2023 IEEE the 7th Conference on Energy Internet and Energy System Integration

HIL-based Distributed Control of Inverter-Air-Conditioner for Power System Frequency Regulation

Yuming Zhao
Shenzhen Power Supply Company
China Southern Power Grid
Shenzhen, China
zhaoym97@sina.c

Tong Wu*
Zhuhai UM Science &
Technology Research Institute
University of Macau
Zhuhai, China,
zumri.tongwu@umac.mo

Silin Chen
Shenzhen Power Supply Company
China Southern Power Grid
Shenzhen, China
chensilin@sz.csg.cn

Hongxun Hui
State Key Laboratory of Internet
of Things for Smart City
Department of Electrical and Computer
Engineering
University of Macau
Macau, China,
hongxunhui@um.edu.mo

2023 IEEE 7th Conference on Energy Internet and Energy System Integration (EI2) | 979-8-3503-4509-4/23/$31.00 ©2023 IEEE | DOI: 10.1109/EI259745.2023.10513319

***Abstract*—The goals of carbon peaking and carbon neutrality goals bring a fast extension of renewable energy such as photovoltaic power(PV) and wind power. While providing abundant clean power, the intermittent output also brings power imbalance problems and results in frequency fluctuation and power shortage. Since the demotion of traditional power generators reduces their regulation ability in power balancing, demand side load is considered a satisfactory regulation resource. Inverter air conditioners(IAC) are a widely approved demand response resource because of their flexibility, universality, and ability to maintain customers' comfort. With a great amount of IAC implemented, adopting a reasonable control strategy is important. Centralized control is a commonly used method; however, to develop the communication efficiency and extensibility potential of IAC in larger city scenarios, this paper proposed a Hardware-In-the-Loop(HIL) distributed control method for IAC participating frequency regulation demand response service with Breadth First Search(BFS) strategy based on the Realtime Digital Simulator(RTDS) platform. The HIL clients are Raspberry Pi-4B and ESP8266 chips, implemented with the IAC model for demand response service.**

***Index Terms*—demand response, inverter-air-conditioner, distributed control, graph theory, breadth-first search.**

I. Introduction

The worldwide carbon-reducing movement strongly encourages the usage of renewable energy. While releasing the stress of fossil energy, renewable energy such as PV power and wind power intermittent issues brings new challenges [1]. With the fluctuation of renewable energy output, the balance between power supply and power consumption shall be broken and therefore comes to many types of power quality problems such as voltage drop and frequency drop, which may finally cause facility damage and blackout. Since the use ratio of traditional generators is continually decreasing, their power regulation ability shall become insufficient in the foreseeable future. Hence, demand-side load gains more attention as a new type of regulation resource [2].

Inverter air conditioners(IAC) is a widely used temperature control equipment, it may take up to 60% of power consumption in modern cities [3]. Since IAC's operation is based on an inverter motor, its power consumption can be adjusted freely by changing the setting temperature or the motor rotating speed directly so that IAC can support flexible regulation capacity to handle the power balance issue. As a common civil or industrial equipment, IAC is a satisfactory tool for citizens to participate in the demand response project [4].

With a large number of IACs implemented as demand response regulation resources, the rationality of the management will greatly affect the efficiency of power regulation performance. Author of [5] proposed a control strategy and physical modeling of IAC demand response based on the power grid peak load shifting with groups of central, aiming to minimize the peak power demand for large building groups to reduce their electricity cost. [6] proposed a method as a type of combination of active cool-energy storage and global temperature adjustment in demand response and can obviously reduce the peak load of the power grid and as less impact on users' comfort. [7] proposed an aggregate resident air-conditioning model and a method to identify its parameters, then, raised a demand response strategy for large-scale resident air-conditioners.

Those cases show great performance in demand response

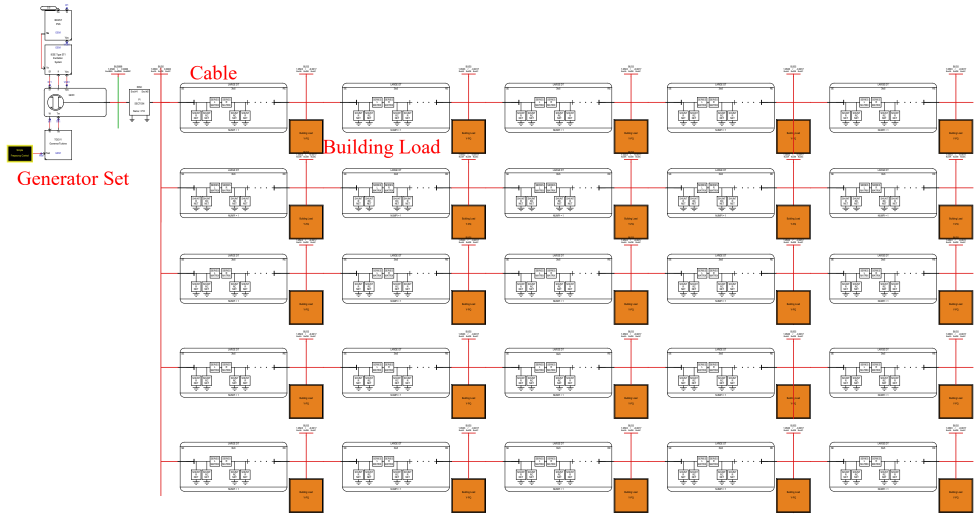

Fig. 1. Distribution Map of Target Scenario

and are based on centralized control, which is highly efficient and convenient in load control. However, with the fast-increasing number of demand response customers in urban, the expansibility of centralized control shall face some challenges. In this study, it is assumed that the grid is operating under the high IAC penetration in urban areas, reflecting current trends in many developed cities, that come with high requirements of communication and scalability. In this case, the distributed control method could be a potential solution. The foremost advantage of distribute control is its scalability and particularly suited for large-scale networks [8]. Another notable advantage is the system's resilience; even if certain components falter, the system as a whole can continue functioning, ensuring uninterrupted demand response activity. Moreover, distributed control systems exhibit robustness in dealing with communication discrepancies. Even if a few agents become offline, power regulation is generally maintained, primarily because most communication takes place between adjacent nodes. This reduces the risk of overarching network congestion. An important benefit is the preservation of agent privacy in a distributed control setting, as each node discloses only minimal information to its neighbors [9]. Nevertheless, it's necessary to acknowledge the inherent challenges. Delays or loss of messages might impair control performance. Additionally, achieving consensus across all nodes necessitates a robust communication strategy and an efficient control algorithm.

An essential part of the study is the application of real-time Hardware-In-the-Loop(HIL) technology to verify the feasibility of distributed control in providing demand response services based on the Realtime Digital Simulator(RTDS) platform, whose accuracy and reliability are highly approved [10] and is designed for high-accuracy power grid simulator and HIL testing. RTDS allows data and control command exchanges between the visual power grid and real devices in reality so that it provides a highly realistic way to verify the effect of IAC regulation on the power grid and obtain highly reliable test results.

II. Distribution Control

A distributed load structure is shown with an associated control approach. Graph theory is applied to define the agents' network and adopted with the associated communication strategy. The approach can be considered as a kind of Breadth-First Search (BFS) method that aims to consensus control. The method is widely used and can achieve consistency of power load nodes or agents in a power network [11]. The distribution system is implemented in a microgrid with 25 buildings implemented with a photovoltaic generator and adjustable IAC. A microgrid with 25 buildings is shown in Fig.1, the grid system is built in RSCAD software based on the RTDS platform for further HIL testing. There is a communication mesh in the form of a 25-node graph as Fig.2 shown. Agent and agent are Non-direction connected. The relationship of those agents is represented by the following 25-rank of the Laplacian matrix and they can used to accomplish the demand response event by distribution communication [12].

$$L = \begin{bmatrix} 2 & -1 & 0 & 0 & 0 & \cdots & 0 \\ -1 & 3 & -1 & 0 & 0 & \cdots & 0 \\ 0 & -1 & 3 & -1 & 0 & \cdots & 0 \\ 0 & 0 & -1 & 3 & -1 & \cdots & 0 \\ 0 & 0 & 0 & -1 & 2 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & 0 & 0 & \cdots & 2 \end{bmatrix}$$

The Laplacian matrix can be summarized as the equation:

$$L_{i,j} = \begin{cases} -1 & \text{if nodes } i \text{ and } j \text{ are connected,} \\ \text{degree}_i & \text{if } i = j, \\ 0 & \text{otherwise.} \end{cases} \quad (1)$$

In this equation, the $degree_i$ represents the number of neighbors connected with node i.

Fig. 2. Distribution Map of Target Scenario

Fig. 3. Hardware Group for distribution Control

The equation shows the connection relation between agents and their neighbors. This structure provides important data for subsequent steps of load regulation and message transmission during a distributed demand response event. The key mechanism of the system is the message transmission and reception. Integral to the demand response event, the message m_j comprises a command c_j and a message flag f_j. When node i gets a fresh message m_j from an adjacent node j, it makes sure the message is not repetitive by the message flag and then reacts by adjusting its load following the command housed within the message. The underlying mathematical representation of this procedure is as follows:

$$s_i = s_i \cdot c_{ji}, \quad \forall L_{j,i} = -1, f_i \neq f_j, \tag{2}$$

where s_i denotes the activating load of agent i; c_j is the command of the received message m_j, and f_i; f_j represent the stored and received message flags, respectively. This equation delineates the action of a node upon receipt of a new message.

Having processed the message and adjusted its load, node i then engages in the transmission of a message to its immediate neighbors, excluding node j which sent the first received message. This act of message propagation is integral to the collaborative functioning of the distributed system, facilitating the synchronization of load adjustments across the network. The formalization of the message-sending operation can be expressed as:

$$m_{i,k} = (f_i, c_i), \quad \forall L_{i,k} = -1, j \notin k, \tag{3}$$

where m_{ik} signifies the message sent from node i to node k, and the condition $L_{i,k} = -1$ ensures that k is a neighbor of i and not conclude node j.

The control strategy is shown as algorithm1. When the demand response initiates, an agent is triggered and starts to spread regulation commands. This node shall adjust its power consumption and communicate this alteration to its direct neighbors. Subsequent nodes receiving the message shall adopt similar load adjustment trends and relay the message further. This iterative process shall persist until the system's abnormal condition disappears and no agents are triggered. To simplify the procedure and avert superfluous message propagation which brings superfluous load adjustment, nodes that have already received the message will remove the message sender temporarily from its sending list until it finishes the communication. The core of the system is based on consensus control, aiming for a uniform load reduction rate across all nodes as dictated by the initial command signal. However, unexpected communication errors and the differences in agent model parameters may lead to variations in final states, although these discrepancies are expected to remain within permissible margins. In essence, the proposed distributed demand response system melds Breadth-First Search with consensus control to adeptly regulate power loads. This versatile and scalable strategy presents a promising avenue for addressing diverse power demand scenarios.

A. HIL Test Environment Implement

As Fig.3 shows, to ensure the adaptability of this distributed architecture to devices with varied computational abilities, the hardware network is built by both Raspberry Pi 4B and ESP8266 chips. The Raspberry Pi 4B, is equipped with a quad-core 1.5GHz processor and up to 4GB RAM, and can support 802.11 b/g/n communication. In contrast, the ESP8266 runs on a 32-bit microcontroller at 80 MHz, yet stands out with its integrated Wi-Fi and efficient power consumption. With both kinds of devices used together, these devices demonstrate the network's flexibility to accommodate different computational strengths. Every device in the network was furnished with an air conditioning load model and was capacitated to interface with neighboring devices via the TCP/IP protocol. The IAC model is set with a series of random parameters such as energy efficient ratio, in order to represent various types of IACs.

A point-to-point network connection is built among those devices and forms a network as Fig.2 shown. And also built a connection with the GT-NET IO card of RTDS, in order to refresh the load data in the simulated power grid and obtain the data of grid frequency calculated by RTDS.

Algorithm 1 Distributed Load Adjustment Algorithm

```
procedure Regulation Demand Detecting
Regulation Start
while true do
    message ← Received Message(node)
    if node.flag ≠ flag then
        node.flag ← flag
        Remove(node.neighbors, sender)
        adjusted load ← AdjustLoad(node, command)
        Load(t+1)=Load(t)*σ
        for all neighbor in node.neighbors do
            Send Message(flag, node, neighbor, adjusted load)
        end for
    end if
end while
Send Message(flag, node, neighbor, adjusted load)
Adjust Load(node, command)
end procedure
note:σ is the load adjustment coefficient from the command.
```

During a demand response event, the initial command is derived from observed frequency deviations. Agents then modulate their load in proportion to this command. There will be multiple messages dispatched to achieve more accurate regulation. Considering the potential over-regulation, commands to increase the load are also adopted.

III. Test Result

The target scenario is designed as frequency fluctuation from power supply reduction caused by intermittent photovoltaic generation. In the mentioned microgrid, the photovoltaic generator and controllable IACs is installed in buildings shown in Fig.1. When the PV power supply suffers a sudden breakdown, power reduction can maximally reach 10MW which causes over 50% of power to be insufficient and brings a great frequency drop, and IACs are invoked as regulation resource.

A. 10MW Loss of PV Power Support

As Fig.4 shown, at the beginning of the demand response event, the system can swiftly counteract the system's frequency drop. In the absence of such regulation, the decrease in frequency could be as pronounced as 1.1Hz. The regulation process experienced multiple iterative adjustments. The initial load tuning reduces a large amount of load and subsequent adjustment rates diminish to avoid over-regulation. However, it led to a slight downward rebound in grid frequency and resulted in a marginally prolonged return to the nominal 50Hz. Nonetheless, the frequency remains within a safe threshold.

Fig.5 illustrates the power changes during demand response across all buildings within the grid. Consistent with the system's design, an immediate significant drop in node load

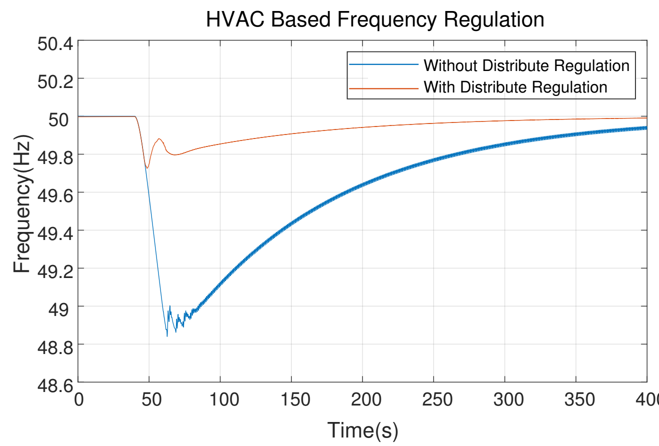

Fig. 4. The frequency regulation results with 10 MW PV Power Decline

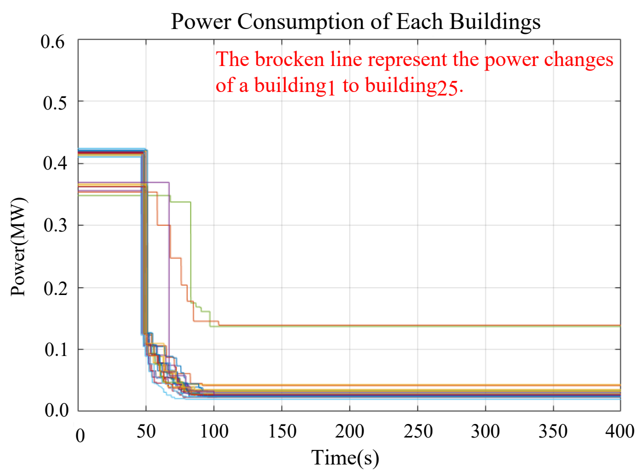

Fig. 5. Power Consumption of Buildings

occurs at the initial of regulation, and rapidly spreads to adjacent nodes. Following this initial phase, the system moderates its load adjustment velocity, causing a gradual decrease in the nodes' load for approximately 30 seconds and back to stable. It's noteworthy that three nodes deviate from the typical response pattern. This is likely caused by the miss of the first batch of commands dispatching or due to signal interference. Consequently, their reaction pace and adjustment magnitude lag behind their counterparts. However, these discrepancies have a negligible impact on the system's overall corrective efficacy, which counteracts the drop in grid frequency well.

B. 7.5MW Loss of PV Power Support

As Fig.6 shown, when there is a 7.5MW Loss of power support, the frequency drop isn't as large as that in the scenario with a 10MW Loss of power support and is effectively managed. Yet, the system's initial load adjustment is still too aggressive and leads to over-regulation. In response to this overshooting, the system increases the load, allowing the grid frequency to stabilize at 50Hz after some oscillations.

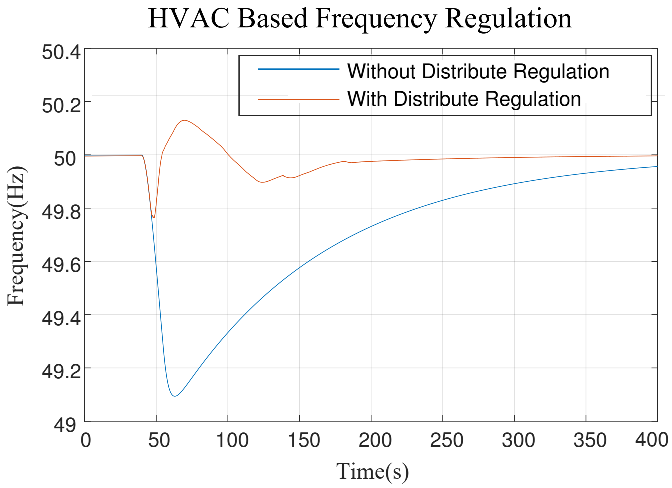

Fig. 6. The frequency regulation results with 7.5 MW PV Power Decline

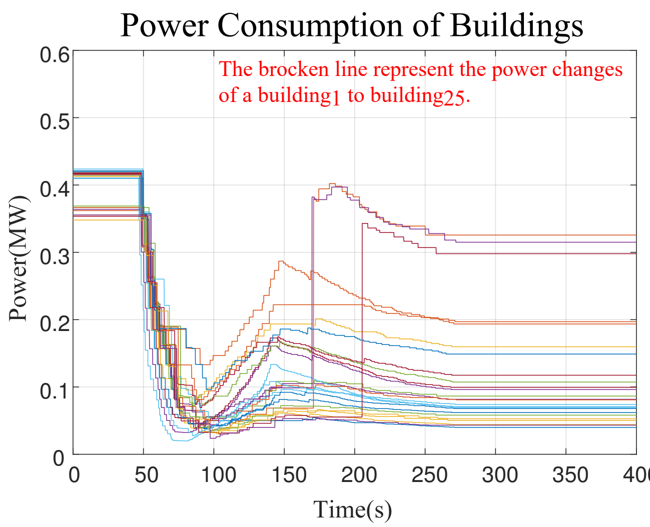

Fig. 7. Power Consumption of Buildings

As shown in Fig.7, once the grid nodes' load reaches its minimum, the grid frequency surges due to the overshoot. After peaking, it slightly recedes and finally settles around 50Hz. Notably, a few nodes exhibit an abrupt load increase. This is likely attributable to communication hiccups during the node load change sampling, causing a delay in recording their load adjustments.

The results show that power load distribution control within the microgrid can effectively engage in demand response frequency regulation, the majority of agents aptly follow the system's directives, marking their viability in demand response capacity provision and analogous applications. Compared with centralized control, distributed control requires longer regulation time. This is primarily due to the time needed for command propagation throughout the network and the potential breakdown in command transmission. Since there is a great challenge in retracting or amending issued commands, it is hard for the system to handle unforeseen errors or disturbances that emerge during the control process. Thus, meticulous parameter setting is imperative.

The observed over-regulation during testing suggests that the prudence design target to multiple parameter sets tailored to distinct scenarios is important. However, scenario recognition might inflate the difficulty in development and implementation costs. An alternative choice could be a more deliberate control method that prioritizes stability and abandons some regulation speed.

IV. Conclusion

Distributed control has performed well in its expansibility and implementation flexibility, even though its regulation is slower, it still demonstrated its viability in IAC frequency regulation. Nonetheless, challenges arise due to its slower response time combined with communication delays. Striking a balance between regulation speed and accuracy becomes particularly challenging. Addressing these issues may require advanced solutions. For instance, crafting diverse strategies tailored to specific scenarios is essential, complemented by a central decision-making entity capable of monitoring the grid. Enhancing communication efficiency to minimize latency is also paramount. Additionally, the advantage of distributed control becomes more obvious when adopting distributed control to offer power reserves. The reduced emphasis on response speed in such applications simplifies parameter design, making it a promising avenue for distributed control deployment.

The reliability of the communication is necessary to be concerned. In the HIL test of this study, device offline or communication cutoff is observed. Though it does not strongly affect the final result of frequency regulation, the communication issue still needs to be addressed and followed up with emergency measures, and there will be a further study about the self-adapted graph mechanism for real-time adjusting of the system.

Acknowledgment

The work is supported by China Southern Power Grid Co., Ltd. under project SZKJXM20210019.

References

[1] G. Notton, M. L. Nivet, C. Voyant, C. Paoli, C. Darras, F. Motte, and A. Fouilloy, "Intermittent and stochastic character of renewable energy sources: Consequences, cost of intermittence and benefit of forecasting," *Renewable and Sustainable Energy Reviews*, vol. 87, pp. 96–105, 2018.

[2] W. Miao, H. Jia, D. Wang, S. Parkinson, C. Crawford, and N. Djilali, "Active power regulation of wind power systems through demand response," *Science China Technological Sciences*, vol. 55, pp. 1667–1676, 2012.

[3] J. Hong, H. Hui, H. Zhang, N. Dai, and Y. Song, "Distributed control of large-scale inverter air conditioners for providing operating reserve based on consensus with nonlinear protocol," *IEEE Internet of Things Journal*, vol. 9, no. 17, pp. 15847–15857, 2022.

[4] J. Hong, H. Hui, H. Zhang, N. Dai, and Y. Song, "Event-triggered consensus control of large-scale inverter air conditioners for demand response," *IEEE Transactions on Power Systems*, vol. 37, no. 6, pp. 4954–4957, 2022.

[5] Y. Zhou, Y. Yi, G. Cui, P. Jin, X. Guo, and C. Yang, "Demand response control strategy of groups of central air-conditionings for power grid energy saving," in *2016 IEEE International Conference on Power and Renewable Energy (ICPRE)*, (Shanghai, China), pp. 323–327, IEEE, 2016.

[6] Q. Meng, Y. Li, X. Ren, C. Xiong, W. Wang, and J. You, "A demand-response method to balance electric power-grids via hvac systems using active energy-storage: Simulation and on-site experiment," *Energy Reports*, vol. 7, pp. 762–777, 2021.

[7] J. Wang, X. Chen, J. Xie, S. Xu, K. Yu, and L. Gan, "Control strategies of large-scale residential air conditioning loads participating in demand response programs," *CSEE Journal of Power and Energy Systems*, vol. 8, no. 3, pp. 880–893, 2020.

[8] S. Patel, S. Attree, S. Talukdar, M. Prakash, and M. V. Salapaka, "Distributed apportioning in a power network for providing demand response services," in *2017 IEEE International Conference on Smart Grid Communications (SmartGridComm)*, pp. 38–44, IEEE, October 2017.

[9] C. Chen, J. Wang, and S. Kishore, "A distributed direct load control approach for large-scale residential demand response," *IEEE Transactions on Power Systems*, vol. 29, pp. 2219–2228, September 2014.

[10] C. Zhang, V. K. Vijapurapu, A. K. Srivastava, *et al.*, "Hardware-in-the-loop simulation of distance relay using rtds," in *Proceedings of the 2007 Summer Computer Simulation Conference*, 2007.

[11] S. Beamer, K. Asanovic, and D. Patterson, "Direction-optimizing breadth-first search," in *SC'12: Proceedings of the International Conference on High Performance Computing, Networking, Storage and Analysis*, pp. 1–10, IEEE, November 2012.

[12] M. Dai, H. Li, and S. Wang, "Multi-agent based distributed cooperative control of air-conditioning systems for building fast demand response," *Journal of Building Engineering*, vol. 77, p. 107463, 2023.