Determining Operating Reserve Requirement in a Competitive Market Using Dynamic Approach

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***Abstract*—Operating reserve is essential for system operator to maintain reliable operation of power system in real time. Traditionally, static approaches are used to establish the required capacity for operating reserves. A novel method is suggested in this paper by considering interrelation between secondary, tertiary reserve and load shedding to determine operating reserve requirement. The first part of this paper explains the basic concept of frequency control. Then new method to determine operating reserve requirement is supposed with consideration of interrelationship among different reserves under a simultaneous co-optimization scheme of various ancillary services.**

***Index Terms*—operating reserve, reserve requirement, primary control, secondary control, tertiary control, simultaneous scheme**

I. INTRODUCTION

Balancing between the power generation and demand is very important aspect in power system operation. Disturbances in the power network cause frequency deviations from a reference value and threat reliability and security. Therefore, system operators are required to maintain sufficient operating reserve to cover [1], [2].

In electricity markets, the amount of operating reserve required capacity is determined by static method that consider operating reserve exceed the capacity of the largest generator in the network or certain rates of the predicted peak load. Even though this method is easy to understand, it cannot fully reflect overall economic feasibility [2], [3].

In this paper, we suggest flexible operating reserve model considering overall costs between capacity cost and delivered energy cost in operating reserve. Thus, the proper required capacity of operating reserve varied with costs between secondary and tertiary reserve.

II. FREQUENCY CONTROL IN POWER SYSTEM

This chapter provides a general description of frequency control system. Frequency control action is required to maintain severe imbalance between load and generation. If large load (or generation) is suddenly increased (or decreased), there will be long term power imbalance between generation and load. This imbalance is firstly removed by the kinetic energy from rotating rotors of generators, turbines, and motors, consequently, the system frequency will change [3]-[5].

A. Primary Frequency Control

The primary frequency control is operated by frequency governors in power plants within synchronous control areas. The primary control is implemented on a local level. The turbine governors adjust the generating units' output in the proportion to changes in frequency [5].

$$\frac{\Delta P_G}{P_{GN}} = -\frac{1}{S_G}\frac{\Delta f}{f_0} = -K_G\frac{\Delta f}{f_n} \qquad (1)$$

where:

ΔP_G : Change of power generator output (MW)

P_{GN} : Generator output (MW)

S_G : Speed droop coefficient

Δf : Changes in frequency (Hz)

f_n : Nominal frequency (Hz)

$K_n = {}^{1}\!/_{S_G}$: The effective gain of the governing system

In the steady state, all the generating units are at same frequency in a synchronous area. The overall changes in total power can be calculated as the sum of changes of all participating generating units:

$$\Delta P_{im} = \Delta P_{GT} - \Delta P_L \qquad (2)$$

where:

ΔP_{im} : Power imbalance between load and generation in a synchronous area

In a short, changes of the demand are due to the frequency sensitivity of demand, but also, changes of generation are due to turbine governors. The governor action is referred to as primary (frequency) control.

Manuscript received May 1, 2015; revised December 25, 2015.

doi: 10.18178/ijoee.4.1.75-78

B. Secondary Frequency Control

If the demand is increased, the turbine speed drops before the governor can control the input of the steam to the increase of demand. As the change in the speed diminishes, the governor action arrives at the required point to maintain a constant speed [5]. However, there will be an offset between a constant speed and set-point speed. Therefore, after disturbance, a static frequency error will remain unless additional control actions are taken. Moreover, the primary control could also change the planed interchanges between different control areas in an interconnection system. The additional control action is conducted by the secondary frequency control. The secondary frequency control is referred as the Load Frequency Control (LFC). It can be done either manually or automatically, automatic LFC is known as the Automatic Generation Control (AGC). This control action generally is implemented as a decentralized control function in isolated power system. However, in an interconnected power system, there are many different control areas, secondary control cannot be decentralized because decentralized control does not share information about imbalance. Such decentralized control would cause unplanned changes in the power exchanges in tie-lines.

To avoid this undesired result, secondary control is activated as a type of centralized control. Each area operators covers power imbalance and maintain planned net tie-line exchanges. This is called as the nonintervention rule [6]-[8].

$$\Delta P_T = \Delta P_L - \Delta P_{Exchange} \quad (3)$$

where:

ΔP_T : The total power generation (MW)

ΔP_T : The total power demand (MW)

$\Delta P_{Exchange}$: The net tie-line exchange power (MW)

The secondary control is executed by controlling the power output of generating units' turbine by changing reference output in governing system. A simple strategy of the secondary control is:

1) Keep the system frequency nearly at the nominal value (50Hz or 60Hz)
2) Maintain the scheduled tie line flow
3) Each area power imbalance should be covered by each area operator

Therefore, the control error for each area consists of a linear combination of the in-area power imbalance (frequency) and tie-line exchange error, which is referred as the Area Control Error (ACE) [4], [8]-[10].

C. Tertiary Frequency Control

The tertiary frequency control is not directly related to the balancing mechanism. The objective of this control is to restore the primary and secondary control reserves, to relieve transmission congestion, to bring the system frequency and the interchanges back to their target value. This control is usually manually activated to recover secondary control reserve after large incidents. Therefore, the tertiary control is supervisory to the secondary control within the synchronous area [7]-[9], [11].

III. METHOD USED TO OPERATING RESERVE REQUIREMENT

Operating reserve is important resource to response unpredicted generation outage, load fluctuation. In most practices and researches, the required capacity of operating reserve is pre-determined as the loss of largest power generation/consumption unit or the loss of line. The most commonly used method sets the required capacity of operating reserve as following equation [10].

$$R_d^t = \max(\mathrm{u}_i^t\ P_t^{\max}) \quad (4)$$

where:

R_d^t : Operating reserve requirement capacity period t

u_i^t : Status of unit i period t (1: on, 0: off)

This approach is to set the required capacity deterministically. On the other hand, the probabilistic method was suggested firstly by Anstine in 1963 [10]. The probability that load exceed generation is expressed as the following equation.

$$PLL = \sum_{Y=0}^{N} \Pr(\mathrm{C} \le \mathrm{Y}) \Pr(\mathrm{L} = \mathrm{Y}) \quad (5)$$

where:

PLL: The probability that load Y exceed planed generation C

Pr: The probability function

Probabilistic method can be considered as a unit commitment risk problem, which means that available capacity in the synchronous power system would be lower or equal than the system demand. The unit commitment risk could represent [10]-[12].

$$UC_{risk} = \Pr[\sum_{i=1}^{N_G} \left(P_i^t + R_i^t\right) + P_d^t] \quad (6)$$

where:

P_i^t : Power generation by unit i during period t

R_i^t : Operating Reserve by unit i during period t

P_d^t : The net tie-line exchange power (MW)

IV. PROPOSED APPROACH: OPERATING RESERVE BASED ON MARKET INTER-RELATION METHOD

A. Overview

In this section, we suppose a novel approach to determine the operating reserve requirement considering the inter-relationship between the secondary control reserve and the tertiary control reserve. In this paper, we only focus on required capacity of the secondary and the tertiary control reserve, the primary control reserve required capacity is neglected in this paper. Moreover, because a complexity, we do not consider the delay time of each reserve activation.

When a sudden disturbance occurs causing imbalance between load and generation, the operating reserve should cover this imbalance. First, the secondary reserve can cover enough under the following situation.

$$\Delta P_{IM}^{t} \le R_{2,\mathrm{C}}^{t} - R_{2,\mathrm{L}}^{t} \tag{7}$$

where:

ΔP_{IM}^{t} : Deviation of power imbalance between period t-1 and period t

$R_{2,\mathrm{C}}^{t}$: Capacity of secondary control reserve period t

$R_{2,\mathrm{L}}^{t}$: Executed energy of secondary control reserve

When the size of disturbance requires additional tertiary control reserve, the secondary and the tertiary control reserve take over such as the following equation.

$$R_{2,\mathrm{C}}^{t} - R_{2,\mathrm{L}}^{t} \le \Delta P_{IM}^{t} \le R_{3,\mathrm{C}}^{t} - R_{2,\mathrm{C}}^{t} - R_{3,\mathrm{L}}^{t} \tag{8}$$

where:

$R_{3,\mathrm{C}}^{t}$: Capacity of the tertiary control reserve period t

$R_{3,\mathrm{L}}^{t}$: Executed energy of the tertiary control reserve

In this paper, we only assume the following restricted conditions.

1) The only purpose of tertiary control reserve is to recover the secondary control reserve. The executed size of tertiary reserve is integers of capacity of the secondary reserve

2) Considered incident causing power imbalance is not bigger than the sum of the secondary control reserve and tertiary control reserve

B. Objective Function

The outline of the proposed algorithm is shown in Fig. 1. We consider a load imbalance model as a random, mean reversion, and jump diffusion process in this paper.

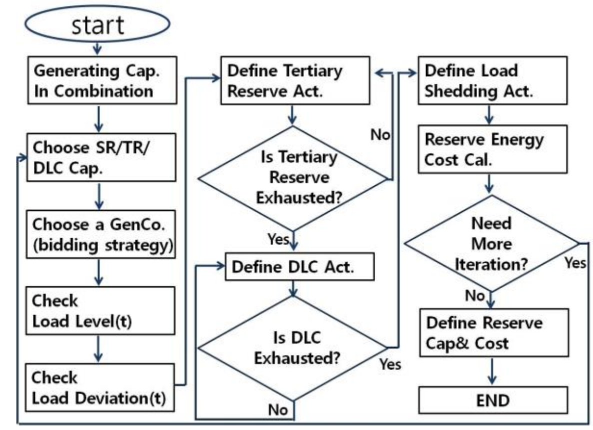

Figure 1. Flow chart for determining operating reserve capacity in the consideration DLC.

The objective function is expressed as the following equation:

$$\min\{\mathrm{C}_{2,c}^{t}(\mathrm{R}_{2,c}^{t}) + \mathrm{C}_{3,c}^{t}(\mathrm{R}_{3,c}^{t}) + \mathrm{E}[\mathrm{C}_{3,\mathrm{e}}^{t}(\mathrm{R}_{3,\mathrm{e}}^{t}) + \mathrm{C}_{\mathrm{loss,e}}^{t}(P_{\mathrm{loss,e}}^{t})]\} \tag{9}$$

where:

$\mathrm{C}_{2,c}^{t}$: Cost of the secondary control reserve capacity

$\mathrm{C}_{3,c}^{t}$: Cost of the tertiary control reserve capacity

$\mathrm{C}_{3,\mathrm{e}}^{t}$: Cost of the tertiary control reserve energy

$\mathrm{C}_{\mathrm{loss,e}}^{t}$: Cost of load shedding (energy loss)

$R_{3,\mathrm{e}}^{t}$: Executed amount of energy of the tertiary control reserve during period t

$P_{loss,e}^{t}$: Amount of load shedding during period t

V. SIMULATION AND RESULTS

In this paper, the simulation for verifying the performance of the proposed approach is performed in MATLAB. The input data of the generating units have been depicted in Table I. The generator 1, 2, 3 and 4 bids for the secondary and tertiary control reserve. The generator 5 and 6 only bids for tertiary control reserve.

TABLE I. GENERATION INFORMATION IN SIMULATION

	SR Cap. [MW]	SR Cap. Price [$/MW]	TR Cap. [MW]	TR Cap. Price [$/MW]	TR Energy Price [$/Mwh]
Gen 1	10	35	10	7	50
Gen 2	10	32	10	10	45
Gen 3	10	25	10	4	42
Gen 4	10	35	10	5	60
Gen 5	N/A	N/A	10	12	35
Gen 6	N/A	N/A	10	15	42

The required capacity of the secondary and tertiary control reserve is expressed in Table II. According to imbalance models, required capacities are different. Mean reversion is set to be remained around 0, the minimum capacity among 3 error models is needed. Whereas, because of the highest randomness of the jump diffusion model, the required capacity for the secondary and tertiary control reserve are larger than under other error models.

TABLE II. SIMULATION RESULTS

Results Error Model	SR Cap. [MW]	Gen. used for SR	TR Cap. [MW]	Gen. used for TR	Total Cost [$]
Random walk	20	G1, G2	20	G2, G6	1548
Mean Reversion	10	G2	0	N/A	643
Jump Diffusion	40	G1,G2 G3,G4	20	G5,G6	2826

VI. CONCLUSION

The paper proposes a novel method for determining operating reserve in the consideration of interrelationship between the secondary control reserve and the tertiary control reserve. Numerical simulation results are presented to demonstrate the effectiveness of the proposed method. Especially, we consider a simultaneous auction for the different reserves. The proposed method further extended to take account for delay time, various market structure, and demand deviation model.

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