IoT and Edge Computing Based Direct Load Control for Fast Adaptive Frequency Regulation

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***Abstract*—Fast and accurate load control is helpful in maintaining grid frequency stability in case of emergency. Conventional under-frequency load shedding schemes (UFLS) suffer from low granularity while individual frequency-load control methods require sophisticated controllers and therefore are cost-prohibitive. This paper presents an innovative framework, Grid Sense, for fast and adaptive load control based on the Internet of Things (IoT), edge computing, and nonintrusive load monitoring (NILM). Grid Sense provides a promising cost-effective solution for large-scale deployment of individual load control using existing communication infrastructure in a distributed manner. Now that the Grid Sense system is being implemented in several pilot projects in State Grid Jiangsu Electric Power Company, this papers summarizes the major technologies utilized, system design considerations, and experimental results during its development process.**

***Index Terms*— IoT, Edge computing, Smart Plugs, Nonintrusive load identification, Frequency regulation.**

I. INTRODUCTION

With increasing penetration of power electronics interfaced devices and renewable energy resources [1]-[2], electric power systems are facing grand challenges from growing system dynamics and randomness. On this account, system operators have witnessed increasing difficulties in maintaining system frequency stability. For China, many ultra-high voltage direct current (UHVDC) transmission lines have been built and put into operation [3] over the past decade. With each carrying gigawatts of power, any of these UHVDC systems, if fails to operate, can cause severe system-wide frequency problems leading to catastrophic blackouts.

Many schemes have been developed in the past for power system frequency control at/under different time scales and scenarios. Conventional hierarchical control including primary, secondary, and tertiary loops work well for trivial/mild disturbances, but become ineffective in the face of severe disturbances or contingencies. Under-frequency load shedding schemes cut off load of an entire area when emergency occurs, and therefore suffers the problem of low granularity. Existing individual load frequency control requires specially designed controllers or modifications to the load circuitry and can be cost ineffective for large-scale deployment. In recent years, a few demand response strategies including direct load control are proposed as alternative approaches for frequency regulation [4]. However, most of them are not fast enough to deal with major contingencies, e.g., the sudden tripping of an HVDC line or major generator which can cause severe system frequency drop within seconds. In addition, large-scale deployment of direct load controls under the existing paradigm is hindered by huge investment required to upgrade the existing infrastructure [5]-[8].

Recent technology advancement in the area of IoT, cloud and edge computing have demonstrated huge potential in changing the way how load can be managed and controlled [9]. By interconnecting a tremendous number of loads into the IoT network and managing them through the cloud, various services can be provided to power systems when help is most needed. Inspired by this idea, a “Grid Sense” system is developed as an IoT and edge computing based load control platform, which serves as a holistic cyber-physical solution for fast adaptive system frequency regulation during emergency conditions. With promising experimental results observed, the Grid Sense system is presently being deployed in several pilot projects in State Grid Jiangsu Electric Power Company. This paper summarizes the technologies utilized, major technical breakthroughs, and experimental results during the development of Grid Sense.

The following innovations and contributions are made:

- An innovative framework based on IoT is developed for direct control of loads in a fast and distributed manner.
- Edge computing paradigm is utilized based on a proposed extended Kalman filtering approach for local frequency tracking, which greatly reduces the communication requirements of the system while ensures its reliability. The proposed algorithm uses minimum computing resources and works on low-cost IoT/SoC chips.
- Nonintrusive load monitoring algorithm is implemented to identify load type locally, so that “soft” and flexible load control becomes feasible.
- An innovative layered coordination scheme is developed so that decisions are made locally in the fastest way (in milliseconds) while coordination and management are done through the cloud.

The rest of this paper is organized as follows. Section II explains the principles and features of Grid Sense in detail, followed by the frequency regulation strategy in Section III. The development and implementation of Grid Sense is described in Section IV. The case studies for frequency

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regulation using Grid Sense are conducted in Section V. Conclusions are drawn in Section VI.

II. PRINCIPLES AND FEATURES OF GRID SENSE

The overall cyber-physical structure of the Grid Sense system is shown in Fig. 1.

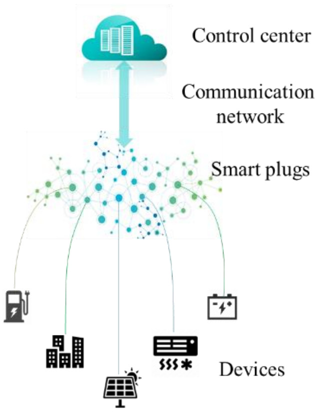


Fig. 1 Structure of the Grid Sense System

The major components are:

- Control center: monitor, control and manage the smart plugs
- Communication network: facilitate the communication between the control center and smart plugs
- Smart plugs: monitor and control the connected devices in real-time
- Devices: include air conditioners, refrigerators, batteries, PV generations, etc. All kinds of home and commercial appliance devices within the rated power can be plugged into the smart plugs

The essential principles and technologies of Grid Sense are elaborated as follows.

- *IoT Devices*

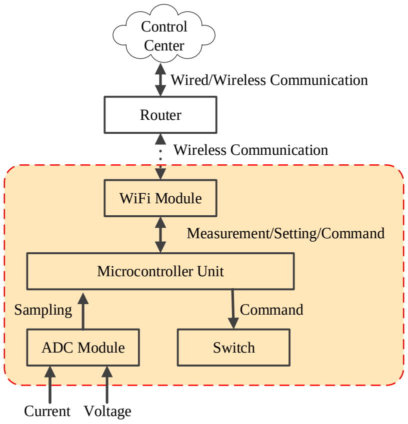


Fig. 2 Function blocks of the smart plug

As an IoT device, the smart plugs play a key role in the Grid Sense system. It can measure the frequency, voltage, current, active and reactive power in real-time; send the measurement to the cloud-based control center; control the switch based on local measurements or the commands from the control center; and receive settings from the cloud. The function blocks of the smart plugs are depicted in Fig. 2.

- *Nonintrusive Load Monitoring*

The NILM method is able to identify the loads from the aggregated measurements [10]. While it is primarily developed for smart meters, it can be used for smart plugs as well. Generally, the NILM methods can be divided into on-line-NILM and off-line-NILM depending on the time length of the measurements required for identification. In the Grid Sense system, we focus on the on-line-NILM to quickly identify the loads for fast frequency regulation. As the number of appliances connected to a smart plug is usually less than that of a smart meter, the accuracy of the smart-plug-based NILM is expected to be enchanced.

- *Edge Computing*

Edge computing is a recently proposed concept related to smart intelligent objects and distributed sensing/control networks. The edge computing technology can completely or largely finish the computation task in the distributed objects to alleviate the amount of data that needs to be transmitted, reducing the communication burden [9]. This idea well fits into smart plugs, which is a distributed intelligent device with moderate communication capability.

- *Cloud Computing*

While edge computing is adopted for fast local control of the smart plugs, cloud computing is utilized to process and analyze the big data received from the smart plugs. Also, the cloud-based control center can collect information about the power system state, load/ renewable forecasting to make the optimal coordination strategies for the smart plugs and avoid insufficient /excessive load shedding in case of a contingency.

- *Load Aggregation*

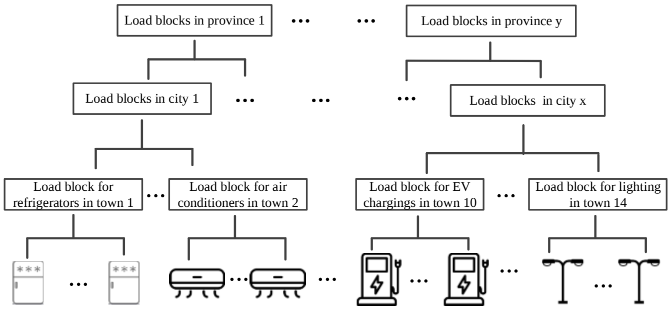


Fig. 3 Aggregation of the loads

The smart plugs periodically transmit the measurements to the control center to keep it updated about their statuses. The control center aggregates the widely distributed smart plugs into hierarchical blocks considering the types of appliances and their locations, as shown in Fig. 3. The total power of each block, as well as the total power of all the blocks P_{total}, can be calculated. The blocks serve as the basis for the control and management of the smart plugs. Note that the blocks are not fixed but can dynamically change, merge or divide as needed.

Based on the above principles, the features and advantages of Grid Sense can be derived as follows:

- Fast: As fast frequency tracking method is adopted, the smart plugs can monitor the frequency change rapidly and switch off the appliance in milliseconds if a severe contingency is detected. The response to a contingency does not depend on the communication, thus will not be affected by the communication delay.
- Adaptive: the control center can monitor the power system states and smart plugs' statuses in real-time , and estimate the potential contingencies. Based on them online optimal coordinations strategies can be carried out and sent to the smart plugs adaptively.
- Cost-effective: Grid Sense utilizes the widely distributed loads for fast frequency regulation, thus the investment needed for building new generation resource, transmission line and storage can be saved. Further, Grid Sense provides an IoT-based approach to monitor, aggregate and control the loads, which reduces the investment needed for specially designed communication and costly hardware.
- High granularity: By combining the edge computing and cloud computing, the NILM method can be implemented to distinguish the load types, and curtail the non-critical appliances with a priority when load shedding is needed, minimizing the impacts of load shedding on the customers.

Therefore, it is promising that the proposed Grid Sense framework can be widely deployed. Actually, besides frequency regulation, Grid Sense has many other potential applications, e.g., demand response and power market, as shown in Fig. 4.

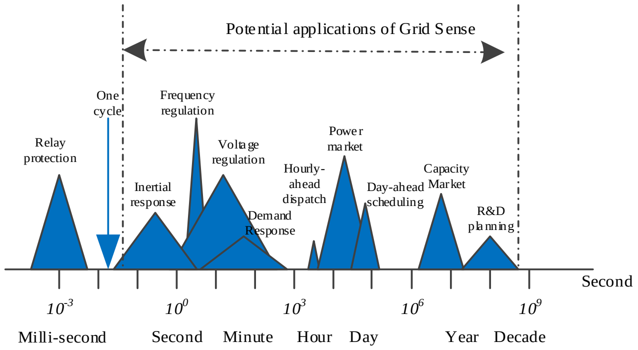


Fig. 4 Potential applications of Grid Sense

III. FREQUENCY REGULATION STRATEGY OF GRID SENSE

In the literature, the strategies for load demand control can be divided into three categories: centralized control, decentralized control and hybrid control [4]. Generally, the centralized control requires fast two-way communication with acceptable delay, while the decentralized control is difficult to achieve a globally optimal result. Thus, a hybrid strategy is proposed in this paper, which combines centralized online contingency estimation and parameter setting of the control center, and the decentralized real-time measurement and decision-making of the smart plugs.

A. *Control Strategy of Control Center*

A typical frequency dynamics curve in response to the sudden loss of a generator or the sudden increase of the loads is shown in Fig. 5. The frequency dips until the nadir frequency f_{nadir} is reached, then the frequency will go up until a new equilibrium is achieved.

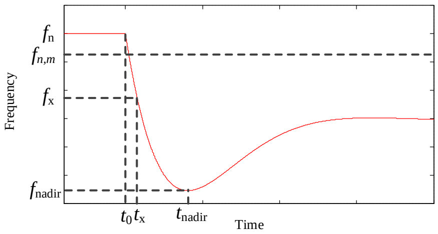


Fig. 5 Typical system dynamics following a power deficit

According to [11], given the initial power deficit ΔP at time t_0=0, the frequency dynamics can be obtained as

$$\Delta f(t) = -\frac{R\Delta P}{DR+K_m}[1+\alpha e^{-\zeta\omega_n t}\sin(\omega_r t+\emptyset)] \tag{1}$$

and the rate of frequency change (ROFC) value $g(t)$ can be calculated as

$$g(t) = \frac{d\Delta f(t)}{dt} = -\frac{\alpha\omega_n R\Delta P}{DR+K_m}e^{-\zeta\omega_n t}\sin(\omega_r t+\emptyset_1)] \tag{2}$$

where $\Delta f(t)$ is the frequency change; D is the amount of load damping; H is the equivalent inertia constant of the system; F_H is the fraction of the power generator by the reheat turbine; K_m is the power gain factor; R is a constant of the govenor speed-droop control. $\emptyset$, $\emptyset_1$, α, ω_n , ω_r and ζ are calculated parameters [11]-[12].

The nadir frequency f_{nadir} is reached when the $ROFC$ becomes zero. Thus, the time t_{nadir} needed to reach f_{nadir} can be calculated.

$$t_{nadir} = \frac{\pi-\emptyset_1}{\omega_r} = \frac{1}{\omega_r}tan^{-1}(\frac{T_R\omega_r}{\zeta\omega_n T_R-1}) \tag{3}$$

Therefore, f_{nadir} can be calculated as

$$f_{nadir} = f_n - \frac{R\Delta P}{DR+K_m}[1+\alpha e^{-\zeta\omega_n t_{nadir}}\sin(\omega_r t_{nadir}+\emptyset)] \tag{4}$$

where f_n is the pre-contingency steady-state frequency.

The control objective of Grid Sense is to ensure that the system frequency does not drop to the point of triggering the UFLS while minimizing the amount of load shedding by the smart plugs. The starting frequency of the UFLS varies in different systems, which is 49 Hz in China with nominal frequency of 50 Hz. For safety, we choose a frequency threshold slightly higher than the starting frequency of the UFLS, denoted as $f_s = 49.1$Hz. Hence, the threshold power loss ΔP_s which makes the frequency drop to f_n as the nadir frequency can be obtained as

$$\Delta P_s = \frac{(f_n - f_s)\times(DR+K_m)}{R\times[1+\alpha e^{-\zeta\omega_n t_{nadir}}\sin(\omega_r t_{nadir}+\emptyset)]} \tag{5}$$

The control center keeps monitoring the power system state and the statuses of the smart plugs, and predict the possible contingencies. Assume the maximum sudden power deficit that could be induced among all the possible contingencies is

ΔP_{max}, the minimal controllable power ΔP_v that needs to be prepared to prevent the frequency from dropping below f_s is estimated as

$$\Delta P_v = \begin{cases} \Delta P_{max} - \Delta P_s & if\ \Delta P_{max} > \Delta P_s \\ 0 & if\ \Delta P_{max} \le \Delta P_s \end{cases} \tag{6}$$

The major control strategy of the Grid Sense control center is described in Fig. 6.

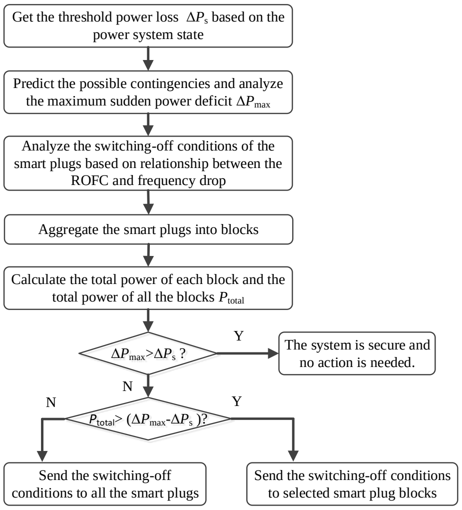


Fig. 6 Control strategy of Grid Sense control center

B. *Control Strategy of Smart Plugs*

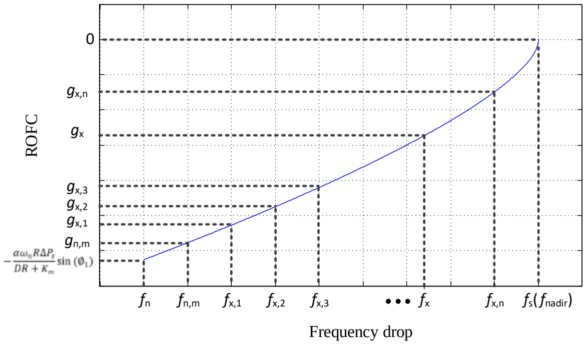


Fig. 7 The relationship between the ROFC and frequency drop

In a frequency response curve caused by the threshold power loss obtained in (5), for any frequency value f_x between f_s and f_n, a ROFC value g_x can be found. A typical relationship between the ROFC and the frequency can be represented in Fig. 7. The control strategy of the smart plugs in response to the frequency drop is derived as follows: if the real-time frequency value is f_x and at the same time the ROFC value is lower than g_x, the switching-off condition is satisfied. For robustness, the smart plug will cut the load only when the switching-off condition is met for three times.

Further, the control strategy is improved considering more practical factors as follows. (1) The frequency may fluctuate in the normal operation. For example, the normal operating frequency range in China can be [49.9 Hz, 50.1Hz]. The smart plugs should not cut the load within this range in order to avoid the mis-tripping caused by noises or measurement errors. The smart plug will take action only when the frequency drops below the lower bound $f_{n,m}$ which is 49.9 Hz in this case. (2) The range between f_s and f_n is divided into a finite number of intervals for practical implementation, as shown in Fig. 7.

IV. IMPLEMENTATION OF GRID SENSE

Currently, the Grid Sense system is being implemented in several pilot projects in State Grid Jiangsu Electric Power Company, the largest provincial power company in China. The development progress is briefly presented as follow.

a). Hardware Prototype b). Packaging

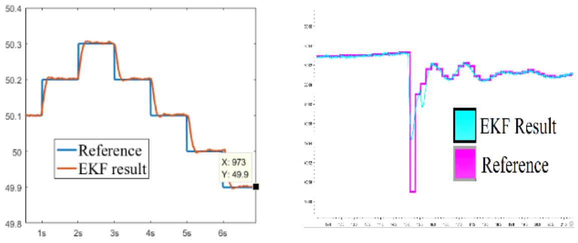
Fig. 8 Development of the Grid Sense smart plugs

The hardware of the smart plugs has been developed and tested as shown in Fig. 8. The extended Kalman filter (EKF) method is implemented in the smart plugs for frequency tracking. The voltage signal sampled by A/D passes a digital low pass filter and is fed into the EKF whose state is as follows.

$$x[k] = \begin{bmatrix} x^c[k] \\ x^s[k] \\ \omega[k] \end{bmatrix} = \begin{bmatrix} A\cos(\delta)\cos(\omega k/f^s) \\ A\sin(\delta)\sin(\omega k/f^s) \\ \omega \end{bmatrix} \tag{7}$$

$$y[k] = A\cos\left(\frac{\omega k}{f^s} + \delta\right) + \varepsilon[k] = x^c[k] + x^s[k] + \varepsilon[k] \tag{8}$$

where $y[k]$ is the signal samples at instant k, A is the magnitude, $\omega = 2\pi f$ is the angle speed, f^s is the sample frequency, δ is the phase angle, $\varepsilon[k]$ is the noise, and $x[k]$ is the system state. One frequency result is reported by the EKF algorithm every 16ms. The dSPACE hardware-in-the-loop test results of frequency step change and real-world UHVDC fault data are shown in Fig. 9.



a). Simulation of Step Change b). True Frequency Dip Event

Fig. 9 Performance of the frequency tracking algorithm

Fig. 10 Control center user interface

The smart plug connects to a router by WiFi while the router is connected to the Internet. The communication between the control center and a large amount of geographically distributed smart plugs is achieved using the MQTT protocol, a lightweight protocol widely used in the IoT.

The cloud-based control center is developed and it can receive the measurements from the smart plugs; detect the locations of the smart plugs; store, analyze and display the space-temporal measurement information on a map. It can also send settings and control commands to massive smart plugs. To facilitate the power system operators, a user-friendly interface is designed, as shown in Fig. 10.

V. CASE STUDIES

In order to verify the performance of the proposed Grid Sense, case studies are performed using a modified IEEE 24-bus system. The original system [13] has 32 generators, and in this modified system the three generators on bus 23 are removed, an interconnection line between bus 23 and an external system is added. Assume the rated power of the interconnection line is 1000 MW, thus the tripping of the interconnection line is the most serious single contingency.

The parameters used in the frequency dynamics model are as follows. The H and R are 5.8s and $1/17$ for a generator whose rated power is less than 100 MW, respectively; 8.1s and $1/20$ for a generator whose rated power is between 100 MW and 200 MW, respectively; 9.3s and $1/22$ for a generator whose rated power is larger than 200 MW, respectively. D is 2.5, F_H is 0.3, T_{R} is 8 and K_{m} is 0.95. Based on the above parameters, it is calculated that t_{nadir} is 3.72 seconds. The threshold power loss ΔP_s is 633 MW which makes the frequency drop to 49.1Hz minimally.

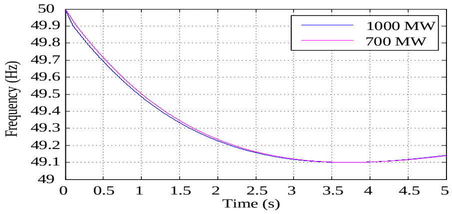


Fig. 11 Frequency regulation performance of Grid Sense with sufficient load

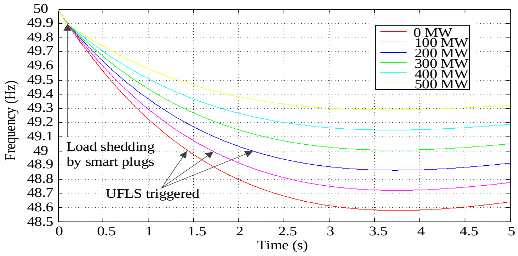


Fig. 12 Influence of the amount of controllable load

Case studies are conducted to verify the frequency regulation performance of Grid Sense, as shown in Fig. 11. When the power of the interconnection line is 1000 MW, the minimal controllable power that needs to be available is 367 MW； and the minimal controllable power will decrease to 67 MW when the power of the interconnection line is 700 MW. It is shown for these two cases that the frequency will not drop below 49.1 Hz, and the system is secure with the required power provided by Grid Sense.

In addition, sensitivity studies are carried out to check the influence of different amounts of controllable load. Assume a sudden power loss of 1000 MW, the system frequency dynamics in the event of different amounts of controllable load is presented in Fig. 12. It can be seen when the amount of controllable load is sufficient, the system is secure; when it is insufficient, it may be unable to prevent the UFLS, but the speed of frequency drop can be reduced.may

VI. CONCLUSIONS

This paper presents an IoT and edge computing-based Grid Sense system for fast frequency regulation utilizing the distributed user-end loads. Its architecture, principles, major technologies, features and control strategies are explained in detail. The practical implementation of Grid Sense is described. Simulation studies are conducted on a modified IEEE 24-bus system, and it validates the proposed Grid Sense framework and control strategy is fast, cost-effective and adaptive.

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