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Modeling and analysis of inverter air conditioners for primary frequency control considering signal delays and detection errors

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Abstract

The primary frequency control (PFC) is becoming more important for maintaining the system balance between the generation and consumption. The progressed intelligent home system has made it easier for household appliances to provide PFC services to power systems. Among the appliances, inverter air conditioners (IACs) can adjust the operating power rapidly by changing the compressor frequency and have little influence on the customer comfort. In this paper, an IAC model is developed considering the thermal model of the room, whose compressor operating frequency is determined by the system frequency deviation and the temperature deviation between the room and the set value. Two control methods for the aggregated IACs are proposed, the centralized detection control (CDC) method and the distributed detection control (DDC) method. The system frequency is detected by the control center in the CDC method, while the system frequency is monitored locally by each IAC controller in the DDC method. Generally, the CDC method can get more accurately frequency detection than the DDC method. However, the control center in the CDC method has to send control signals to each IAC in real time, which causes communication delays for the IACs to adjust the operating power. As for the large-scale aggregated IACs, the simulation results show that the signal delays in the CDC method have more negative effects than the detection errors in the DDC method.

Keywords: inverter air conditioner, primary frequency control, sigal delay, detection error

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1. Introduction

The large-scale blackouts are increasing recently. For example, the blackout in Taiwan affected 6.68 million households on August 15, 2017 [1] and the blackout in Brazil affected 22.5% grid output on March 21, 2018 [2]. These blackouts raise awareness of the importance of the primary frequency control (PFC) for maintaining the balance between the generation and consumption. Traditionally, the PFC is provided by the generation units, such as the thermal power units and the gas turbine units [3]. However, traditional generation units are decreasing and may be not sufficient to deal with the large-scale contingency reserves.

With the development of the information and communication technology, the intelligent home systems have made great progress and been used by more houses, which makes it easier for household appliances to provide PFC services to power systems [4]. Among the appliances, air conditioners have a large share in the power consumption and can be regulated in a short time without much influence on the customer comfort [5]. Apart from the traditional fixed speed air conditioners, inverter air conditioners (IACs) can adjust the operating power rapidly by changing the compressor frequency and have little influence on the IAC life time [6]. Therefore, the IACs are suitable to provide PFC for the power systems. The IAC model is developed based on the experimental data in [7]. Reference [8] proposes an equivalent model of IAC, so that the aggregated IACs can be regard as a traditional generator to provide FRC services. However, the signal delays between the control center and each IAC are not considered in the exiting studies. Due to the accuracy of the system frequency detection devices, the detection errors should also be included in the IAC dispatch model.

This paper develops an IAC model considering the thermal model of the room. The IAC compressor operating frequency is controlled based on the system frequency deviation and the temperature deviation between the room and the set value. Two control methods for the aggregated IACs are proposed, the centralized detection control (CDC) method and the distributed detection control (DDC) method. The system frequency is detected by the control center in the CDC method, while the system frequency is monitored locally by each IAC controller in the DDC method. Generally, the CDC method can get more accurately frequency detection and have less errors than the DDC method. However, the control center in the CDC method has to send control signals to each IAC in real time, which causes signal delays for the IACs to adjust the operating power. As for the large-scale aggregated IACs, the simulation results show that the signal delays in the CDC method have more negative effects than the detection errors in the DDC method.

2. Modeling of inverter air conditioners

The power consumption of an inverter air conditioner (IAC) is related to the current indoor temperature and the ambient temperature. Therefore, it is necessary to build the thermal model of a room, which can be described as [8]:

$$c_A \rho_A V \frac{dT_A}{dt} = H_{gain}(t) - H_{IAC}(t) \tag{1}$$

where the c_A and ρ_A are the heat capacity and density of the air, respectively. V and T_A are the room volume and the indoor temperature, respectively.

H_{gain} is the heat gains of the room, which can be expressed as:

$$H_{gain}(t) = \left(U_{O-A} A_S + c_A \rho_A V \xi\right)\left(T_O(t) - T_A(t)\right) + H_{dis}(t) \tag{2}$$

where the U_{O-A} and A_S are the heat transfer coefficient and the surface area of the room, respectively. ξ is the air exchange times. T_O is the ambient temperature. H_{dis} is the random disturbances from people.

It is assumed that the IAC operates in the cooling mode. The refrigerating capacity H_{IAC} can be described as:

$$H_{IAC}(t) = l_Q P_{IAC}(t) + \sigma_Q \tag{3}$$

where P_{IAC} is the operating power. l_Q and σ_Q are the constant coefficients.

The operating power of an IAC is linearly correlation with the compressor frequency, which is expressed as:

$$P_{IAC}(t) = \kappa_P f_c(t) + \mu_P \tag{4}$$

where f_c is the operating frequency of the compressor. κ_P and μ_P are the constant coefficients.

3. Primary frequency control provided by aggregated inverter air conditioners

3.1. The control strategy of an inverter air conditioner

If the power consumption of the IAC can be regulated with the system frequency, the IAC can provide PFC service to the power system. As for an IAC, the compressor accounts for the maximum share of the power consumption. Therefore, the operating frequency of the IAC compressor should be regulated with the system frequency, which can be expressed as [8]:

$$\Delta f_c(t) = \theta \cdot \Delta T_{dev}(t) + \eta \cdot \int \Delta T_{dev}(t)dt + \delta \cdot \Delta f_s(t) \tag{5}$$

$$\Delta T_{dev}(t) = \Delta T_A(t) - \Delta T_{set}(t) \tag{6}$$

where ΔT_{dev} is the temperature deviation of the indoor temperature and the set temperature. θ and η are the constant coefficients of the proportional integral controller. Δf_s is the system frequency deviation. When the system operates in the stable state, the Δf_s is zero. δ is the regulating factor of the frequency. The operating frequency of the IAC compressor will change temporarily when the system frequency fluctuates around the rated frequency.

3.2. The centralized detection control of aggregated inverter air conditioners

The regulation power of one IAC is insignificant for the power system. Therefore, a large number of IACs should be aggregated and controlled to provide PFC service. There are two ways to detect the system frequency deviations, centralized detection control (CDC) method and distributed detection control (DDC) method.

The CDC structure is shown in Fig. 1, where the serial number shows the control procedure. The system frequency is detected by the control center. If the frequency deviates from the rated value, the control center will send signals to IACs to take actions to increase or decrease the compressor operating frequency. With the increase of the system frequency deviation, more IACs will participate in the response, which can be expressed as:

$$N_{IAC} = \begin{cases} 0 & , \left|\Delta f_s\right| \le \Delta f_s^{\min} \\ \dfrac{N_{IAC}^{\max}}{\Delta f_s^{\max} - \Delta f_s^{\min}} \Delta f_s & , \ \Delta f_s^{\min} \le \left|\Delta f_s\right| \le \Delta f_s^{\max} \\ N_{IAC}^{\max} & , \left|\Delta f_s\right| \ge \Delta f_s^{\max} \end{cases} \tag{7}$$

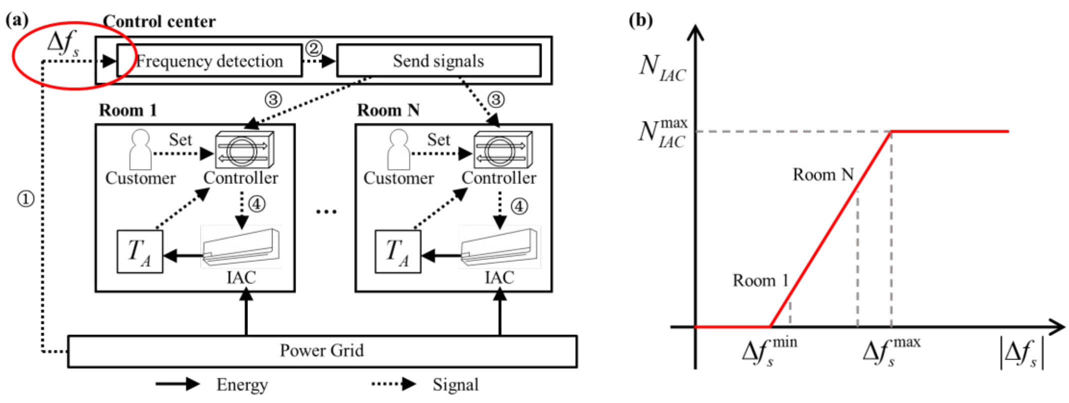


Fig. 1. The centralized detection control structure of aggregated inverter air conditioners.

3.3. The distributed detection control of aggregated inverter air conditioners

The distributed detection control (DDC) method is shown in Fig. 2. Different from the CDC method, the system frequency is detected by each controller of the IAC. In order to make more IACs participate in the response with the increase of the frequency deviation, the control center will set different frequency thresholds for IACs. The frequency thresholds are randomly distributed among the IACs.

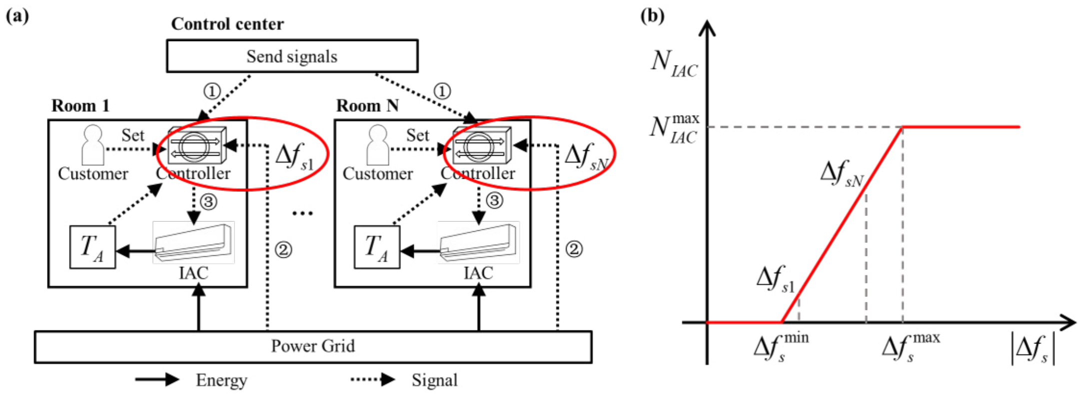


Fig. 2. The distributed detection control structure of aggregated inverter air conditioners.

3.4. The advantages and disadvantages of the two detection control methods

Generally, the number of the frequency detection devices in the CDC method is far fewer than that in the DDC method. The frequency detection accuracy in the CDC method will influence the control of all the IACs. Therefore, the detection device in the CDC should be selected more strictly, which can monitor the system frequency more accurately, compared with that in the DDC method. However, the control center has to send signals to the IACs in real time, which will lead to some communication delays.

The control center in the DDC method will set frequency thresholds to each IAC in advance. The system frequency deviation is detected locally. If the system frequency deviation is over the threshold, the controller will take action and the IAC will change the compressor operating frequency. Therefore, there are less communication delays in the DDC method. However, in order to reduce the cost of the large number of controllers, the frequency detection is not so accurate as that in CDC method and has more detection errors. The case studies will analyze the effects of the communication delays and the detection errors in the two methods.

4. Case studies

4.1. The test system

The test model is shown in Fig. 3 [8]. The number of the aggregated IACs is 30,000, and the corresponding room areas follow the normal distribution. The mean value is $100\,m^2$ and the standard deviation is $40\,m^2$. The height of the rooms is $2.5\,m$. The heat capacity c_A and the density ρ_A of the air are $1.005\,kJ/(kg\cdot °C)$ and $1.205\,kJ/m^3$. The heat transfer coefficient and the air exchange times are $3.60\,W/(m^2\cdot °C)$ and $0.50\,(1/h)$, respectively. The heat power of disturbances Q_{dis} are 0.43kW. The constant coefficients κ_P and μ_P are 0.04kW/Hz and 0.02kW, respectively. The constant coefficients l_Q and σ_Q are 3 and -0.11kW, respectively. It is assumed that the ambient temperature is 33ºC and the set temperature of the IACs is 26 ºC. The minimum threshold of the system frequency deviation is 0.01Hz, and the maximum threshold is 0.03Hz. The compressor's frequency range is 1~150Hz. The constant coefficients of the proportional integral controller θ and η are 0.52Hz/ºC and 0.032Hz/(s· ºC), respectively. The proportional parameter δ is 200. The parameters of the reheat steam generator are shown in Table 1. It is assumed that the initial load is 560MW and the load deviation ΔP_D is 80MW.

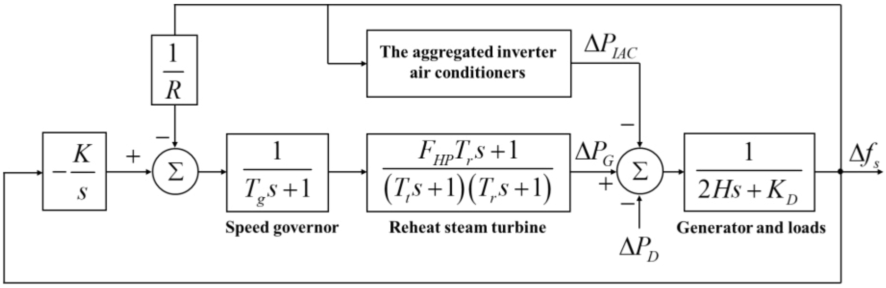


Fig. 3. The test system.

Table 1. The parameters of the reheat steam generator [8].

Symbols	Descriptions	Values	Units
P_G	generation capacity	800	MW
H	generator inertia	10	n/a
K_D	load-damping factor	0.50	n/a
T_g	speed governor time constant	0.2	s
T_r	reheat time constant	7.0	s
T_t	turbine time constant	0.3	s
F_{HP}	high pressure turbine section	0.3	n/a
R	speed droop parameter	0.05	n/a
K	integral gain	0.50	n/a
f_s	rated system frequency	50	Hz

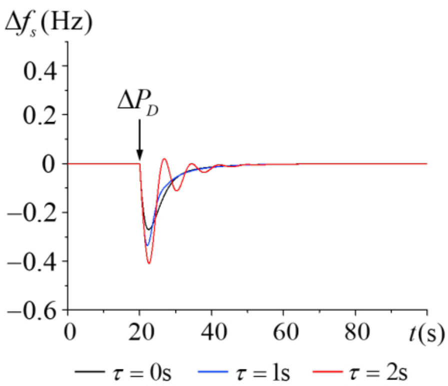
4.2. The analysis of the signal delays in the CDC method

The aggregated IACs is controlled by CDC method and have signal delays. The system frequency deviation in the simulation can be expressed as:

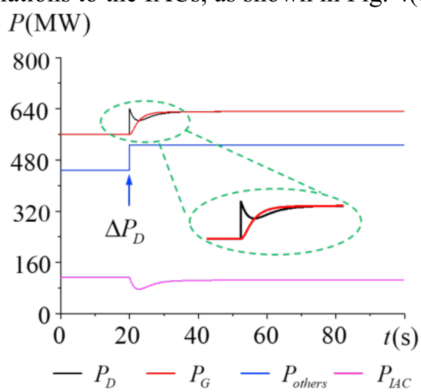
$$\Delta f_s(t) = \begin{cases} 0 & ,t \le \tau \\ \Delta f_s(t-\tau) & ,t > \tau \end{cases} \tag{8}$$

where τ is the delay time.

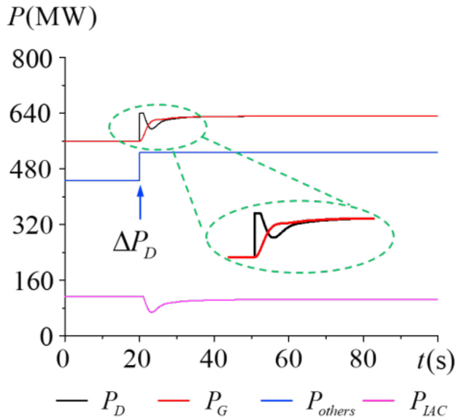
Three cases are studied with different delay time ($\tau = 0$s, 1s, 2s). Fig. 4 shows the simulation results, where $P_D = P_{IAC} + P_{others}$. It can be seen that IACs can reduce the power consumption when the system frequency drops. Due to the delay time of the frequency detection in Case 2 and Case 3, the power consumption of IACs has no response at the moment of deviation occurrence, which get changed in 1s and 2s later, respectively, as shown in Fig. 4(c) and (d). Moreover, the signal delay brings the power oscillations to the IACs, as shown in Fig. 4(d).



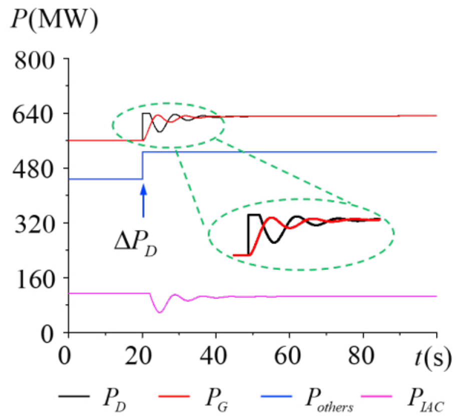
(a) The system frequency deviations.



(b) The power deviations ($\tau = 0$s).



(c) The power deviations ($\tau = 1\mathrm{s}$).



(d) The power deviations ($\tau = 2\mathrm{s}$).

Fig. 4. The simulation results of the signal delays in the CDC method.

The maximum frequency deviation $\Delta f_s^{\max}$ is larger with the increase of the delay time, as shown in Fig. 4(a) and Table 2. In Case 1, the $\Delta f_s^{\max}$ is 0.270Hz, and increases to 0.409Hz in Case 3. The signal delay also brings frequency oscillations to the system during the frequency recovery process, as shown in Fig. 4(a). Therefore, we can conclude that the primary frequency control is time-sensitive. Several seconds delay may disable the frequency regulation function of IACs. From this viewpoint, the DDC method, which detects the system frequency locally, has more advantages in reducing the delay time than the CDC method.

Table 2. The simulation results of the signal delays in the CDC method.

Case	$\Delta f_s^{\max}$ (Hz)	$\Delta P_{IAC}^{\max}$ (MW)
Case 1	-0.270	-36.56
Case 2	-0.335	-44.80
Case 3	-0.409	-55.04

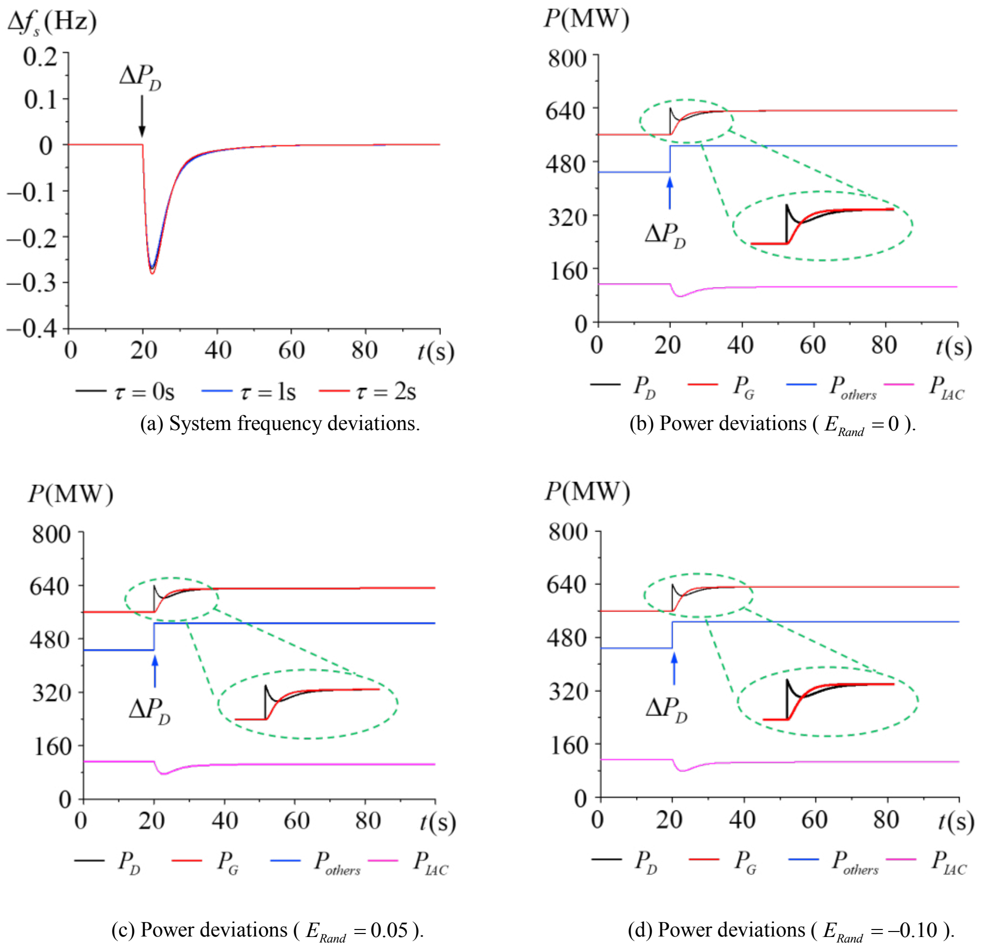
4.3. The analysis of the detection errors in the DDC method

The aggregated IACs is controlled by DDC method and have system frequency detection errors. The system frequency deviation in the simulation can be expressed as:

$$\Delta f_s(t) = \left(1 + E_{Rand}\right)\Delta f_s(t) \tag{9}$$

where E_{Rand} is the frequency detection errors.

Three cases are studied with different frequency detection error ($E_{Rand} = 0,\ 0.05,\ -0.10$). The simulation results are shown in Fig. 5 and Table 3. It can be seen that the maximum frequency deviation $\Delta f_s^{\max}$ will be smaller when the frequency detection error enlarges the actual deviations. On the contrary, the $\Delta f_s^{\max}$ will be larger when the detection error narrows the actual deviations.



(a) System frequency deviations.

(b) Power deviations ($E_{Rand} = 0$).

(c) Power deviations ($E_{Rand} = 0.05$).

(d) Power deviations ($E_{Rand} = -0.10$).

Fig. 5. The simulation results of the detection errors in the DDC method.

In the actual system, the frequency detection errors caused by the IACs' detection devices are randomly distributed among zero. Therefore, as for the aggregated IACs, the positive errors and the negative errors can approximately counteract. The impacts of the detection errors can be ignored.

Table 3. The simulation results of the detection errors in the DDC method.

Case	$\Delta f_s^{\max}$ (Hz)	$\Delta P_{IAC}^{\max}$ (MW)
Case 1	-0.270	-36.56
Case 4	-0.265	-37.60
Case 5	-0.281	-34.32

5. Conclusions

Both the centralized detection control (CDC) method and the distributed detection control (DDC) method can make the aggregated inverter air conditioners (IACs) provide primary frequency control services. The signal delays in the CDC method will enlarge the system frequency deviation and bring frequency oscillations. The detection errors in the DDC method have little influences on the system frequency deviation. Therefore, as for the large-scale aggregated IACs, the DDC method is more appropriate than the CDC method.

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References

[1] Wu H, et al. Administrative investigation report on the 815 power failure. Executive Yuan, Taiwan, Republic of China, Tech. Rep. 1060907, Sep. 2017. <http://www.ey.gov.tw>

[2] U.S. News. Tens of Millions in Northern Brazil Hit by Massive Power Outage. <https://www.usnews.com/news/world/articles/2018-03-21/tens-of-millions-in-northern-brazil-hit-by-massive-power-outage>

[3] Rebours YG, Kirschen DS, Trotignon M, Rossignol S. A survey of frequency and voltage control ancillary services—Part I: Technical features. IEEE Trans. Power Syst., vol. 22, no. 1, pp. 350-357, Feb. 2007.

[4] Siano P. Demand response and smart grids—A survey. Renew. Sustain. Energy Rev., vol. 30, pp. 461-478, Feb. 2014.

[5] Hui H, Ding Y, Liu W, Lin Y, Song Y. Operating reserve evaluation of aggregated air conditioners. Appl. Energy, vol. 196, pp. 218-228, Jun. 2017.

[6] What is Inverter Technology AC, Bijli Bachao, Tech. Rep., 2017. <https://www.bijlibachao.com>

[7] Shao S, Shi W, Li X, Chen H. Performance representation of variable-speed compressor for inverter air conditioners based on experimental data. Int. Journ. Refrig., vol. 27, no. 8, pp. 805-815, Dec. 2004.

[8] Hui H, Ding Y, Zheng M. Equivalent Modeling of Inverter Air Conditioners for Providing Frequency Regulation Service. IEEE Trans. Ind. Electron. doi: 10.1109/TIE.2018.2831192, in press, 2018.