A study for on-demand generation regulation control

by Adelhard Rehiara

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TRANSLATED PAPER

A study for on-demand generation regulation control

Yoshifumi Zoka | Keita Koshimoto | Masaki Muraoka | Yasunori Kuwada | Yuki Mashima | Adelhard Beni Rehiara | Yutaka Sasaki | Naoto Yorino

Hiroshima University, Kagamiyama,
Higashihiroshima, Japan

Correspondence
Yoshifumi Zoka, Hiroshima University, 1-4-1 Kagamiyama, Higashihiroshima 739-8527, Japan.
Email: zo@hiroshimau.ac.jp

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Abstract

This paper proposes a real-time generation regulation system named as "on-demand generation regulation control" system, which is suitable for small independent power grids with unstable renewable energy generators. It has been developed as a part of "robust demand and supply control manager" and plays an important role of flexible frequency control that includes vehicle to grid and generation restriction when necessary. The main feature of the system is the integrated framework to effectively deal with hard-to-predict control options in a flexible way by observing the unstable generator outputs and all generators/batteries status including electric vehicles. In addition, a feedback system is also proposed to flexibly adjust the regulation capacity in case unexpected disturbances occur. The performance of the proposed system is verified through numerical simulations based on an actual test site with successful results.

KEYWORDS
EV charging control, feedback, generation regulation, on-demand control, renewable energy, uncertainty

1 | INTRODUCTION

Distributed generators have gained widespread recently from the standpoints of response to the global warming and saving energy. Particularly, massive introduction of intermittent (unstable) renewable generators such as photovoltaic systems (PVs) and wind turbines (WTs) into power systems brings about concerns regarding voltage distribution, demand-supply balance, stability, and other issues affected by increase in hard-to-predict output fluctuations. On the other hand, microgrids and other small grids with autonomous decentralized control have attracted attention as solution to these concerns. In ordinary demand-supply operation, long- to short-term demand-supply forecasts are made and corrected successively on monthly, weekly, and daily basis; in addition, load frequency control (LFC), local control, and other techniques are employed for demand-supply adjustment. In the past, the only major fluctuation sources were loads, and deviations from schedules were not that strong; however, in case of high penetration of intermittent renewable generators, new uncertainties must be added to conventional demand-supply forecasts. That is, forecasting gets complicated with more factors to be predicted, and demand-supply balancing control becomes difficult. In this context, we proposed robust demand and supply control manager (DS manager)[1] as a demand-supply control system to deal with uncertainties of intermittent renewable generators. With DS manager, long- to short-term demand-supply forecasting and scheduling are performed as in conventional demand-supply adjustment, but uncertainties of operated intermittent renewable generators are taken into account. However, short-period fluctuations of intermittent renewable generators must be controlled in real time. Moreover, long-period fluctuations, too, must be controlled in real time in case of off-target forecasts.

Thus, in this paper, we propose an on-demand control system that maintains stable demand-supply adjustment even though output fluctuations of intermittent renewable generators exceed the limits of forecasts and schedules. As regards dealing with output fluctuations of intermittent renewable generators, the first thing that comes to mind is the use of battery storage for frequency regulation. However, battery storage implies increase in cost, and researchers seek for alternatives such as vehicle-to-grid that utilizes charge/discharge control of home-owned electric vehicles (EVs) to create reserve capacity for grid operation.[2] For example, there are studies[3] that consider user's convenience with regard to EV state of charge and other factors. However, the number of EVs connected to grid is constantly changing, thus creating a new uncertainty, and this number must be monitored in real time to estimate regulation capacity. On the other hand, there is also a proposal to maintain grid stability through output restriction (shedding) of intermittent renewable generators when output fluctuations exceed regulation capacity of the grid.[4] For example, there is research on disconnection control of WTs to handle frequency fluctuations in governor-free area.[5] However, output restriction must be minimized through real-time grid monitoring in order to utilize intermittent renewable generators without waste.

The on-demand control system proposed in this study aims at the maintenance of grid stability by means of EV charge control and restriction of intermittent renewable generators; in so doing, both EV charge control and generator output restriction are integrated in a single framework based on system information aggregated via a network, and the emphasis is put on flexible grid operation. In the proposed system, adjustment capacity available in the grid and adjustment capacity required to maintain grid stability are calculated depending on the fluctuation period. When regulation capacity is not sufficient for fast fluctuation components, characteristics of EV charge control are changed so as to compensate for the deficiency. If regulation capacity is insufficient because of few EVs connected, or output of intermittent renewable generators strongly fluctuates, the deficiency can be cleared by output restriction. However, deficiency of regulation capacity does not necessarily affect frequency. On the contrary, disturbances in frequency may occur even though regulation capacity is sufficient. Such cases are related to mutual cancellation of fluctuation components, fluctuation period, and so on, and specific conditions have to be properly evaluated. Thus, when restricting intermittent renewable generators, decisions are made based on both regulation capacity comparison and frequency staying rate.

In addition, aggregated information is not only used in contingency control, but is also fed back to DS manager, and so on. Normally, generator's adjustment capacity is maintained at a certain level in economic load dispatch (ELD) scheduling, but in the proposed system, adjustment capacity can be tuned to grid conditions. As a result, one can expect for radical elimination of regulation capacity deficiency, and furthermore, for response to output fluctuations of intermittent renewable generators that are difficult to handle with contingency control.

The proposed on-demand control system features integration of multiple control schemes based on real-time information, thus aiming at maintenance of grid stability. Below, an overview of DS manager is given, and the context of this study is explained in Section 2. Then, details of the proposed system are given in Sections 3 and 4; after that, effectiveness of the system is verified via numerical simulations in Section 5.

2 | DS MANAGER

Concept diagram of the DS manager is shown in Figure 1. This manager integrates near-real-time forecast, scheduling, and control to flexibly respond to uncertainties of intermittent renewable generators. The system is divided into three orders (day-h, h-min, and min-s); information is shared among the orders via offline/online database. The day-h and h-min orders are used for forecast and scheduling with regard to uncertainties of intermittent renewable generators. Dynamic economic load dispatch (DELD)[6] in the h-min order utilizes unit commitment data and forecast to schedule generator outputs and reserve capacity in real time up to a specified time ahead. The min-s order is in charge of control, particularly, LFC control. The on-demand control system proposed in this study belongs to the min-s order; in case of off-target forecast or massive interconnection of intermittent renewable generators that cannot be handled in conventional way, EV charge control and restriction of intermittent renewable output are performed as contingency control, while feedback is sent to DELD for demand-supply rebalancing.

3 | ON-DEMAND CONTROL SYSTEM

3.1 | Overview

In conventional demand-supply adjustment, load fluctuations are divided by the fluctuation period into cyclic, fringe, and sustained components controlled, respectively, by governor-free operation, LFC, ELD, and so on. Output fluctuations of intermittent renewable generators can be also classified in the same way; particularly, sustained and cyclic components are hard to predict, which requires real-time control. Sustained components can be handled by forecast/scheduling module of the DS manager, but real-time control is needed to respond to generation excess/deficiency. In the on-demand control system, information aggregated via a network is used to handle various components of renewable energy fluctuations through EV charge control and output restriction. First, the number of connected EVs is determined, and charge control is performed in real time in order to utilize rapid-response EVs as regulation capacity for cyclic components. Besides, when intermittent renewable generators adversely affect demand-supply balance, outputs of the generators are restricted to maintain stability. In so doing, a combination of adjustment capacity available in the grid, adjustment capacity required to maintain grid stability, and frequency staying rate is used to separate excess generation due to sustained components from oscillation due to fringe and cyclic components, and appropriate restriction is applied to respective outputs. However, when the number of connected EVs is insufficient, excess generation due to sustained components can be hardly

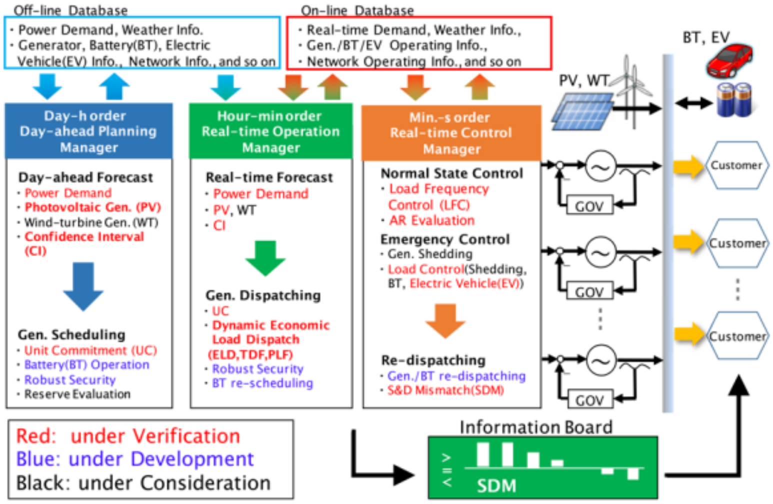


FIGURE 1 Outline of proposed comprehensive robust demand-supply control system [Color figure can be viewed at wileyonlinelibrary.com]

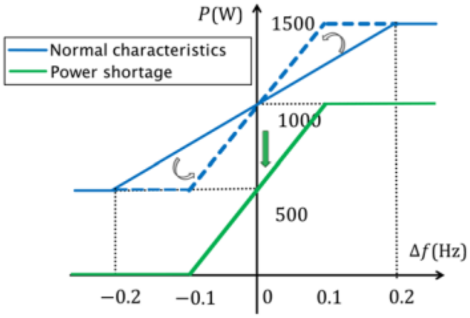


FIGURE 2 Example of effective EV charging characteristic [Color figure can be viewed at wileyonlinelibrary.com]

handled by output restriction, and one must resort to load shedding.

3.2 | EV charge control

EVs gaining popularity in terms of environmental protection are used as reserve capacity of the grid. However, the number of EVs connected to the grid is constantly changing; therefore, in the on-demand control system, reserve capacity is monitored through real-time estimation of EVs via an information network. For this purpose, EV charging characteristics are defined so as to adjust charge amount to frequency deviation (Figure 2). In addition, EVs feature rapid response, which promises regulation capacity for cyclic components that cannot be sufficiently handled by LFC. The on-demand control system uses the same approach as was proposed for LFC logic with regard to different responsiveness of existing generators and batteries.[7]

In addition, we aim at a greater contribution to grid frequency control through on-demand updating of charge control characteristics according to changes in grid state. In normal operation, charge control is performed as shown by the solid blue line; on the other hand, when regulation capacity of the grid is insufficient, the gradient of charging characteristic is increased as shown by the dashed blue line; as a result, control sensitivity is enhanced to secure required capacity. Providing EVs with a linear characteristic following frequency deviation was already proposed in the past,[2] but here we aim at a flexible on-demand response. Besides, when output of intermittent renewable generators is restricted or restored, power excess or deficiency may occur in the grid; thus, demand-supply imbalance is compensated by regulation of charging power level as shown by the solid green line.[8,9] In this paper, we focus on integration of multiple systems including EVs; as regards technicalities of EV control, please refer to the literature.[10] Here, we assume local autonomous control of EVs, which makes possible high responsivity; particularly, a control cycle of 1 s is assumed for EVs.

3.3 | Restriction and restoration of intermittent renewable output

3.3.1 | Overview

Output restriction of intermittent renewable generators is a function to maintain grid stability by shedding generator output when fluctuation components of the generators adversely affect demand-supply balance. Besides, the adverse factors are classified into excess generation due to sustained components and oscillation due to fringe and cyclic components, and handled differently. That is, sustained components are restricted by cutting dc components, while fringe and cyclic components are restricted by relatively reducing fast fluctuations. In the on-demand control system, regulation capacity and frequency staying rate are monitored, and their combination is used to decide on output restriction or restoration, and to calculate appropriate amounts.

3.3.2 | Calculation of regulation capacity and frequency staying rate

Regulation capacity means adjustment reserve capacity of generators to respond to fluctuations of load and renewable energy. In the on-demand control system, adjustment capacity available in the grid and adjustment capacity required to maintain grid stability are calculated. In addition, effective output restriction and restoration are performed by estimation of fringe and cyclic components. Required regulation capacity is calculated by Equation (1) depending on the fluctuation period, using past output data with fluctuation range reliability of 95%. This calculation is based on the finding that load fluctuations follow normal distribution;[11] besides, normal distribution is also assumed for intermittent renewable generators:

$$C_L^{(s/f)} = 4\sigma_L^{(s/f)} = 4\left(\sigma_{PV}^{(s/f)} + \sigma_{WT}^{(s/f)} + \sigma_{Load}^{(s/f)}\right), \tag{1}$$

where C_L is the required regulation capacity, σ_L is the standard deviation found from fluctuations of loads and intermittent renewable generators, σ (*PV/WT/Load*) is the standard deviation in fluctuations of PV/WT/Load, s is slow, and f: is fast.

Regulation capacity available in the grid is calculated by Equations (2) and (3) depending on the fluctuation period; here, slow components are treated using LFC capacity, while fast components are treated using governor capacity with respect to allowed frequency fluctuation range and EV regulation amount. Here, α is set to 10% generator rating, that is, to 0.1, but this setting may change by the feedback system (to be explained later):

$$C_0^{(s)} = \alpha \cdot \sum_{i}^{N} P_i \cdot S_i, \tag{2}$$

$$C_0^{(f)} = \beta \cdot N + K \cdot f_{\mathrm{lim}}, \tag{3}$$

where C_0 is the available regulation capacity, α is the regulation capacity coefficient, P_i is the rated output of i-th intermittent renewable generator, S_i is the generator's commitment/decommitment state (0 or 1), β is the fluctuation range of EV charge, N is the number of connected EVs, f_{lim} is the allowed frequency fluctuation range (0.02), and K is the system constant.

Frequency staying rate shows the possibility that grid frequency stays within a certain region. In this study, we assume high penetration of intermittent renewable generators in a small grid where frequency fluctuations are particularly likely to occur; therefore, frequency staying rate should be calculated in short periods of time. Thus, past 1-min frequency data were sampled at 1 s, and frequency staying rate was calculated from the number of data in upper and lower hazardous regions; the rate was updated every second. In addition, frequency staying rate was calculated in the whole hazardous region:

$$R_{fu} = (N_{du}/S_f) \cdot 100, \tag{4}$$

$$R_{fl} = (N_{dl}/S_f) \cdot 100, \tag{5}$$

$$R_f = R_{fu} + R_{fl}, \tag{6}$$

where R_{fu} is the frequency staying rate in upper hazardous region, N_{du} is the number of frequency data staying in upper hazardous region $(1 - S_f)$, R_{fl} is the frequency staying rate in lower hazardous region, N_{dl} is the number of frequency data staying in lower hazardous region $(1 - S_f)$, and S_f is the number of frequency samples (60).

3.4 | Restriction/restoration criteria

The on-demand control system aims at suppression of dc component and oscillating components in intermittent renewable generators. Conditions for output restriction and restoration are summed up in Table 1. In case of upward frequency deviation while sufficient regulation capacity is available, dc component is recognized as responsible for the deviation; when regulation capacity is insufficient, oscillating components are recognized as responsible for the deviation. Restoration is performed when regulation capacity is sufficient and frequency staying rate is not violated.

3.4.1 | Calculation of restriction/restoration amount

In the on-demand control system, restriction amount for dc component and oscillating components as well as restoration amount when the grid has stabilized are appropriately determined. Besides, a margin is set on restriction restoration amount. First, restriction for dc component is calculated by Equation (7). In so doing, surplus power supply is calculated from average frequency deviation Δf_{ave} and system constant K so that dc component of grid frequency becomes equal to reference frequency. Since scheduling cycle in DELD is 300 s, frequency deviation is also averaged over past 300 s:

$$M_{new} = M \times \frac{SMA_f - K\Delta f_{ave}}{SMA_f} \times margin, \tag{7}$$

where M_{new} is the interconnection amount after restriction/restoration, M is the current interconnection amount of intermittent renewable generators, SMA_f is the simple moving average of past output fluctuation data for grid frequency, and Δf_{ave} is the average frequency deviation.

Next, Equations (8) and (9) are used for restriction of oscillating components. Ratio m of postrestriction interconnection amount of intermittent renewable generators to current

TABLE 1 Criteria of restriction and restoration

(a) Restriction			
Conditions	$R_{fu} > 5(\%)$	$R_f > 5(\%)$	$C_L^{(s/f)} > C_0^{(s/f)}$
DC components	○	–	×
Oscillating components	–	○	○
(b) Restriction			
Conditions	$R_f > 5(\%)$	$C_0^{(s/f)} > 3/2C_L^{(s/f)}$	
Restoration	×	○	

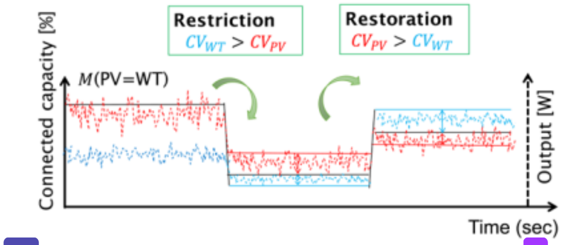


FIGURE 3 Estimation of restriction/restoration amount [Color figure can be viewed at wileyonlinelibrary.com]

interconnection amount is found using ratio $m^{(s/f)}$ of postrestriction interconnection amount of intermittent renewable generators to current interconnection amount. A similar expression is sued in case of restoration:

$$m^{(s/f)} = \frac{C_0^{(s/f)}}{C_L^{(s/f)}}, \tag{8}$$

$$M_{new}^{(s/f)} = M \times m^{(s/f)} \times margin, \tag{9}$$

where m is the ratio of postrestriction interconnection amount of intermittent renewable generators to current interconnection amount and $M_{new}{}^{(s/f)}$ is the interconnection amount after restriction/restoration.

3.4.2 | Individual control

M_{new} is calculated interconnection amount of existing intermittent renewable generators, being equal for all generators (PV and WT). However, assigning same interconnection amount to all generators, without regard to the magnitude of fluctuations, would be inefficient. Thus, in the on-demand control system, interconnection amount is determined individually as shown below, with regard to coefficient of variation (CV) in Equations (16) and (17) expressed via the magnitude of fluctuations with respect to output of each generator. This concept is illustrated in Figure 3. Restriction in Figure 3 is applied to WTs with high CV rather than to PVs with wide fluctuation range. Thus, generators with poor quality can be suppressed to achieve efficient restriction:

$$M_{PV}^{(s/f)} = M_{new}^{(s/f)} + h_{pv}^{(s/f)} \cdot R_{PV}, \tag{10}$$

$$M_{WT}^{(s/f)} = M_{new}^{(s/f)} + h_{WT}^{(s/f)} \cdot R_{WT}, \tag{11}$$

$$h_{PV}^{(s/f)} = \frac{CV_{WT}^{(s/f)}}{CV_{PV}^{(s/f)} + CV_{WT}^{(s/f)}} \times \frac{CV_{WT}^{(s/f)} - CV_{PV}^{(s/f)}}{CV_{PV}^{(s/f)} + CV_{WT}^{(s/f)}}, \tag{12}$$

$$h_{WT}^{(s/f)} = \frac{CV_{PV}^{(s/f)}}{CV_{PV}^{(s/f)} + CV_{WT}^{(s/f)}} \times \frac{CV_{PV}^{(s/f)} - CV_{WT}^{(s/f)}}{CV_{PV}^{(s/f)} + CV_{WT}^{(s/f)}}, \tag{13}$$

$$R_{PV} = \frac{Cap_{WT}}{Cap_{PV} + Cap_{WT}}, \tag{14}$$

$$R_{WT} = \frac{Cap_{PV}}{Cap_{PV} + Cap_{WT}}, \tag{15}$$

$$CV_{PV} = \frac{\sigma_{PV}^{(s/f)}}{SMA_{PV}}, \tag{16}$$

$$CV_{WT} = \frac{\sigma_{WT}^{(s/f)}}{SMA_{WT}}, \tag{17}$$

where h is the internal ratio due to coefficient of variation, R is the generation rate of intermittent renewable generators, Cap is the introduction amount of intermittent renewable generators, and CV is the coefficient of variation.

CV makes possible relative evaluation of output fluctuations of intermittent renewable generators; internal ratios and their range are determined by Equations (12) and (13).

4 | FEEDBACK TO DELD

4.1 | Overview

The on-demand control system combines contingency control functions (EV charge control, restriction of intermittent renewable generators, and load shedding) with demand-supply rebalancing. Real-time aggregated information is used not only for contingency control, but also as a feedback to scheduling module of DS manager; thus, the problem of reserve power deficiency is solved radically through schedule correction according to the grid state. Normally, LFC capacity is provided on a certain level by DELD[2] in scheduling module of DS manager; on the other hand, in the on-demand control system, feedback is used to flexibly provide LFC capacity. As a result, the problem of reserve power deficiency is solved radically; moreover, one can expect for a smaller burden on contingency control, and for response to power shortage caused by sustained components that are difficult to suppress by restriction of intermittent renewable generators.

4.2 | Calculation of feedback amount

With DELD, optimal power generation is scheduled up to 1 h ahead in increments of 5 min under multiple constraints. One of these constraints pertains to the upper and lower limits. This constraint is set in order to further restrict operating region dictated by generator functions so as to provide reserve power for LFC or governor-free operation. In the on-demand control system, required LFC capacity is calculated as a feedback amount; in DELD, the upper and lower limits are corrected accordingly, thus making possible adjustment of LFC capacity. Below, we explain about determination of the upper limit of LFC capacity. Upper limit closing rate is calculated in Equation (18) as a ratio of LFC reference (p.u.) to LFC upper limit (p.u.). That is, the upper limit closing rate of 100% means that LFC capacity is exhausted. Therefore, when the upper limit closing rate exceeds 80% immediately before LFC schedule, the upper limit of LFC capacity is extended (Equation (20): condition 1); furthermore, when upward frequency violation is detected, the highest priority is given to capacity assurance, and extension to the upper limit of 0.1 is provided (Equation (20): conditions 1 and 2). In this paper, extended upper limit is set to 0.1 (the double reference value) but in actual operation, the setting can be chosen with regard to economic performance, safety, and other factors. Lower limit is treated in a similar way:

$$R_{LFC}^{(u/l)} = \frac{LFC_{signal}}{LFC_{(u/l)}} \times 100, \tag{18}$$

$$\left.\begin{array}{ll} (condition\ 1) & R_{LFC}^{(u/l)} > 80\,[\%] \\ (condition\ 2) & R_{(fu/fl)} > 5\,[\%] \end{array}\right\}, \tag{19}$$

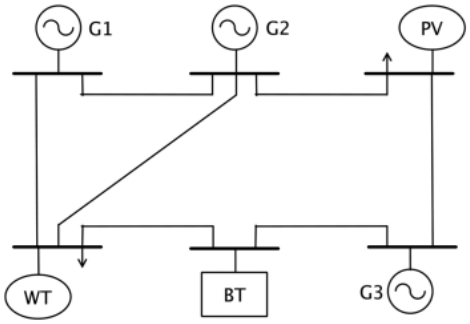


FIGURE 4 Test system model

$$LFC_{u/l}^{post} = \begin{cases} LFC_{(u/l)}^{pre} \times \frac{R_{LFC}^{(u/l)}}{80} & (condition\ 1) \\ 0.1 & \end{cases}, \tag{20}$$

where ${R_{LFC}}^{(u/l)}$ is the upper/lower limit closing rate of LFC reference, $LFC_{\ signal}$ is the LFC reference, $LFC_{(u/l)}$ is the upper/lower limit of LFC capacity (± 0.05 – ± 0.1), *pre* is before scheduling, *post* is after scheduling, *u* is upper, and *l* is lower.

5 | SIMULATIONS

In this section, we present typical examples of numerical simulations to verify effectivity of the proposed system.

5.1 | Simulation models

Here, we explain about modeling of generators and a small independent power grid for simulations. The models were built with MATLAB/Simulink by MathWorks.

5.1.1 | Small grid model

In this study, we assumed a small independent power grid. In so doing, we intentionally introduced PVs and WTs to a greater extent than normally allowable. The modeled grid is shown schematically in Figure 4. The model pertains to a real power grid that was built on a remote island for experimental study.

5.1.2 | Generator models

The modeled generators were diesel engine (DE), PV, and WT.

- DE is composed of a synchronous generator, an engine, a governor, and an exciter. Park's model was used for the synchronous machine, a DE model by CRIEPI[12] was used for the engine and the governor, and IEEE standard model[13] was used for the exciter.

TABLE 2 Rated output

Generators	DEI	DE2	DE3	PV	WT
Rated output (KW)	2000	1250	2250	1000	1000

TABLE 3 Simulation cases

Cases	EV charging control	Restriction	Feedback	EV pattern
Case 1	–	–	–	Pattern 1
Case 2	○	○	–	Pattern 1
Case 3	○	○	–	Pattern 2
Case 4	○	○	○	Pattern 2

- PV is composed of solar cells series-parallel connected in modules, which are, in turn, arranged in an array. All the components were modeled, and actual data of insolation and air temperature were used.
- With WT, kinetic energy of wind is converted into rotation energy and is used then to generate electric energy. In so doing, electric energy that can be obtained per unit time is expressed as follows:

$$P = \eta \times \frac{1}{2}\rho A v^2 [W], \tag{21}$$

where η is the power generation efficiency, ρ is the air density (kg/m^3), A is the blade area (m^2), and v is the wind speed (m/s).

Weibull distribution model was adopted for wind speed in Equation (21).

5.2 | Simulation settings

Simulation period was set as follows:

Start: 0 (s), end: 10,800 (s)

Ratings of each generator are given in Table 2.

In this paper, we consider four cases in simulations. As shown in Table 3, each case presents different parameters–enabled functions of the on-demand control system and patterns of connected EVs acquired via information network (Figure 5). Insolation, generator output, and load are same in all simulation cases.

5.3 | Simulation results

Results obtained in each case are shown in Figures 6 to 9.

Results for cases 1 and 2 include (1) generation outputs, (2) frequency, (3) interconnection amount of intermittent renewable generators, (4) EV charging energy, (5) regulation capacity for fast fluctuations, and (6) regulation capacity for slow fluctuations. Results for cases 3 and 4 include (1) generation outputs, (2) frequency, (3) EV charging energy, (4) LFC reference, (5) DELD scheduled values, and (6) regulation capacity for slow fluctuations. Particularly, (4) pertains to LFC reference received from a control center, and (4) pertains to output values scheduled by DELD in increments of 5 min.

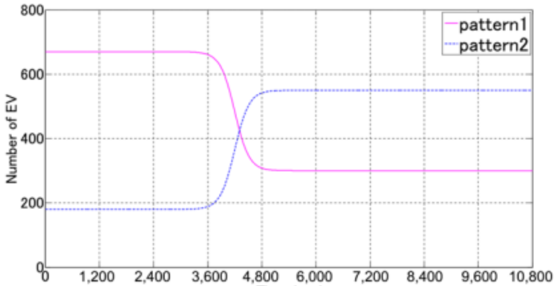


FIGURE 5 EV patterns [Color figure can be viewed at wileyonlinelibrary.com]

(1) Case 1 This is the base case when all functions of the on-demand control system are disabled. Here, causes of frequency fluctuations are confirmed by analysis of regulation capacity.

Consider first the period around 2400 s. In this period, abrupt drop in PV output coincides with a strong short-period fluctuation (Figure 6a). Required adjustment capacity grows in both cases and exceeds capacity available in the grid (Figure 6e and f); in so doing, frequency greatly decreases. Therefore, this drop in PV output could not be predicted, and regulation capacity proved insufficient.

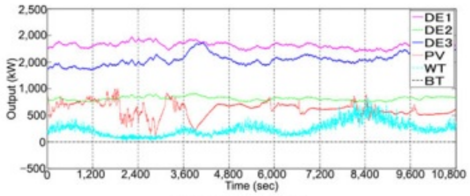
Next, consider the period around 8400 s. Here, WT output grows and small fluctuations increase, while PV output fluctuates as well. Regulation capacity required for fast fluctuations increases (Figure 6e), and frequency goes beyond 61 Hz (Figure 6b). In so doing, EV control is not applied, and charging energy is kept at its reference (1000 W).

(2) Case 2 In this case, EV charge control and output restriction are enabled in the on-demand control system. In cases 1 and 2, EV patterns are set so that the number of connected EVs decreases in second half of simulation. Effectiveness of EV charge control and output restriction are confirmed in the first half and second half, respectively.

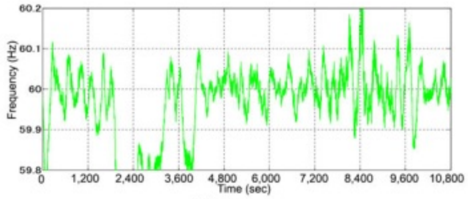
First, around 2400 s, sufficient regulation capacity is provided for fast fluctuations (Figure 7e), and frequency fluctuations are sufficiently absorbed by EV charge control.

Next, frequency fluctuations around 8400 s are absorbed by EV charge control; in addition, restriction is imposed to suppress surplus power. The restriction function is used only in this period, which is indicative of efficient real-time estimation. Besides, individual control works properly to determine the restriction amount; it should be noted that in this simulation, PV and WT produce power of almost same quality, which explains the small difference.

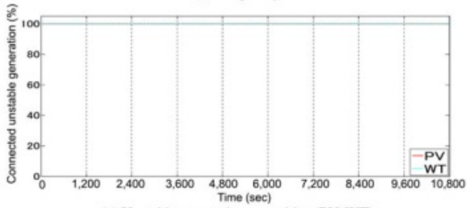
(3) Case 3 In this case, EV charge control and output restriction are enabled in the on-demand control system, but



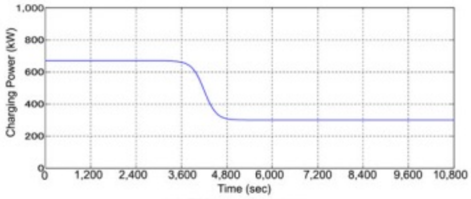
(a) Generation outputs



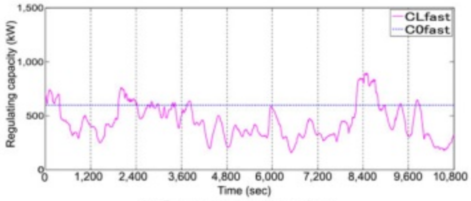
(b) Frequency



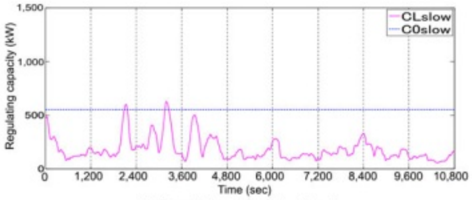
(c) Unstable generation capacities (PV, WT)



(d) EV charging power

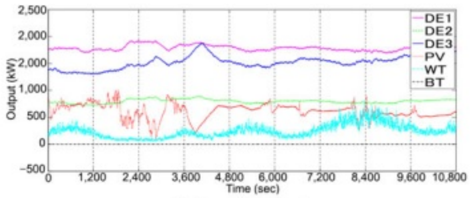


(e) Regulating capacities (fast)

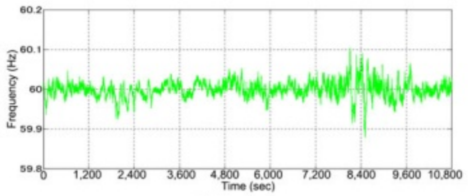


(f) Regulating capacities (slow)

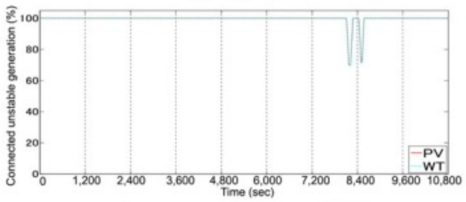
FIGURE 6 Results of case 1 [Color figure can be viewed at wileyonlinelibrary.com]



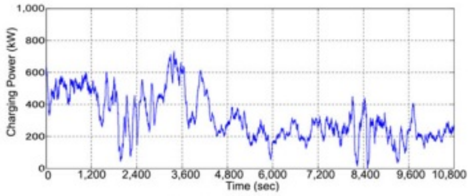
(a) Generation outputs



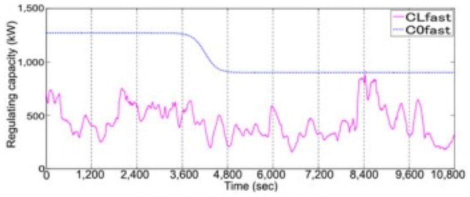
(b) Frequency



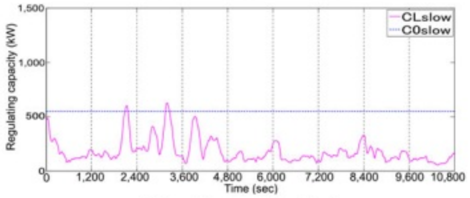
(c) Unstable generation capacities (PV, WT)



(d) EV charging power



(e) Regulating capacities (fast)



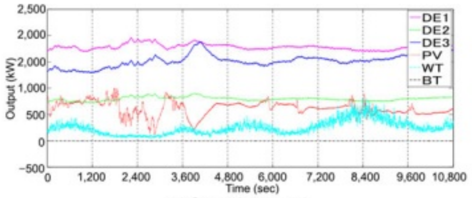
(f) Regulating capacities (slow)

FIGURE 7 Results of case 2 [Color figure can be viewed at wileyonlinelibrary.com]

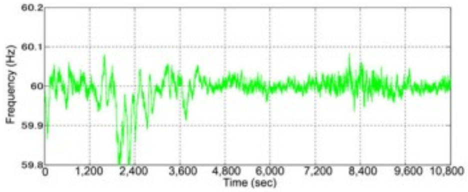
EV pattern is set so that the number of connected EVs increases in second half of simulation.

Consider first the period around 2400 s. As distinct from case 2, the number of connected EVs is small, and frequency fluctuations are not absorbed because of the shortage of EV adjustment capacity. LFC reference coincides with the lower limit, and any further control is impossible. Besides, frequency drop caused by such excess/deficiency of generation can be hardly handled by output restriction.

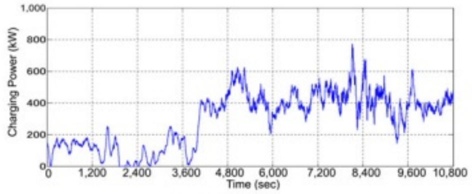
On the other hand, around 8400 s, the number of connected EVs grows as compared to case 2, and frequency fluctuations can be suppressed without output restriction.



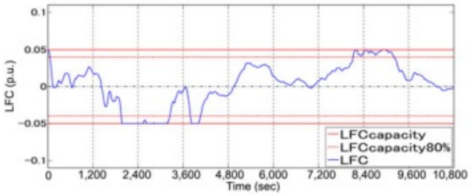
(a) Generation outputs



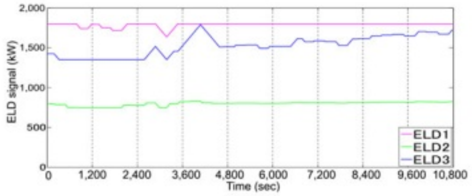
(b) Frequency



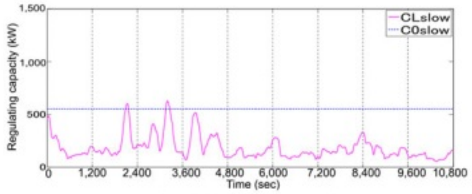
(c) EV charging power



(d) LFC signal

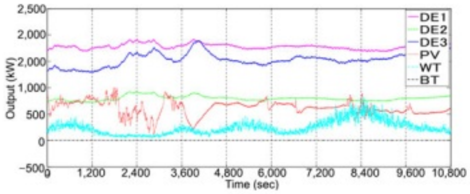


(e) DELD signal

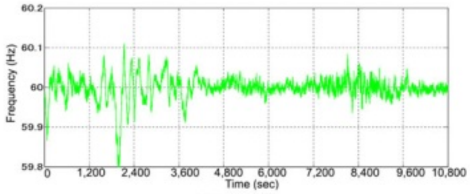


(f) Regulating capacities (slow)

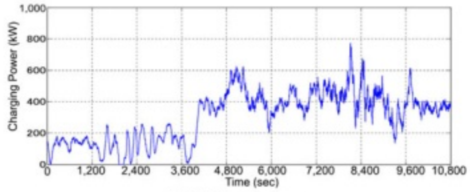
FIGURE 8 Results of case 3 [Color figure can be viewed at wileyonlinelibrary.com]



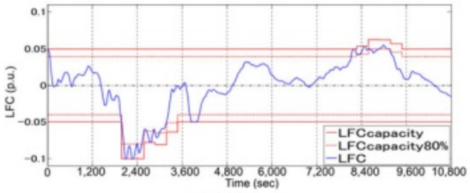
(a) Generation outputs



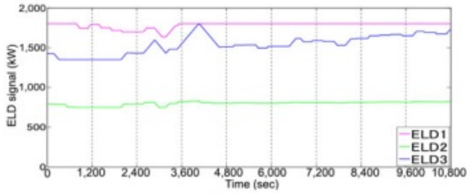
(b) Frequency



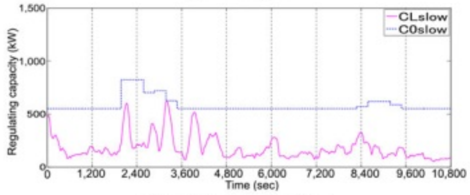
(c) EV charging power



(d) LFC signal



(e) DELD signal



(f) Regulating capacities (slow)

FIGURE 9 Results of case 4 [Color figure can be viewed at wileyonlinelibrary.com]

(4) Case 4 In this case, all functions of the on-demand control system are enabled. Here, the usefulness of feedback is confirmed by comparison with case 3. In both cases 3 and 4, outputs of intermittent renewable generators are not restricted.

In the period around 2400 s, as compared to case 3, DELD schedule is modified so that outputs of DE1, 2 are increased (Figure 9e). This is because the upper limit of LFC capacity for every generator is changed from 5% to 10% due to feedback so that the adjustment capacity (Equation (2)) grows by 1.4 times (Figure 9f). Thus, LFC control can be used more flexibly (Figure 9d), and frequency is brought back within its proper range faster than in 5 min (Figure 9b). As frequency returned to its reference, LFC capacity was promptly reduced so as to follow LFC reference (Figure 9d). Besides, the extension of LFC capacity was reflected in calculation of adjustment capacity (Figure 9f), thus confirming the system integration based on information sharing.

6 | CONCLUSION

In this paper, we proposed an on-demand control system for DS manager that maintains stable demand-supply adjustment even though output fluctuations of intermittent renewable generators exceed the limits of forecasts and schedules. The proposed system is intended for efficient EV charge control and output restriction of intermittent renewable generators; moreover, more flexible assurance of regulation capacity is implemented through feedback to DELD. In addition, we conducted numerical simulations to verify the effectiveness of integrating multiple control methods via an information network. In future, we would like to consider load shedding, demand response, and other issues.

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AUTHORS' BIOGRAPHIES

Yoshifumi Zoka, senior member. In 1995, Zoka completed the first term of doctorate at Hiroshima University (Graduate School of Engineering, Systems Engineering), in 1997 he was employed as an assistant by the University, in 2007 he became an assistant professor, and now he is an adjunct professor. From 2002 to 2003, he was a visiting assistant at University of Washington. He is a Doctor of Engineering. He received the 2006 IEIEJ Paper Encouragement Award. He has a membership of IEEE, IEIEJ, and JSER.

Keita Koshimoto, student member. In 2017, Koshimoto started the first term of doctorate at Hiroshima University (Graduate School of Engineering, System Cybernetics). He is involved in research of supply-demand control.

Masaki Muraoka, member. In 2017, Muraoka completed the second term of doctorate at Hiroshima University (Graduate School of Engineering, System Cybernetics), and was employed by West Japan Railway Co. When at University, he was involved in research of supply-demand control.

Yasunori Kuwada, nonmember. In 2015, Kuwada completed the first term of doctorate at Hiroshima University (Graduate School of Engineering, System Cybernetics), and was employed by JFE Steel Corp. When at University, he was involved in research of supply-demand control.

Yuki Mashima, nonmember. In 2014, Mashima completed the first term of doctorate at Hiroshima University (Graduate School of Engineering, System Cybernetics), and was employed by JFE Chugoku Electric Power Co. When at University, he was involved in research of supply-demand control.

Adelhard Beni Rehiara, nonmember. In 1999, Rehiara graduated from University of Vidyagama. In 2008, he completed postgraduate studies at HAN University, Netherlands. In 2015, he started the second term of doctorate at Hiroshima University (Graduate School of Engineering, System Cybernetics).

Yutaka Sasaki, member. In 2008, Sasaki completed the doctorate at Hokkaido University (Graduate School of Information Science and Technology), and was employed by Hiroshima University as an assistant professor (Graduate School of Engineering). In 2012, he became a visiting researcher at Washington State University. He is involved in research of planning, operation, and control of power systems. He is a Doctor of Information Science. He has a membership of IEEE, IET, IEIEJ, and JSER.

Naoto Yorino, fellow. In 1983, Yorino completed postgraduate studies at Waseda University, and was employed by Fuji Electric. In 1984, he started doctorate at Waseda University, and in 1985 he became an assistant at Waseda University. In 1987, he completed doctorate, and was employed as an assistant by Hiroshima University, in 1990 he became an assistant professor, and in 2005 he was a professor. In 1991, he was a visiting researcher at McGill University. He is a Doctor of Engineering. In 1985, he received the George Montefiore Award. He has a membership of IEEE, IREP, CIGRE, and IEIEJ.

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