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The Demand Response and UPFC Coordinated Frequency Control Strategy

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Abstract. In order to improve the stability of the power system, suppressing the low frequency oscillation of power system is already a problem that every country is eager to solve. Many power workers have done a lot of theoretical research and experimental verification on low-frequency oscillation and have got remarkable achievements. Energy from the Demand Side has been widely used in our daily life, and thousands of demand response loads have been used in frequency control whose controlling effects are quite obvious; meanwhile, because of the development of electrical technology, many smart grid devices can be fully used, and they have improved the stability of power system, which is consistent with the original intention of putting demand response loads into power system. UPFC can improve the system damping, and effectively suppress the low-frequency oscillation of the system as well as improve the stability of the power angle, so if UPFC and demand response are combined, the low frequency oscillation of the power system can be better suppressed.

1. Introduction

Demand response can provide added damping in oscillation control without bringing in any energy consumption, so it is environment and economy-friendly and more consistent with the socialist modernization construction; at the same time, with some time prolonged processes being eliminated, demand response control can be easier and sound than traditional control measures. In the stable aspect of power system, the Unified Power Flow Controller (UPFC) can achieve fast efficient adjustment to current, rational control to active and reactive power flow, improvement of circuit delivery capacity and optimization of the overall operation; in the dynamic aspect, it can dynamically support the voltage of the access points, and improve the general voltage stability through quick reactive compensation technology.

2. Controlling Methods and Mechanism of Demand Response

As the research system will be affected by small disturbances, the variation of variables can be seen as putting a small deviation to the original process. The variables can be:

\begin{equation}
T_d \frac{d\Delta E_q^*}{dt} = E_{qe} - \Delta E_q^* + \Delta I_d (x_d - x_d')
\end{equation}

\begin{equation}
\frac{d\Delta \delta}{dt} = \Delta w v_c
\end{equation}

\begin{equation}
T_e \frac{d\Delta w}{dt} = \Delta P_e - \Delta P_e' - D\Delta w
\end{equation}
The above equation should be the linear differential equation of synchronous generator.

Demand Response loads engaged in the low frequency oscillation of power system can be separated into two categories according to their characteristics. The first category is equipment that can not only change the state of switches but also continually adjust the amount of loads engaged in the power system, and the other category can only change the state of switches[1].

**Figure 1.** Frequency regulation characteristics of demand response loads

When a controller detects that the deviation $\Delta f$ is lower than $\Delta f_{th}$, the controller will disconnect the load so as to restore the electric frequency to a stable level. In order to prevent the negative impact of the instant disconnection of many loads and stagger the turn-off time, $\Delta f_{th}$ should be set to every engaged load. The current domestic and overseas solutions are mostly adopt instant measures to the $\Delta f_{th}$ of every equipment. While because of the $\Delta f_{th}$ of different equipment may influence the controlling effect directly, it is obvious that such measures are unsuitable[2].

Taking the frequency deviation caused by the active power deficiency as example, the amount of PDR that needs to be closed should be set as:

$$P_{DR} = \begin{cases} -P_{DRm} & \text{If } \Delta f > \Delta f_{\text{max}} \\ -k_{DR} \Delta f & \text{If } -\Delta f_{\text{max}} \leq \Delta f \leq \Delta f_{\text{max}} \\ P_{DRm} & \text{If } \Delta f < -\Delta f_{\text{max}} \end{cases} \quad (2)$$

$\Delta f_{\text{max}}$ is the maximum frequency deviation provided by engaged demand response loads; $P_{\text{total}}$ is the total load engaged in the controlling system, and the coefficient $k_{DR}$ should be:

$$k_{DR} = - \frac{P_{DRm}}{\Delta f_{\text{prm}}} \quad (3)$$

### 3. Design for Coordination Control of Demand Response and UPFC

The function of auxiliary controller is to increase system damping and suppress low-frequency oscillations by improving the control strategy of UPFC. Based on the damping characteristics introduced in the last chapter and the principle of power system stabilizer, the UPFC auxiliary controller shown in the Figure 1 is designed. Taking the line current I as reference direction, the voltage of series side is decomposed into 2 vectors $V_p$ and $V_q$, the former one is parallel to I and the latter one is vertical to I. Then the active power and reactive power of the series side can be expressed as $IV_p$ and $IV_q$ [3], which are adjusted by changing $V_p$ and $V_q$ to carry out line power. $T_w$ in Figure 2 is a DC blocking time constant, $T_1$ and $T_3$ are time constants of lead compensation, and $T_2$
and $T_4$ are constants of lag compensation. This auxiliary controller adopts proportional control, taking the oscillation frequency of system $\Delta \omega$ as input. It outputs the control signal after passing the DC blocking section and amplitude limiting unit, which is similar to the control of PSS [4].

\[
\Delta \omega \xrightarrow{\frac{T_{ss}}{1 + T_{ad}}} K \xrightarrow{1 + T_1 + T_3} \xrightarrow{1 + T_2 + T_3} v_p^0 \xrightarrow{1 + T_1 + T_3} v_p
\]

**Figure 2.** UPFC auxiliary controller block

$V_p$: This variable is the vector of the series voltage $V_s$, which is in phase with line current. In a steady state, input $V_p^0$ is set as zero, making the active power interchange between UPFC and alternating current system only occurs when this variable is regulated by POD controller (during the transient period)[5].

### 4. Analysis of Examples

#### 4.1. Single-machine infinite-bus system

As the Figure 3 shows, what is different from the single-machine infinite-bus system model is that the load $ab$ is equipped with UPFC, and UPFC is combined with demand response to suppress the low-frequency of the electrical power system. To increase additional damping, parameters including PDR, the amplification factor $K_w$ and constants of compensation time $T_1$ and $T_3$ should be optimized (set $T_2 = T_4 = 0.05s$)[6].

**Figure 4.** Simulation results of demand response with different capacities

Figure 4 shows the system eigenvalues with different numbers of demand response resources in the single-machine infinite system, and it suggests that higher quantities of demand response resources can provide more damping for the system.

In the following part, it will illustrate the influence that different values of the gain parameter $K_w$ have on the low-frequency oscillation suppression effects in the electrical power system.

From the Figure 5, it can be inferred that, the value of $K_w$ can affect the suppression effect to a great extent, when the demand response reaches a certain size (30% of the total load). In the process of the five experiments, when $K_w$ is 0.6, the suppression effect is the best and the suppression of the low-frequency oscillation in power system takes the shortest time.
The power flow from node A to node B (MW) -0.2

The following part will discuss the suppression effect that the time advance constant T1 and the time delay constant T3 bring to the low-frequency oscillation in power system [7].

It can be inferred that, from Figure 6, different time parameters cause the difference of suppression effects, which is not very obvious. The additional damping is the most obvious only when T1 and T3 are about 0.5s.

Although many sets of data should be measured to optimize parameters, this paper does not list every set of data but adopts the three-dimensional Figure 7 to show the relationship between different Kω values and damping ratios because of the limited space.

According to the data mentioned above, set the objective function and get the PDR varying in the range of 200MW-1000MW, UPFC operation gain parameter Kω varying in the range of -3-3 and time parameters T1 and T3 varying in the range of 0.01s – 0.1s. This objective function, which is in the single-machine infinite bus system, reflects the coordination of demand response and UPFC to suppress low-frequency oscillation effect. The control variables are demand response, the gain parameter of UPFC controller Kω, time advance constant T1 and time delay constant T3.

The objective function: \( f = \lambda_1 \sigma + \lambda_2 \xi \).

After 100 iterations, the result is that \( f_{\text{val}} = -0.3243 \), when \( K\omega = 0.3846 \), PDR=645.6097kw, T1=0.0562s and T3=0.0643s.

4.2 The Two-area and Four-machine Power System

According to the report about LFC at home and abroad, the LFO of the tie line between two interconnected power systems with the lowest frequency of about 0.2–0.7Hz is called inter-area low frequency oscillation; the LFO between different power plants in the same area with the frequency of
about 1Hz is called regional low frequency oscillation; the LFO between different units in the same power plant with the highest frequency of about 1.5~2.5Hz is called in-plant low frequency oscillation[8]. The Two-area and Four-machine Power System is shown in Figure 8.

Figure 8. The Two-area and Four-machine Power System Model Engaged in Low Frequency Oscillation Suppression with UPFC

Figure 9. The Simulation Results under Demand Response with Different Capacities

Figure 9 shows the single machine infinite bus system eigenvalues under different numbers of available resources of demand response in the two-area and four-machine power system. It shows that a high quantity of demand response resources can be used to provide more damping for the system, and the demand response of the same quantity can produce different suppression effects because of the different locations of the two nodes. Next, the effect of various gain parameters Kw on the low frequency oscillation suppression under the two-area and four-machine power system will be discussed.

Figure 10. The Simulation Results under Different Gains

Figure 10 shows that if the demand response reaches a specific size (22% of the total load), the change of Kw value will largely influences the suppression effect. In the 5 experiments, when the Kw value is -0.5, the suppression effect is the best and the time of low frequency oscillation suppression of the power system is the shortest. When the Kw value is over 0.5, the real part of eigenvalue of equation of motion in the electronic system is positive and the damping ratio is negative, so the system is no longer stable.

Then, the suppression effect of the values of time-advance parameter T1 and time–delay parameter T3 on the low frequency oscillation of the power system will be discussed.

Figure 11 shows that different time parameters will affect the suppression effect. But the change is not obvious and only when the values of T1 and T3 are around 0.05s, the additional damping is the most obvious.

The parameters should be optimized, so it is necessary to measure and obtain multiple sets of data. For lack of space, the data will not be listed. Figure 12 is the three-dimensional Fig about the relation among damping ratio, different Kw values and PDR.
the power flow between Node 7 and Node 8 (MW)

Figure 11. Simulation Results with Different Time Parameters

Figure 12. The relationship between different Kw values and damping ratios

The objective function: \( \min f = \lambda_1 \sigma + \lambda_2 \psi \)

After 100 iterations, obtain \( f_{\text{val}} = -0.3243 \) when \( Kw=0.3846, \ PDR=645.6097 \text{kw}, \ T1=0.0562 \text{s}, \ T3=0.0643 \).

5. Conclusion
The control strategy design about the coordination of demand response and UPFC to suppress low frequency oscillation
Finally, optimize related control parameters of the coordinated control system containing demand response and UPFC by using the genetic algorithm and obtain the optimal control parameter, being the optimal strategy for the coordination of demand response and UPFC to control low frequency oscillation in the power system.

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