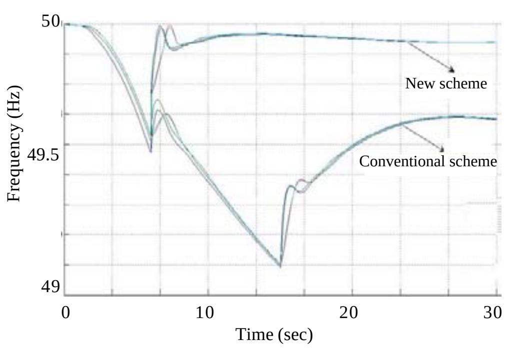

Fig. 4: The system frequency response when drop the load using two different schemes

The division's result is two areas. Partition 1 consists of generator G_1 and G_2 and load L_1 and L_2.L_1's power correlation is 1; L_2's power correlation is 413/1767(0.234). Partition 2 consists of generator G_3, G_4 and load L_2. L_2's power relational grade is 0.766.

Figure 3 shows the system frequency response of two partitions. When disturbance power (ΔP = 75MW) occurs at generator $1^{\#}$.

System frequency stabilizes to the same value at last. It is thus clear that system is unstable. Load shedding

Table 1: Traditional algorithm parameters

Action rounds	Frequency threshold value	Shedding quantity
1	49.5Hz	5%
2	49Hz	5%
3	48.5Hz	5%
4	48Hz	5%
5	47.5Hz	5%

Table 2: General disturbance parameters contrast

Evaluationcriterion	Traditional scheme	New scheme
General load shedding quantity	70MW	63MW
Action rounds	2	1
Stability frequency	49.7Hz	49.83Hz
Stability time	23s	13s

scheme should be adopted to recover system power balance. Traditional load shedding scheme is just like Table 1. New scheme will drop load according to power partition.

Figure 4 shows the different frequency response when drop the load using conventional method and new scheme. System frequency can regain stability more quick by new scheme. System frequency response effect situation is just like as Table 2.

Traditional schemes adopt gradually approximation way, the appropriate shedding quantity is difficult to get; if the disturbance is more than the first round, frequency will continue to fall. Other rounds exist in the same question. After many rounds of load shedding, system frequency may rise finally. This will lead to drop load much more or less and can't meet system's request. The new plan is to take an optimum method because of the quantity of dropping load is calculated reasonably. This may acquire a better effect on system stability.

CONCLUSIONS

In this paper, two-area system equitable model is studied. System frequency response is displayed about it after a power system sufferspower disturbances. The result shows the change of frequency has space distribution characteristic. System power partitions are very significant to multi-generator system.Based on the model, an adaptive under frequency load shedding method is studied. The simulation result shows the frequency response model analysis is accurate. New adaptive load shedding scheme is better than traditional method in response speed and control performance.

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