Extraction of Dynamic Frequency Response Characteristics and Modelling of Modern Air Conditioners

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***Abstract*—Modern inverter-based air-conditioners (IACs) are generally equipped with power-electronic components to achieve higher efficiency and more advanced controllability. Thus, their operating behaviours can be very different from the conventional air-conditioners with direct motor connections, and their new characteristics have not been adequately studied in the current literature. Thus, hardware experiments are conducted to extract the novel dynamic frequency response features of modern inverter-based air-conditioners under a range of different frequency disturbances. Then, a new IAC model with physical meanings is developed by accommodating the discovered new features such as time delays, load frequency relief and the minimum operating power limit. Further, this letter also demonstrates that the developed air-conditioner model can accurately represent the dynamics of the IACs under various frequency events. The extracted dynamic frequency response behaviours and the developed air-conditioner model will provide a solid foundation for the modern appliance modelling in a large scale and will assist to improve the accuracy of the inertia response representations of distribution network's loads.**

***Index Terms*—Air Conditioner, dynamic response modelling, laboratory experiment, frequency dynamic response, load modelling, home appliance, load frequency relief (LFR).**

I. Introduction

OVER the last two decades, substantial usage of power electronic devices has completely changed electricity networks, from power generation (wind and solar photovoltaic) to modern home appliances (inverter-based air-conditioners and fridges). This increase in power electronics has affected the system response behaviours to disturbances, which are now fundamentally different from traditional power grids dominated by synchronous and induction machines. Such a transition to power-electronized electricity networks may put the security of power system operation at risk, including decreases in load frequency relief (LFR), different need for inertia and real power reserve [1]. As a result, power networks are becoming more vulnerable and unpredictable to disturbances [2].

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The modelling of home appliances (e.g., air conditioner—AC) can be classified into two categories: steady-state modelling and dynamic-state modelling. The steady-state AC modelling has been investigated extensively in the literature [3-8], which mainly focus on modelling with normal operating conditions. For the AC modelling in the dynamic state, it is usually modelled as an induction motor [9-11]. However, dynamic response modelling of the new type inverter-based home appliances (e.g. inverter-based air-conditioner—IAC) under network disturbances is rare. The dynamic response characteristics of IAC under network disturbances can be significantly different from those of traditional induction machine-based ACs and the existing approaches (steady-state or dynamic modelling) may not suitable for inverter-based ACs. Thus, the existing load models (e.g., exponential load and induction motor load) used by power industries may not accurately represent modern inverter-based home appliances. Consequently, evaluations of power network dynamic response based on the traditional load models are not trustworthy any more. Therefore, more accurate load models of modern appliances are urgently needed for accurately assessing power network dynamic response and stability.

As the adoption of IACs in residential houses is becoming exceptionally fast around the world, there has been a strong need to consolidate the fundamental characteristics of these appliances, which can provide a solid foundation for future power network stability and control. Therefore, the dynamic response characteristics of IACs are studied through experiment and the corresponding IAC models are developed in this letter. The major contributions of this study are summarized below.

- A practical experimental platform is established for the testing of home appliances with real time digital simulator (RTDS), amplifier, IACs, and induction motors, which can create realistic frequency disturbances and make accurate and synchronized measurements.
- New dynamic frequency response characteristics of modern IACs are observed and extracted based on extensive laboratory experiments.
- An innovative IAC model with physical meaning is developed to accurately represent the dynamic frequency response behaviours of the IACs under a wide range of frequency disturbances.

II. DYNAMIC FREQUENCY RESPONSE CHARACTERISTICS

A. Experiment Platform Development

A practical experimental platform is established to obtain dynamic response characteristics of electrical appliances (including modern IACs) as illustrated in Fig. 1. First, a range of frequency disturbances are programmed through a fully controllable voltage source in RTDS. Generally, the time resolution in RTDS is around 5-10μs, which is fast enough for simulations of frequency events. Then, the programmed disturbances are sent through a giga-transceiver analogue output (GTAO) card with $\pm 10V$ limits to power amplifiers, which can then amplify the analogue input signals by 100 times (e.g. 2.3V to 230V) to form a valid and controllable grid. At this point, the programmed disturbances have been amplified to a real-life scale as those observed in the real network. Next, when the amplified disturbances are exerted on the tested units (i.e., IACs and induction motor), the corresponding responses are measured through voltage and current sensors and sent back to RTDS through a giga-transceiver analogue input (GTAI) card. RTDS automatically synchronize all the input and output signals, which provides an accurate platform for the experiments. At the same time, the phasor measurement unit (PMU) is used to measure the power, frequency and voltage with 10ms resolution. Finally, all the measurements are stored in an experimental result database for feature extraction and modelling. Overall, the state-of-the-art experimental setup in Fig. 1 can provide a controllable, complete and repeatable platform, which can desirably fulfil the dynamic response testing of the IACs and traditional induction motor.

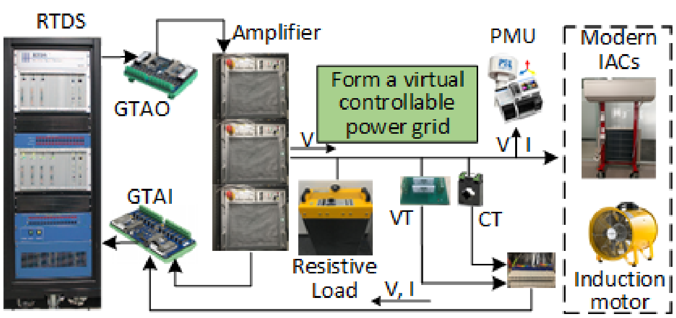


Fig. 1. Developed experiment platform for appliance behaviours extraction

The details of the 75 testing scenarios are shown in Table I. The IACs can operate under normal cooling, powerful cooling and heating modes. 25 cases are created for each IAC operating mode regarding the frequency nadirs of disturbances from 47 Hz to 49.4 Hz with an increment of 0.1 Hz. The frequency drop time and recovery time depends on different average RoCoF values and nadir levels in each curve. The objective is to make the shape of the curves closer to those of the actual frequency event. In the frequency disturbance scenarios, the frequency drop time varies from 2.23s to 4.51s and the frequency recovery time ranges from 2.27s to 3.75s. Besides, to compare the differences of dynamic frequency responses between modern IACs, IACs from two popular manufactures (named as IAC-A and IAC-B) are purchased as testing units.

TABLE I EXPERIMENT SCENARIOS FOR IACS

Cases	Operating mode	Frequency	Tested units and load
1 to 25	Normal cooling mode	Minimum nadir: 47Hz Maximum nadir: 49.4Hz Nadir changing step: 0.1Hz 50Hz, 49.6Hz, drop time, recovery time, Nadir	**IAC-A:** 1 phase 230V, 50Hz cooling:1520W heating:1610W **IAC-B**: 1 phase 230V, 50Hz cooling: 1480W heating: 1650W **Motor load**: 520W copper wound motor **Resistive load**:230Ω
26 to 50	Powerful cooling mode		
51 to 75	Heating		

B. Dynamic Response Characteristics During Disturbances

Based on the experimental results, the dynamic response characteristics of modern IACs are found to be significantly different from the conventional loads, and even the dynamic response behaviours of IACs from the two manufactures are also different.

One typical experimental result is taken as an example to illustrate the differences of dynamic response behaviours under a frequency disturbance as shown in Fig. 2 and Fig. 3. It needs to be noted that "P/Ppre-event (%)" represents the percentage of the measured active power to the initial power (measured active power before the event).

As shown in Fig. 2, both the traditional induction motor and the IAC-B responded to the frequency event with LFR of 4.4%/Hz and 18%/Hz, respectively, while the IAC-A has no LFR capability and the power was constant during the frequency event. Thus, the IAC-B provides more frequency support and is more grid friendly compared with IAC-A. Therefore, modern IACs become difficult to model due to the inconsistent behaviours between IACs from different manufacturers.

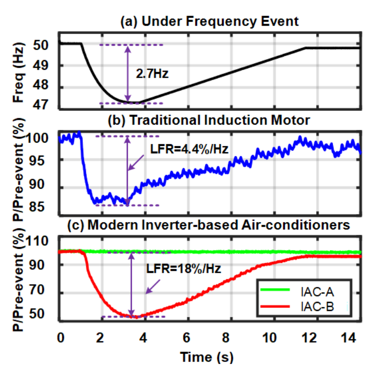


Fig. 2 Load response comparison after a frequency event

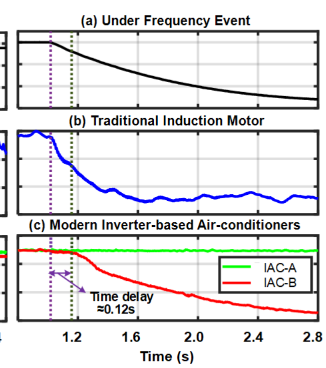


Fig. 3 Time delay comparison (0.8s-2.8s of Fig. 2)

As detailed in Fig.3, the traditional induction motor delivered frequency support immediately by load power reduction, which is regarded as an inertia response. However, there was a 6-cycle (around 0.12s) time delay from the IAC-B, which is no longer a proper inertia response. Such a delay cannot be modelled by either LFR or motor element in the traditional load models, as these elements inherently deliver inertia without any delay. If the traditional model is still used for modern appliances, the whole network inertia response will be wrongly assessed, and the system security will be significantly compromised. This can cause a higher rate of change of frequency (RoCoF) during frequency events, and can further result in an unwanted massive generator disconnection due to the abnormal RoCoF.

Another operating behaviour of IAC-B found through the experiment is the minimum operating power. As shown in Fig.4, the minimum operating power (Pmin) of IAC-B is 600W.

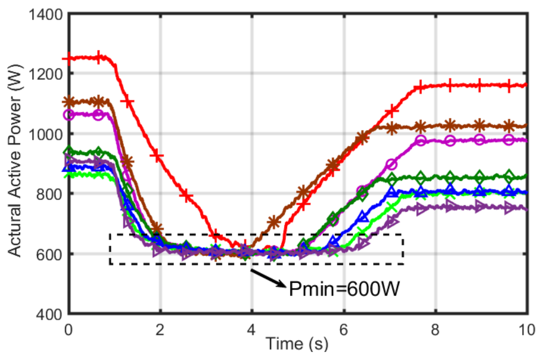


Fig. 4. Measured IAC-B power with a flat bottom during the under-frequency events

In summary, modern IACs are significantly different from conventional air-conditioners with direct motor connections. Therefore, modern load dynamics cannot be represented by traditional load models. Thus, more accurate dynamic response models of IACs are urgently needed for accurately assessing power network stability and security.

III. Air Conditioner Frequency Response Modelling and Validation

A. Modelling of the Air Conditioner Dynamic Frequency Response

The models are developed for the IAC-A and IAC-B, which can be used to represent the load with similar dynamic response behaviours to these IACs in future. In order to make the developed model more practical for implementation, it will be developed from the fundamental load model with physical meanings. The traditional load with load frequency relief characteristics can be modelled as in (1) [3].

$$\mathrm{P(t)} = P_0 \cdot \left(\frac{V(t)}{V_0}\right)^a \cdot \left(1 + k_P \cdot \frac{f(t) - f_0}{f_0}\right) \tag{1}$$

where P(t), V(t) and f(t) are the measured power, voltage and frequency of the load in the time domain, while P_0 , V_0 and f_0 are the measured power, voltage and frequency before the disturbance. k_P denotes the frequency dependency factor or LFR of active power (LFR $= k_p\%/1\%$, which means that a frequency change of 1% (0.5Hz for a 50Hz system) is expected to results in an active power change of $k_P\%$. This traditional load model does have the physical meaning, however, it is not suitable to accommodate the inertia response delay and the minimum power limit. Therefore, a new IAC model is established in a time-series and piece-wise format to solve these issues as shown in (2).

$$\begin{cases} \mathrm{P(t)} = P_0 \cdot \left(\frac{V(t)}{V_0}\right)^a \cdot \left(1 + k_P \cdot \frac{f(t-t_d) - f_0}{f_0}\right) & \mathrm{P(t)} \geq \mathrm{Pmin} \\ \mathrm{P(t)} = \mathrm{Pmin} & \mathrm{P(t)} < \mathrm{Pmin} \end{cases} \tag{2}$$

where P(t), t_d and $f(t - t_d)$ are the active power of the IAC at time t, response time delay of IAC to disturbance, and frequency of the load at time $t - t_d$. In this study, the voltage is a constant value ($\mathrm{V(t)} = V_0$) during the frequency disturbances, thus, there is no need to identify a. Therefore, the variables of k_P, t_d and Pmin are to be determined in this model. For the IAC-A, there is no LFR, so $k_P = 0$. For IAC-B with characteristics of LFR and time-delay, the variables k_P, t_d and Pmin need to be identified.

Based on the obtained characteristics of the IAC-B from the experiments, t_d and Pmin are 0.12s and 600W, respectively. Then k_P needs to be derived through an identification approach. In this study, a nonlinear regression approach [8] was used to identify k_P through 75 sets of experimental results. The identified k_P is shown in Fig. 5. k_P varies between 7 to 11. To simplify the IAC model and make the developed model more convenient for real implementation, k_P is obtained by the average value of the identified k_P values (k_{P_avg}=9). This means a 1% frequency drop (0.5Hz) is expected to result in a 9% active power drop.

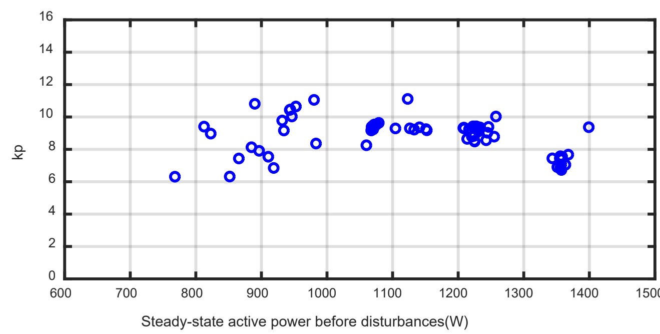


Fig. 5. Identified *kp* through 75 experiment scenarios of the IAC-B

B. Model Validation and Comparison

Based on the obtained k_p ($k_p = 9$), time-delay ($t_d =$ 0.12s), minimum operating power (Pmin=600W), and steady-state frequency ($f_0 = 50$Hz), the IAC dynamic response to frequency disturbance can be represented by the developed model in (2) for validation against the measured dynamic curves through the experiment platform developed in Section II. The inputs of the model are measured frequency, voltage and the active power of IAC before the disturbance. While the output of the model is the estimated active power of IAC after the disturbance.

To show the performance and the superiority of the proposed IAC dynamic model compared with the traditional IAC model represented by (1), the comparison results of the measured actual power response, the estimated power response by the proposed model, and the estimated power response by the traditional model are demonstrated in Fig. 6. As it can be observed from the sub-figures, the estimated IAC power curves by the proposed IAC model are well aligned with the actual responses at different initial power and frequency deviation levels, such as high initial power of 1200W, low initial power of 890W, a large-frequency drop of 2.9Hz, and a small-frequency drop of 0.8Hz. Besides, the scenario of power drop to the minimum power of 600W is also included in the validation results of Fig. 6. Thus, the proposed model can accurately represent the dynamic frequency response after disturbances for the IAC-B. On the contrary, the power responses estimated by the traditional model cannot accurately capture the power changes, especially the period when the power dropped to lower operating conditions.

The other advantage of the proposed model is that the developed model can capture the time delay of the IAC frequency response to the disturbance as shown in Fig. 7. The dynamic frequency response modelled by the proposed approach matches the actual one. In contrast, the estimated frequency response by the traditional approach dropped immediately with the disturbance, which didn't capture the time delay of the IAC response after disturbance.

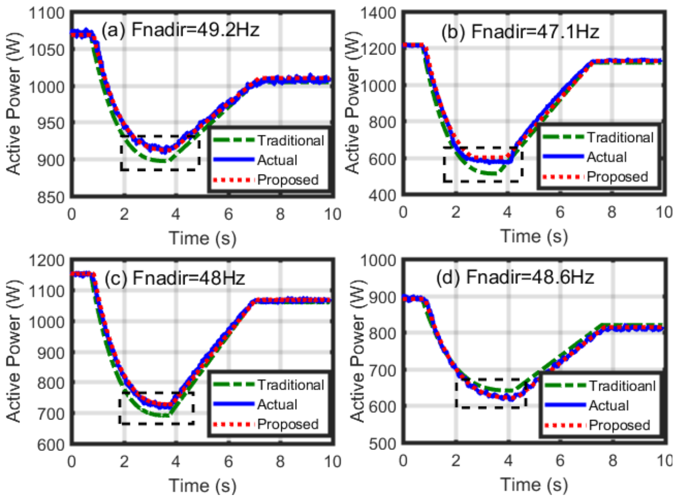
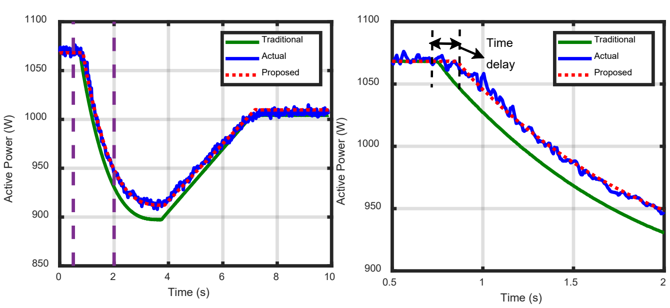


Fig. 6 Dynamic response comparison between measured actual and estimated active power by both proposed and existing approaches



Overall, the proposed model can accurately represent the dynamic frequency response behaviours under different operating conditions and various network frequency disturbances.

IV. Conclusions

A practical experimental platform has been developed for home appliance testing. New dynamic frequency response characteristics of modern inverter-based air-conditioners have been found based on extensive experiments via the established experiment platform. Further, an innovative modern IAC model with physical meaning for dynamic frequency response has been proposed, and the performance of the developed model is validated with the actual experimental data.

The developed new IAC model not only has the physical meanings for easier implementation but also accommodates the time delay, load frequency relief and the minimum power limit. The newly discovered feature of the time delay is critical to the inertia and RoCoF assessment. However, such a crucial feature is not covered by the traditional air-conditioner models.

The developed experiment platform can be used for behaviours extraction of other home appliances. The new findings of the load frequency relieve and time delay during frequency response will provide an insight to understand the new dynamics of the power-electronized distribution networks. Moreover, the developed dynamic response model will be very helpful for frequency control design, accurate active power reserve estimation, and inertia dispatch for secure and economic network operation.

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