Presented as late breaking results contribution
21st IFAC World Congress (Virtual)
Berlin, Germany, July 12-17, 2020

A Simple Approach for Real Time and Autonomous Measurement of Regulating Power

Takaharu Hiroe, Kazunari Ide

CIS Department, ICT Solution Headquarters Mitsubishi Heavy Industries, LTD.
1-1-1, Wadasaki-cho, Hyogo-ku, Kobe, 652-8585, Japan
(email: {takaharu_hiroe, kazunari_ide}@mhi.co.jp)

Abstract: For stable electric power supply operation, creation of incentive to regulating power is necessary. However, unlike electric energy (kWh) has electricity meters for billing purposes; regulating power does not have even measuring devices as that simple. In this paper, we discuss a policy of *net-mileage* (kW) for real time and autonomous measurement of the regulating power. The main difference from well-known *mileage* policy is that it counts only the regulating contribution of *mileage*, it measures fast regulating power like governor free mode operation, and it also measures the contribution of the demand side. Simulation case studies are presented to show the effectiveness.

Keywords: Frequency control, Power control, Power system economics, Power measurements

1. INTRODUCTION

In early days when electricity supply began, the structure was similar to an isolated island. The total electrical power supply of the local utility is equal to the total electrical demand of the region (Borberly and Kreider, 2001). Therefore, the electric utilities adjust the supply to meet the demand of the region. Concretely, based on the well-known droop (Stevenson ,1975), the electric power system of the region could be operated by simple operation rules. Namely, increase the power generation when the frequency decreases, and reduce it when the frequency increases. The droop just represents the static balance between frequency deviation and additional power generation, which is referred as regulating power. It may not be satisfactory in transient operation, due to the time delay. If the time delay is large, the frequency becomes oscillatory and operation of the power supply system may become difficult. The local electric utility has been playing the main role avoiding oscillations, by suppling regulating power properly and implicitly. Thus, the regulating power is a necessary measure for electric utilities to supply electricity stably. However, unlike demand and supply of electric power, regulating power has no way to be measured and therefore it has no price.

In fact, it had not been meaningful to clarify regulating power from electric power, since they were provided by the single local electric utility. However, in order to stably operate today's electric power system where electric power is distributed beyond regions and new electric power utilities participate in regions, it is necessary to differentiate the quality of their supplies. Thus, the pay-for-performance model is spreading globally to create incentives to regulating power.

As a performance measure of the regulating power, *mileage* (PJM, 2015) is the most typical. However, *mileage* measures the change or difference of supplied electric power, and it has nothing to do with the direction. Therefore, it is not clear whether the change is effective for stability. For example, suppose an Independent System Operator (ISO)/Regional System Operator (RTO) send a regulation control signal to increase the supply by 1 MW. Then, if supply is increased by 1 MW without delay, it is perfect as regulating power. Conversely, if a plant reduces supply by 1 MW, it must be evaluated negatively, because it damages the stability. However, *mileage* does not distinguish between them. Therefore, ISO/RTO solves this contradiction by the correlation coefficients between regulation control signal and actual supply as a performance factor on *mileage*. However, the procedure is not very simple.

In this paper, we consider simplification of the measuring policy of regulating power. By following to simple rules of droop, we use line frequency as the regulation control signal. Then we introduce the idea of *net-mileage*, which takes the stability consideration into *mileage*. In *net-mileage*, if the supply moves in the opposite direction to the frequency, the movement is a increment to *net-mileage*. Conversely, if it moves in the same direction, it is a deduction from *net-mileage*. As a special merit of *net- mileage*, we would like to emphasise that it can measure the contribution of the demand side including factories, office buildings, etc.

In this paper, we show that the concept of *net-mileage* works as intended by simple numerical simulations.

2. REGULATING POWER MEASURED BY MILEAGE

Mileage is the most typical pay-for-performance model (PJM, 2015). It is the sum of the absolute values of the time difference of supplied active power. For example, a power plant supplies active power time sequence $\{P_0, P_1, \cdots, P_n\}$ to the grid for a time period $\{0,1,\cdots,n\}$, *mileage* is defined by

$$M_t = \sum_{\tau=1}^{n} \frac{|P_\tau - P_{\tau-1}|}{P_{max}},$$

where P_{max} is regulation capacity.

From the definition, it is clear that *mileage* does not care about stability or regulating contribution. Therefore performance factor ρ, indicating whether P is complying or ignoring control signal, is computed as the multiplier on *mileage*. And the product ρM is used for performance quantification (PJM, 2015).

We consider performance quantification based on *mileage* mainly has three issues. The first is computational complexity. Although the calculation of the *mileage* M is quite straightforward, the calculation of the performance factor ρ that pairs with it is rather complicated. The second is autonomy. The performance score calculation requires information from the regulatory signal issued by ISO/RTO. It is not autonomous compared to electric meters. The third is response speed. Due to the latency of the communication line between ISO/RTO and the power plant, it is considered that a fast component of regulating power such as in governor free mode operation may have to be omitted in measurement.

3. STABILITY CONSIDERATION IN MILEAGE

3.1 Concept of Net-Mileage

As an easy way, we are thinking of a deferred payment system like the current pay-as-you-go system. In the supply and demand adjustment of the electric power system, consumption must be compensated by supplying additional power in a timely manner as much as consumed. Therefore the timeliness is the quality of the adjustment. However, we cannot simply measure it like with electricity meters. Thus, the idea of *mileage* was created and is used presently. As described above, *mileage* in total measures the timeliness of the control signal. Therefore, its true contribution to the power system stability strongly depends on the control signal from ISO/RTO. If the control signal has a large time delay, measured *mileage* may be different from the true regulating power.

We believe that the frequency itself is regarded as a regulation control signal, because it has played a central role in supply and demand adjustment since the beginning of the AC power supply system. If we think of governor free as the typical way of the adjustment, the rules are very clear; (1) reduce power supply when frequency increases, (2) increase power supply when frequency decreases.

These rules have been working well from the beginning and continue to work well now. And they lead us to the *net-mileage* counting rule, based on two values of time difference of active power supplied ΔP_t and that of frequency $\Delta\omega_t$, according to whether ΔP_t is complying with the frequency stability like the droop characteristic in governor free mode operation or not.

Rule1: If ΔP_t is complying with the droop characteristic, that is signum of $\Delta\omega_t \cdot \Delta P_t$ is negative, then $|\Delta P_t|$ is added to *net-mileage*.
Rule2: If ΔP_t is ignoring the droop characteristic, that is signum of $\Delta\omega_t \cdot \Delta P_t$ is positive, then $|\Delta P_t|$ is subtracted from *net-mileage*.

Net-mileage is calculated in following manner. At the boundary of power plants and the grid, line frequency $\{\omega_t, \omega_{t-1}, \cdots\}$ and active power supplies $\{P_t, P_{t-1}, \cdots\}$ are sampled periodically. Their time differences are written by

$$\Delta\omega_t = \omega_t - \omega_{t-1}$$
$$\Delta P_t = P_t - P_{t-1}.$$

Then, applying the rules *net-mileage* $\mathcal{M}$ of a certain time period, for example of a day, is calculated by

$$\Delta\mathcal{M}_\mathrm{t} = -\mathrm{sgn}(\Delta\omega_t \cdot \Delta P_t)|\Delta P_t| \quad (1)$$
$$\mathcal{M} = \textstyle\sum_{t\in\{\text{a day}\}} \Delta\mathcal{M}_t. \quad (2)$$

Please note that the right hand side of (1) is eventually simplified to $-\mathrm{sgn}(\Delta\omega_t)\Delta P_t$.

3.2 Pay-as-performance in Net-Mileage

In the previous section, we focused on the concept of *net-mileage*. Therefore, we assumed that the active power responds to frequency changes simultaneously. However, in reality, it responds with a delay. If a frequency change $\Delta\omega_\mathrm{t}$ takes place at time t, the response appears in ΔP_{t+i} $(i = 1,2,3\cdots)$ where i indicates the delay time. Conversely, ΔP_t is the sum of responses to preceding frequency changes $\Delta\omega_{t-i}$ $(i = 1,2,3\cdots)$. Naturally, faster responses are more valuable to the stability. Thus, in order to differentiate the value according to the delay time i, we introduce pay-for-performance weights $\{w_1, w_2, \cdots, w_n\}$ on the preceding values of frequency $\{\Delta\omega_{t-1}, \Delta\omega_{t-2}, \cdots, \Delta\omega_{t-n}\}$, which will be set by the System Operators according to the shortage of the regulating power. And we define weighted preceding frequency $\Delta\widetilde{\omega}_t$ as in FIR model form

$$\Delta\widetilde{\omega}_t = \textstyle\sum_{i=1}^{n} w_i \cdot \Delta\omega_{t-i}, \quad (3)$$

then *net-mileage* is modified as follows:

$$\Delta\mathcal{M}_\mathrm{t} = -\mathrm{sgn}(\Delta\widetilde{\omega}_t \cdot \Delta P_t)|\Delta P_t| \quad (4)$$
$$\mathcal{M} = \textstyle\sum_{t\in\{\text{a day}\}} \Delta\mathcal{M}_t. \quad (5)$$

This is an example of how w is defined.

$$w_i = e^{-\frac{\Delta t}{\tau_w}\cdot(i-1)} \Big/ \textstyle\sum_{i=1}^{n} e^{-\frac{\Delta t}{\tau_w}\cdot(i-1)} \quad (6)$$

Fig. 1 shows an example of weight on preceding frequency value with $\tau_w = 0.5$ (s), $\Delta t = 0.05$ (s). It has a rather long tail. Using an IIR form in (3) is an option to shorten the length of weights vector.

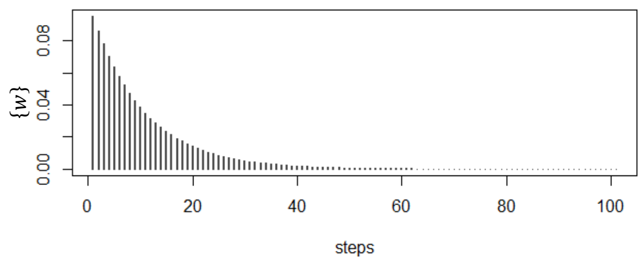

Fig. 1. An example of weights on preceding frequency values

4. DYNAMICAL SIMULATION MODEL

As a demonstration of the idea of *net-mileage*, numerical simulations of a power system by linearized swing equations were done. We considered a power system with 100 power stations, which stand for suppliers or consumers. Their dynamics were modeled by swing equations of 2-pole synchronous machines as

$$J\ddot{\theta} = \omega_N^{-1}(P_T - P),$$

where J is inertia (kg-m2), θ (rad/s) EMF angle, P_T is mechanical power supplied (MW) and P is active power supplied to grid lines (W) (Kundur, 1994). J, θ, P_T and P are column vectors of 100×1. θ, P_T and P are the deviation from their initial equilibrium points. ω_N is $60 \times 2\pi$ (rad/s). Each entry of mechanical power is modeled by

$$P_T = -k_G \omega_N^{-1} P_N \omega,$$

where P_N is nominal active power, k_G is droop coefficient (MW/rad/s) and ω is mechanical angler speed deviation from the synchronous speed. Each entry of active power P is modeled by

$$P = y_G(\theta - \theta_L),$$

where θ_L is line voltage angle of connection and y_G is constant coefficient about the equilibrium operation point. Fig. 2 shows the connection of stations and grid lines. There is a matrix Y_L about power propagation in grid lines satisfying

$$\mathrm{diag}[y_{G1}, \cdots, y_{G100}]\ (\theta - \theta_L) - Y_L \theta_L = 0.$$

Finally, line voltage angle is obtained from the EMF angle of the machines.

$$\theta_L = (Y_L + \mathrm{diag}[y_{G1}, \cdots, y_{G100}])^{-1}\ \mathrm{diag}[y_{G1}, \cdots, y_{G100}]\,\theta$$

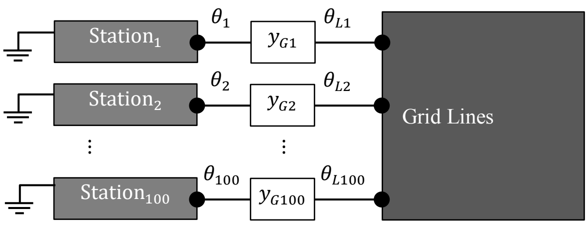

Fig. 2. Connection of Stations and Grid Lines.

5. SIMULATION STUDIES

5.1 Model Parameters

Nominal active power P_N of suppliers was equally set to 1MW. Droop coefficient k_G was drawn from uniform distribution. Inertia J and admittance y_G were computed following pre-determined values.

$$P_N = 1\ (\mathrm{MW}),\ k_G \sim \mathrm{unif}[0,30]\ (\%\mathrm{MW}/\%\tfrac{\mathrm{rad}}{\mathrm{s}})$$
$$T_S = 8\ (\mathrm{s}), \qquad J = P_N \omega_N^{-2} \cdot T_S\ (\mathrm{kgm}^2)$$
$$y_G = 2P_N\ (\mathrm{MW/rad}).$$

Admittance matrix between connection points was set by

$$Y_L = c_G y_G \begin{bmatrix} 99 & -1 & \cdots & -1 & -1 \\ -1 & 99 & & -1 & -1 \\ \vdots & & \ddots & & \vdots \\ -1 & -1 & & 99 & -1 \\ -1 & -1 & \cdots & -1 & 99 \end{bmatrix}. \qquad (7)$$

where c_G is the ratio of a line admittance to self-admittance of the machine. Disturbance P_D is modeled by normal distribution and a low-pass filter as

$$v \sim \mathrm{Normal}(0,1)$$
$$P_D = \frac{3}{3s+1} v.$$

and it is injected to station 1

$$J_1 \ddot{\theta}_1 = \omega_n^{-1}(P_{T1} - P_1 + c_D P_D).$$

where c_D is amplitude coefficient determined by

$$c_D = \frac{5 \times 10^{-3}}{\sqrt{\mathrm{Var}(P_D)}} \sum_{i=1}^{100} P_{Ni}.$$

5.2 Simulation Results

Two cases of disturbance response simulations of a power system were carried out with the same model parameters mentioned above. Power disturbance P_D and weighting coefficient $\{w\}$ ($\tau_w = 0.5$ (s), Δt=0.05 (s)) in (6) were the same in both cases. Fig. 3 shows the time history of P_D. Line admittance is the only difference between them.

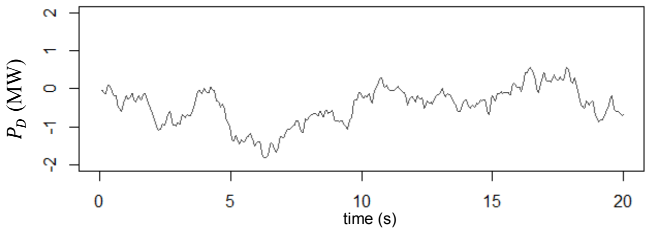

Fig. 3. Time history of power disturbance P_D

In the first case, admittance of each line is 10 times as much as self-admittance y_G. That is $c_G = 10$ in (7). Since there are 99 inter connection lines in total, this case is like a collection of 99 single machines and a time varying infinite bus power system. Fig. 4 shows the responses of other stations $i \in \{2,3,\cdots,100\}$, including P_i, ω_{Li} and *net-mileage*.

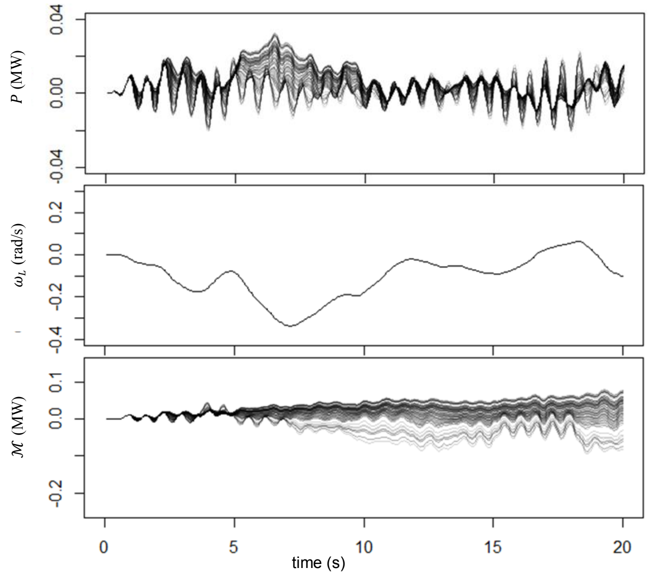

Fig. 4. First case simulation result of disturbance responses, (P in 1st panel, ω_L in 2nd panel and *net-lineage* $\mathcal{M}$ in 3rd panel) of a power system ($c_G = 10$ in (7)).

Please note that these variables P and ω_L are deviations from the initial equilibria. Since connection points of the grid are tightly coupled by large line admittance, line frequencies lay on the same plot line.

In the second case, admittance of each line is set to 1/100 of self-admittance of each station. Since each station has 99 inter connections in total, grid admittance is almost the same as the self-admittance of each station. Fig. 5 is the second case version of Fig. 4. Due to the limitation of line admittances, line frequencies ω_L are different for each connection point.

Fig. 6 shows the relation between droop coefficient k_G and *net-mileage*. Clearly, in both cases, the ascending order of *net-mileage* coincides with that of the droop coefficients'. Therefore, *net-mileage* is useful as a performance index to measure the amount of regulating power that contributed to stability.

In order to use *net-mileage* for billing purposes, we neutralize that by simply subtracting the mean value of *net-mileage* of all stations from that of each station. Fig. 7 shows *net-mileage* of each station after the neutralization for two cases. For the ease of understanding, horizontal axis which stands for stations is sorted in ascending order by droop coefficient k_G, except for station 1, which is shown at the left end of the axis. Since disturbance power is solely applied to station 1, its *net-mileage* is by far the worst of all.

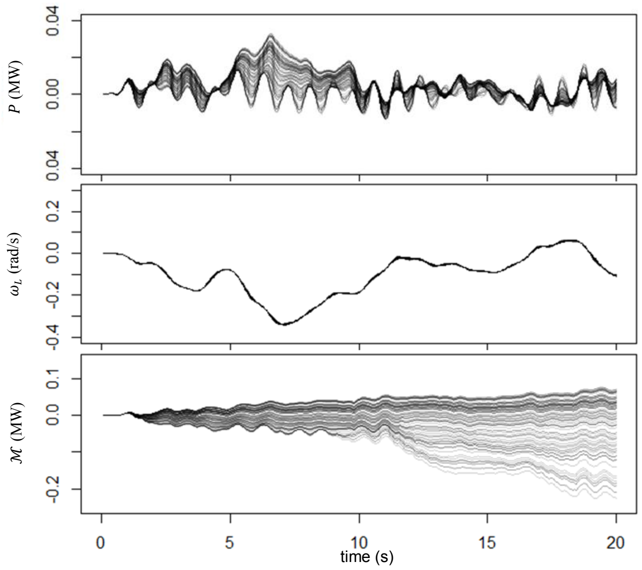

Fig. 5. Second case simulation result of disturbance responses, (P in 1st panel, ω_L in 2nd panel and *net-lineage* $\mathcal{M}$ in 3rd panel) of a power system ($c_G = 0.01$ in (7)).

6. CONCLUSION

In this paper, we introduced a policy of *net-mileage* for real time and autonomous measurement of regulating power. The main difference from well-known the *mileage* policy is that *net-mileage* counts regulating contribution by the coincidence of changing direction of active power and that of line frequency. Because of this simplicity, it can measure fast regulating power like governor free mode operation. Moreover, it also measures the regulating contribution from the demand side exactly in the same manner.

Two case studies of power systems using dynamical models were presented to show the effectiveness of *net-mileage*. The results show that *net-mileage* aligns in ascending order of droop coefficients. Therefore, *net-mileage* is useful as a performance index of regulating power that has contributed to stability.

Finally, this paper is a preliminary study of *net-mileage*. Practicability including robustness consideration against nonlinearity and measurement noise are left for future work.

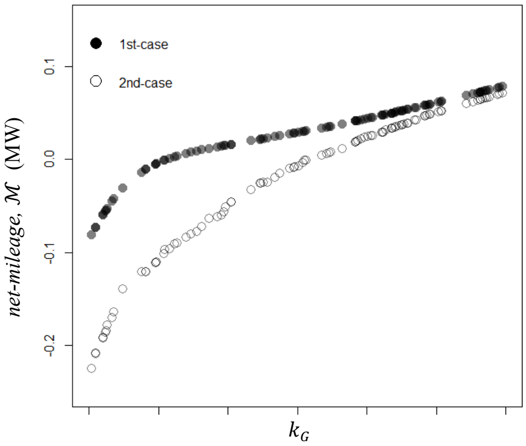

Fig. 6. Relation between droop coefficient k_G and *net-mileage* from first case and second case simulation results

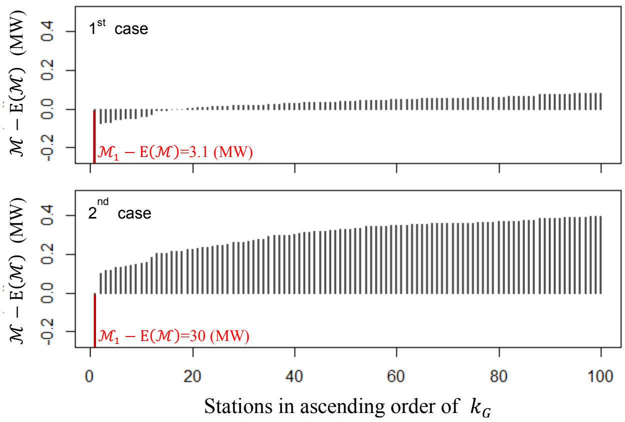

Fig. 7. *Net-mileage* after adjustment by subtracting its mean value for billing purposes. Stations are sorted in ascending order by droop coefficient k_G, except for station 1, which appears at the left end of horizontal axis. (top panel: 1st case , bottom panel: 2nd case)

REFERENCES

Borberly, A. and Kreider, J. F. (2001). *Distributed Generation: The Power Paradigm for the New Millennium*. CRC Press, Boca Raton, FL.

William D. Stevenson, Jr. (1975). *Elements of Power System Analysis Third Edition*, McGraw-Hill, New York, ISBN 0-07-061285-4.

PJM (2015). PJM manual 12: *Balancing operations revision: 32* effective date: April 6 2015", [online] Available: http://www.pjm.com/markets-and-operations/ancillary-services.aspx.

P. Kundur (1994), *Power System Stability and Control*, McGraw-Hill, New York.