Decentralized Coordination of Inverter Air-Conditioners for Virtual Energy Storage

State-of-the-Art Seminar Report

for Doctor of Philosophy

Submitted by

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The integration of intermittent renewable energy sources, such as solar and wind, poses significant challenges for modern power grids due to the unpredictable, time-varying nature of their generation. Mitigating the intermittency of renewables typically requires energy storage solutions, such as batteries, flywheels, or pumped hydro systems, which are often constrained by high capital costs, geographic limitations, and, in some cases, environmental hazards.

An alternative solution that is being intensively researched is Virtual Energy Storage (VES). VES utilizes the flexibility of various electrical loads, such as air conditioners (ACs), water heaters, and refrigeration systems. By using a building's thermal inertia, the power consumption of an AC can be shifted without a noticeable change in occupant comfort. Coordinating a large population of such flexible loads can significantly change aggregate demand, helping the grid manage the intermittency of renewables. Previous studies have mostly focused on ON/OFF ACs common in Western countries. However, inverter ACs are becoming more popular. Unlike their ON/OFF counterparts, inverter ACs use variable-frequency compressors, which present unique control challenges and opportunities for continuous power adjustment. Most coordination strategies for inverter ACs are either centralized or use direct compressor frequency control, which are not suitable for a scalable solution. They also rely heavily on thermal models, which are difficult to obtain.

This research proposal focuses on coordination of inverter air conditioners to provide VES. The primary objective of this proposal is to develop and validate a decentralized coordination architecture to ensure that the aggregate power demand tracks a desired aggregated demand. In a decentralized architecture, a coordinator broadcasts a low-dimensional signal to a collection of ACs. Based on this signal, each AC's local controller independently controls high-level variables, such as temperature set points or operating bands. The local controller maintains the user's Quality of Service (QoS) by keeping indoor temperatures within comfortable bounds.

Overall, the literature reviewed demonstrates the potential for Virtual Energy Storage (VES) using ACs. At the same time, it reveals a clear gap regarding development of non-centralized coordination control strategies for inverter ACs. A common assumption is that the compressor frequency of an inverter AC is directly controllable, which is not true. Most works rely on room thermal models, which are difficult to obtain. The evaluation of coordination strategies is mostly done in simulation environments, while implementation on hardware remains largely unexplored. We are particularly interested in working on inverter-based air-conditioners. We also plan to use probabilistic randomized coordination strategy, and limit local control to high-level parameters such as set-point temperature and operating band. Motivations for such particular interests are:

- Most of the works for VES with inverter AC using centralized coordination, which is not scalable to a large collection of ACs. Also, for controlling a single AC, majority of the works used direct compressor frequency control mechanism, which is challenging for practical implementation. Therefore, with the increasing popularity of inverter ACs, research on inverter ACs with *decentralized coordination* and *high level variable control* is required for the development of VES.
- Existing methods that show promising results require models that are difficult to obtain, making control computation challenging. So, we need methods that do not require thermal models of individual buildings.
- Majority of the works in the literature use simulations to evaluate the performance of their respective algorithms for VES. The main reason is that experimental implementation is costly: building a physical test-bed with even a few dozen ACs - let alone thousands - is expensive.

Objectives

1. Design of a coordination architecture for inverter ACs:

   (a) Design of a method to compute an appropriate low-dimensional broadcast signal based on the deviation between aggregate demand and desired demand. Our goal is to develop a coordination strategy which does not require the knowledge of individual building's model parameters. The probabilistic randomized approach used for decentralized coordination of ON/OFF ACs is a promising approach to meet this goal.

   (b) Design of a control mechanism that determines the actuation command in the local controller based on the set-point, and broadcast signal, and locally sensed states (e.g., indoor temperature and power consumption, and ON/OFF state). This control mechanism will also ensure QoS.

2. Validation of coordination architecture:

   (a) Design of a simulating platform: Our approach is to use a high-order RC network model to model the thermal behavior of each room. Power consumption will be modeled using the type of model developed in our preliminary work [1].

   (b) Experimental evaluation: The developed architecture will be experimentally tested on a small number of ACs installed in various locations in the IIT Guwahati campus. These ACs will be of distinct make and model so that their electrical behavior is distinct. They will be installed in different locations so that their thermal behavior is also distinct. This way the effect of heterogeneity on performance can be tested. Both the coordination and control algorithms will be implemented on microcontrollers. We will develop a data communication architecture to enable reliable information exchange between the coordinator and local controllers.

3. Analysis of how much storage capacity can be provided by in a collection of ACs for VES will also be studied in this research.

4. The effect of humidity on the power consumption of AC might be significant in a humid weather. This part is not well explored in this literature. Therefore, we plan to examine the effect of humidity on the performance.

Bibliography

[1] S. Paul and P. Barooah, "A data-driven thermal model of a building with an inverter-based air-conditioner for demand dispatch," in *2025 Eleventh Indian Control Conference (ICC)*. IEEE, 2025, pp. 684–689.