Dynamic AGC Units' Dispatching Based On Loss Sensitivity Identification with the Consideration of Wind Energy

Shuang Zhang[1], Jingyi Zhang[2], Xuehong Yang[1], Hongqiang Li[1], Feng Gao[1] and Chao Lu[2,*]
[1]Power Science Research Institute of State Grid Ningxia Power Co, Yinchuan, China
[2]Tsinghua University, Beijing, China
[*]Corresponding author

***Abstract*—the emergence of high penetration of sustainable energy in the power system has increased the demand for faster-ramping units participating in the frequency regulation service. To fulfill the automatic generation control (AGC) and compensate the influence of sustainable energy fluctuations simultaneously, ramping capacity should be considered in the AGC dispatching model. Meanwhile, conventional dispatching model did not consider the impact of transmission loss, or relied on offline network model and parameters, failing to reflect the actual relationships between the sustainable energy units and conventional generators. In this paper, an online approach is proposed for AGC units' dispatching considering the above issues. First, the power loss sensitivity is online identified using recursive least square (RLS) method based on the real-time data of phasor measurement units (PMUs), setting up power balance constraint and contributing to a more accurate dispatch model. Then, we propose a dynamic optimization model of dispatch, which establishes a connection between the conventional units with fast ramping capacity and the sustainable energy farms with rapid fluctuations. The proposed identification method and optimization model are simulated in the IEEE-9 bus system, and the results verify their validity and feasibility.**

Keywords-ramping capacity; loss sensitivity; sustainable energy; AGC optimal dispatch; on-line identification

I. INTRODUCTION

Keeping the stability of frequency is an important approach to guarantee a safe power system. With the increase of sustainable energy penetration, wind energy in particular, the dispatching of AGC units becomes an important issue in the field of frequency control [1]. The random characteristic of the wind speed results in a serious degree of disturbance of the power system, leading to the increasing need of faster-ramping thermal units. Several works have been proposed to improve the ramping capacity of the thermal units by cooperating circulating fluid bed (CFB) units with the heating units, etc. [2-3]

The AGC units dispatch is essentially an optimization problem; therefore, different optimization methods have been applied to solve this issue, such as dynamic programming method [4], ant colony optimization, genetic algorithm [5-6], particle swarm optimization (PSO) technique [7-8], improved immune algorithm [9] and etc. Despite different optimization methods, the objective function limits to the minimization of generation cost without considering the ramping capacity.

On the other hand, frequency control requires real-time balance of generation, load and loss, and meets the generation limits. In many existing studies, the transmission loss is ignored; therefore, the result of dispatching is suboptimal, because the transmission loss affects the output of the generation units directly, thereby affecting the power distribution. Conventional loss calculation is based on B-coefficient method [10], and then improved with inverse Jacobian transpose method [11] and Z-bus loss allocation [12]. These methods are based on the off-line models and parameters which are contained with bias in real power systems, therefore, the performances are doubtful. With the implementation of PMUs, the active power of most nodes can be real-time measured, which provides a new direction to calculate the transmission loss.

To solve the above issues, a real-time AGC units' dispatch approach considering wind power and ramping capacity of thermal units is proposed in this paper. First, transmission losses sensitivity is identified and transmission loss is calculated. Then a dynamic optimization model combining the generation cost (considering the transmission loss) and fast-ramping capacity is proposed.

II. ONLINE IDENTIFICATION OF LOSS SENSITIVITY

During the process of AGC optimal allocation, how to accurately and rapidly identify the transmission losses of current power system is of importance in practice. The development of PMUs and wide area measurement system (WAMS) makes it possible to achieve the real-time measurement of the state variables of power system. In the platform of WAMS, the variation of all the units can be obtained directly, thus, the transmission loss can also be calculated using the real-time measurement data. Thus, a loss sensitivity identification method based on PMU measurements becomes possible.

Transmission losses are related to the changes of power flows. The change of active power output at node j called ΔP_j will result in the change of transmission loss called ΔP_l with the active power output of other nodes (except for the balance node) unchanged. Thus, under current system operating status, the relation between the active power output of node j and transmission loss can be approximately described as follows:

$$\Delta P_l = \frac{\partial P_l}{\partial P_j}\Delta P_j + \varepsilon_j \tag{1}$$

The partial derivative $\partial P_l / \partial P_j$ is defined as the loss sensitivity to the active power at node *j*. ε_j represents the deviation that the approximate description above brings.

Similarly, the number of the nodes (except for the balance node) at which the active power change extends to *N*, then the approximate relation between the power output of *N* nodes and transmission losses can be described:

$$\Delta P_l = \frac{\partial P_l}{\partial P_1}\Delta P_1 + \frac{\partial P_l}{\partial P_2}\Delta P_2 + \cdots + \frac{\partial P_l}{\partial P_N}\Delta P_N + \varepsilon \tag{2}$$

Where ΔP_l is the total loss change, ε is the deviation of all.

For actual power system, in *m* continuous sampling intervals, formula (2) can be expanded to formula (3):

$$\begin{bmatrix} \Delta P_l^{(1)} \\ \Delta P_l^{(2)} \\ \vdots \\ \Delta P_l^{(m)} \end{bmatrix} = \begin{bmatrix} \Delta P_1^{(1)} & \Delta P_2^{(1)} & \cdots & \Delta P_N^{(1)} \\ \Delta P_1^{(2)} & \Delta P_2^{(2)} & \cdots & \Delta P_N^{(2)} \\ \vdots & \vdots & \ddots & \vdots \\ \Delta P_1^{(m)} & \Delta P_2^{(m)} & \cdots & \Delta P_N^{(m)} \end{bmatrix} \begin{bmatrix} \frac{\partial P_l}{\partial P_1} \\ \frac{\partial P_l}{\partial P_2} \\ \vdots \\ \frac{\partial P_l}{\partial P_N} \end{bmatrix} + \begin{bmatrix} \varepsilon^{(1)} \\ \varepsilon^{(2)} \\ \vdots \\ \varepsilon^{(m)} \end{bmatrix} \tag{3}$$

The matrix form is as follow:

$$\Delta P_l = \Delta \boldsymbol{P} \frac{\partial P_l}{\partial \boldsymbol{P}} + \boldsymbol{\varepsilon} \tag{4}$$

The matrix of the changes of active power of different nodes $\Delta \boldsymbol{P}$ in (6) can be measured directly through WAMS, while the vector of the changes of transmission losses denoted as $\Delta \boldsymbol{P}_l$ can be calculated through the data of real-time measurement. At the condition of $m = N$, the unique solution can be obtained when the matrix $\Delta \boldsymbol{P}$ is invertible. If the matrix $\Delta \boldsymbol{P}$ is not invertible, we can increase the sampling times *m* to make $\Delta \boldsymbol{P}$ column full rank. As for the condition of $m > N$, the vector of loss sensitivity can be obtained with least square (LS) method. For the character that RLS algorithm does not need to reserve all the data, (once a new set of data arrives, the parameters will be estimated), the required amount of calculation and storage space is very small, therefore, online real-time identification can be achievable. From the mathematical point of view, equation (4) is expressed as a standard multiple linear regression equation, where the active power changes of different units' output are the independent variables, the transmission loss is the dependent variable, the sensitivity coefficients are the regression coefficients. The equation (6) will be established through repeatedly creating equation (4) at different continuous sampling intervals, furthermore, the sensitivity coefficients will be calculated through the modeling method of multiple regressions. Under normal circumstances, the measuring information of the WAMS platform is highly abundant. The computing time of the algorithm we proposed may not catch up with the refresh rate of the PMU data sequence. The parameter estimation should be conducted once again when the former calculation has been done, which helps to reflect the current operating status of the system and calculate the transmission loss sensitivity matrix accurately.

Hence, the constraint of the power balance can also be described as follows with the loss sensitivity, which is on-line identified with the data of the current operating status:

$$\sum_{i \in ND} \Delta P_{di} + \sum_{j \in NG} \frac{\partial P_l}{\partial P_{Gj}} \Delta P_{Gj} = \sum_{j \in NG} \Delta P_{Gj} + \sum_{l \in NW} \Delta P_{wl} \tag{5}$$

where *ND* represents the set of load nodes, *NG* is the set of conventional generation units, and *NW* is the set of wind generation units.

III. Dynamic Optimization model considering the ramping capacity

A. Objective Function

In the frequency ancillary service market, the regulation cost f_i of unit *i* participating can be formulated as follow:

$$f_i = C_i (\Delta P_i^t)^2 \tag{6}$$

where, C_i is the bidding price of unit *i* in the ancillary service market, ΔP_i^t is the power output change of unit *i* at the interval *t*.

The objective function of AGC dispatching model *F* is as follow:

$$F = \min \sum_{i \in N} f_i = \min \sum_{i \in N} C_i (\Delta P_i^t)^2 \tag{7}$$

where N is the group of the units participating in the AGC.

B. Operating Constraints

1) The power balance constraint using loss sensitivity

As mentioned above, the real-time changes of units' outputs and transmission loss measured by PMUs are utilized to identify and update the loss sensitivity matrix in real time. We can obtain the transmission loss during the optimization process via the loss sensitivity matrix, and then the constraint of the power balance can also be described as follow with the loss sensitivity:

$$\sum_{i \in ND} \Delta P_{di}^t + \sum_{j \in N} \frac{\partial P_l}{\partial P_i} \Delta P_i^t = \sum_{i \in N} \Delta P_i^t + \sum_{l \in NW} \Delta P_{wl}^t \tag{8}$$

It is worth mentioning that the calculation speed is an important index of power system dispatch. Compared with the loss sensitivity calculation method based on the trend of network, the methodology we put forward above greatly enhances the calculation speed with the assurance of the computing accuracy at the same time, which can meet the requirement of real-time dispatch better.

2) Capacity constraints

The output of generators has operating range, while the constraints can be described as follow:

$$P_{i,\min} \le P_i^t \le P_{i,\max} . \tag{9}$$

where $P_{i,\min}$,$P_{i,\max}$ are the minimum and maximum output of unit *i*.

3) Ramping constraints

For a given regulation time Δt, the regulation outputs of every unit are limited by its ramping rate:

$$V_{i,\text{down}}\Delta t \le \Delta P_i^t - \Delta P_i^{t-1} \le V_{i,up}\Delta t . \tag{10}$$

where P_i^{t-1} is the output of unit *i* at the interval *t*-1.$V_{i,,down}$, $V_{i,up}$ are the uplift and fall-off ramping rate of unit *i*.

The ramping constraints establish a connection between fast-ramping units and the wind farms with rapid fluctuations in the dynamic AGC dispatching model. With the ramping constraints, a multi-period AGC dispatching will be achieved.

IV. SIMULATION ON IEEE-9 BUS SYSTEM

We utilize the IEEE-9 bus system to explain the identification of loss sensitivity methodology and prove the validity of the optimal dispatching model. Generator 1, 2, 3 are the AGC units. The data of the current active power supply, the upper and lower limits of active power supply, and the coefficients of regulation cost and the upper and down ramping rates of the AGC units are shown in Appendix. The overall load of the system is 3.15 p.u. and the basic value of the power is 100MVA. The simulation platform is PSASP 7.1.

A. Identification of Loss Senstivity

Under the present operating circumstance, we bring a stochastic perturbation with small amplitude into the active power outputs of the loads. The perturbation amplitude is 5% of the current outputs of the loads. The loss sensitivities of units are identified in a real-time scale with the utilization of the active power supply of common units and variation of transmission losses supervised at different time, where the recursive least square (RLS) method is also used. To prove the feasibility and superiority of the loss sensitivity identification method clearly, the simulation result is compared with the inverse Jacobian method which is provided in Table I. The loss sensitivity of the balancer of the system is set to 0 as a reference.The time consumptions of the three methods are also provided in the Table I.

From Table I, we can get the similar results by using the identification with the RLS method and inverse Jacobian method, which guarantees the validity of the method we propose. Comparing with the inverse Jacobian method, the method we propose has improvement in the computing speed on the assurance of full use of the data, which is helpful to the real-time generating control. It is worth mentioning that the algorithm we propose utilizes the current disturbance data to reflect the influence of the output of the generation units on the transmission losses. The proposed method utilizes the data that can reflect the real operational condition of power systems, while the inverse Jacobian method utilize the off-line data and models.

TABLE I. THE RESULTS OF LOSS SENSITIVITY.

	Unit 1	**Unit 2**	**Unit 3**	**Comupting Time/ms**
RLS	0	0.043828	0.036678	4.12
Inverse Jacobian	0	0.0441	0.0363	32.14

B. The Analysis of Dispatch Results of AGC Units

With the loss sensitivity matrix identified in A, we can model the dynamic dispatching model of IEEE-9 bus system. Yalmip toolbox is used to solve the dynamic optimization model.

For the sake of simulation, the case system is examined in the presence of a sequence of random step changes at bus 6. The load change pattern is shown in FIGURE.I. With the dynamic AGC dispatching model of IEEE-9 we proposed, we will analyze the effects of ramping rate constraint and the loss sensitivity on the results of optimization as follows:

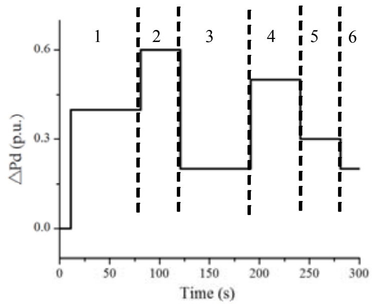

FIGURE I. THE LOAD DISTURBANCE CURVE.

C. Ramping Constraint

In order to prove the ramping constraint as an active one, we adopt two scenarios. In scenario A1, the ramping constraint is taken into account, while not in scenario A2. With the load change in FIGURE.I, we get the corresponding system response respectively.

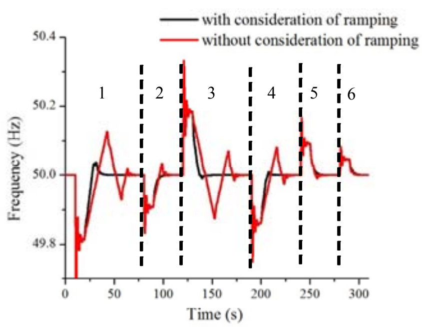

FIGURE II. FREQUENCY RESPONSE IN SCENARIO A1 AND A2.

FIGURE.II shows the frequency response to the stochastic load change of two scenarios. We can see that the frequency response curve gets more smooth，and returns to 50Hz in a much shorter time with the ramping constraint(the black curve shows). The superiority gets more obvious when a larger load disturbance occurs (region 1,3 and 4 in FIGURE.II).

D. Loss Sensitivity

In this case, we suppose to evaluate the impact of loss sensitivity in dispatch optimization model. We ignore the loss sensitivity (Scenario B1) and the current load change at bus 6 is 0.1p.u. Based on the assumption, we optimized the dispatch model, get the corresponding optimal dispatch factor comparing the one with the identified loss sensitivity (Scenario B2). The actual overall output, and the total regulation cost are also listed in TABLE II.

TABLE II. OPTIMAL OF THE LOSS SENSITIVITY.

	Optimal dispatch factor			**Total output**	**Regulation cost**
	α_1	α_2	α_3		
Scenario B1	0.3161	0.3327	0.3512	0.1072	220.637
Scenario B2	0.3336	0.3209	0.3455	0.10344	216.743

From the TABLE II, with the loss sensitivity identified the dispatch factor of unit 1 increases, whose loss sensitivity is smaller, while the other two decrease. Smaller loss sensitivity means a smaller transmission loss is caused with the same output of the generator. In this way, as is shown in the TABLE II the total output and the regulation cost in scenario B2 is superior in B1, which illustrate that the importance of consideration of loss sensitivity. With the consideration of loss sensitivity, the economy of the AGC dispatching improves to an extent.

V. CONCLUSIONS

In this paper, a fast online approach based on the RLS method is proposed to calculate loss sensitivity using real-time data by PMUs which helps to set up the power balance constraint. This sensitivity is obtained through identifications based on the measurements in the real power system, instead of simulations based on offline models and parameters, so it can reflect the real relationships between the wind farms and AGC generators. Also, we propose a dynamic dispatching model, which establishes a connection between the AGC units with fast ramping capacity and the wind farms with rapid fluctuations more directly and reasonably.

The simulation is carried out in the IEEE-9 bus system to show the effectiveness of our method. The simulation results verify the validity and feasibility of the identification method and the optimization model we proposed.

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TABLE III. THE PARAMETERS OF THE 3 UNITS

Unit	**Power output(p.u.)**	$P_{i,,\min}$ **(p.u.)**	$P_{i,\max}$**(p.u.)**	$V_{i,,down}$**(p.u./min)**	$V_{i,up}$**(p.u./min)**	C_i **(10^4*$/(p.u.)^2)**
1	0.7164	0.3	2.25	-0.072	0.072	6
2	1.63	0.5	1.95	-0.048	0.048	5.5
3	0.85	0.3	1.25	-0.038	0.038	5