MINISTRY OF EDUCATION
Academic Research Fund (AcRF) Tier 1 – Final Report

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2. Abstract of Final Report

The electrical distribution system needs to become more consumer centric in order to improve its resilience and energy efficiency. This entails each consumer being able to produce and consume energy from the grid, i.e., the consumer becomes a 'prosumer'. To realize the advantages of such a consumer-centric paradigm while incorporating distributed generation in the form of renewables and storage elements, the microgrid concept has been gaining popularity. Microgrids are the local networks consisting of generations and loads that are capable of operating in parallel with, or independently from, the main electric grid. In essence, the residential apartments can be transformed into microgrids, and the distribution grid can be viewed as multiple microgrids interconnected with each other.

The broad objectives of this project are to design the electrical power systems of the future residential apartments, describe the infrastructure needed, control schemes governing the energy management system (EMS), and finally to address the potential stability issues in the overall distribution grid. In addressing these, the specific aims were to effectively integrate prosumers, distributed energy resources (DER), and allow ancillary services such as demand response (DR). Meanwhile, the transition from the legacy grid to the proposed design should be able to be smoothly executed.

To achieve the integration of the consumer loads and DER, a transitional microgrid topology is described in this project. The EMS functionality is realized in a decentralized fashion so as to make the system resilient to communication failure, as well as to enable plug-and-play functionality of future DER/loads. Small-signal stability of such a microgrid is evaluated by developing detailed models for each of the components, including photovoltaic generation, battery storage, diesel generators and residential appliances. To verify the accuracy of these models, simulations are carried out using the Real Time Digital Simulator (RTDS), which is capable of doing small-time-step simulations using detailed models. An experimental microgrid test-bed with a total generation capacity of 21 kW was developed to demonstrate the working of the developed control schemes.

This project has generated several technical contributions that can are highly relevant to the forefront of research in this field. Firstly, it is demonstrated that the community participation in ancillary services such as DR can be encouraged by suitable design of the topology and policy making. Second, it is shown that while the individual microgrids may have the capability to manage energy resources internally, contingencies can impact the overall stability of the distribution grid. Third, the analysis in this project demonstrate that while the stability assessment process of microgrid is un-scalable to system size, the accuracy-complexity tradeoff can be resolved with suitable approximations, depending on the goal of such assessment. Finally, the security of such microgrids was analyzed demonstrating that stealth attacks are indeed possible on the control infrastructure, and that suitable mitigating strategies should be implemented to ensure resilient operation of the grid.

The research carried out as part of this project has resulted in 2 journal publications, and 3 conference publications. An additional 2 papers have been submitted to relevant journals and are currently under review. The key outcomes of this research have been distilled for public consumption on our website, as well as integrated into graduate-level coursework as part of the knowledge-transfer program.

3. Introduction and Objectives

This project focused on the design and operation of residential apartments as microgrids capable of operating in stand-alone, or grid-connected modes. Such an operation would allow the efficient use of distributed energy resources such as renewable generation and storage, while potentially increasing the flexibility of the consumer demand using energy management systems and ancillary programs such as demand response. The overall objective was to increase the efficiency of energy consumption by residential consumers.

In particular, the following were the objectives of this project:

1. Improving the utilization of distributed energy resources such as solar photovoltaic generation and storage elements.
2. Design of demand response infrastructure for residential consumers.
3. Design of an energy management system for the residential microgrid.
4. Establishment of a knowledge transfer program to inform students and engineers about the benefits of developing residential apartment microgrids.

All of the above objectives have been achieved fully during the duration of this project. From our research, we found that the stability of multi-inverter systems is non-trivial and is a promising area for future study. For instance, secondary control schemes implemented for ensuring stable and efficient power-sharing among the inverters is of high interest to the academic and industrial community.

4. Project Management and Execution

The following details the work performed in this project:

1. Design of the microgrid architecture for residential buildings.
2. Development of a decentralized control scheme for the above microgrid topology.
3. Mathematical modeling of microgrid components including solar photovoltaic generation, battery storage, and residential appliance usage. This includes determining suitable model simplifications that neglect details of internal controls/components while preserving the accuracy. These simplifications ensure the scalability of the proposed analysis to large systems.
4. Development of the models in RTDS for real-time digital simulations that allow us to conduct simulations in small-time-steps.
5. Development of an efficient energy management system for increasing the efficiency of residential energy use.
6. Development of a baseline estimation tool that is tailored to reduce computation costs, while maintaining accuracy for the Singaporean context.
7. Analysis of multiple apartment microgrids as a multi-inverter system, and its stability analysis under contingencies.
8. Development of a hardware testbed to test the accuracy of the mathematical models and simulations, and the effectiveness of the proposed control strategies.
9. Security analysis of microgrids from stealth attacks that inject false data into the system.

5. Project Findings

The main findings from this project are detailed below.

1. **Microgrid architecture for residential buildings:** DC residential microgrids promise higher efficiency, and can easily integrate distributed generation, storage, and energy-efficient loads. Although many modern loads can directly be fed from a DC supply, some loads such as

white goods will continue to depend on AC supplies. To bridge this transition from the present fully-AC distribution to a future fully-DC distribution, this project developed a hybrid AC-DC microgrid architecture for residential buildings. This topology is designed to work in a decentralized mode of control and allows for seamless transition between the grid-connected and islanded modes of operation.

2. **Control philosophy of the residential microgrid:** It was determined that decentralized control was the most robust architecture that can provide plug-and-play functionality for residential loads and sources. As microgrid control strategies are case-specific, for the proposed apartment microgrid, a new decentralized control strategy needed to be proposed. The proposed double-droop scheme was found to maintain stability and interrupted operation in both grid-connected as well as autonomous mode, with the system voltages and frequencies in the desired range. Further, the proposed design was verified to be general, and applicable to any apartment size.

3. **Modelling of microgrid components:** The various parts of the microgrid, viz., generation sources such as diesel generators, solar photovoltaic sources and battery storage were modelled in various platforms including Matlab/Simulink (for offline simulations), and RTDS (for real-time simulation). The resulting dynamics were captured under grid-connected and autonomous operating modes. A droop-based controller design was carried out to perform energy management functionality and to ensure the microgrid stability. It was found that calibrating the experiments for different operating scenarios was time consuming. Hence, the use of a real-time emulator was adopted. RTDS simulations captured the transient dynamics seen in the experiments and could be easily tuned for different case studies.

4. **Modelling the energy usage of residents:** In the course of this project, a bottom-up model for generating the load profiles of residents of varying household sizes was developed. This model is capable of modelling residents' behaviors during the presence of demand response events and produces synthetic load profiles such that at the system level, the simulated demand matches those profiles reported by the distribution system operator.

5. **Efficient energy management system for residences:** A complexity analysis of the load scheduling problem in the residential building was conducted. The optimization problem statement was formulated in its most general form so as to incorporate various types of loads such as non-interruptible, interruptible, electric machines (motors), thermostatically controlled loads, and electric vehicles. The main observation was that the addition of the number of loads does not multiply the complexity (i.e. the running time depends linearly on the number of loads) of this problem as the optimal schedule for each load is not sensitive to the presence or absence of other loads. Consequently, the introduction of sophisticated algorithms, such as evolutionary computation schemes like Particle Swarm Optimization (PSO) that have been used previously in literature may be unnecessary. However, the analysis of the effect of incorporation of DR on the running time of the optimization algorithm shows that complexity increases significantly only in the case when DR event occurs during a low electricity price period, which, of course, does not correspond to a realistic situation. Hence, simpler solutions such as reformulation of the original optimization problem, or relaxation of integer constraints should be sufficient to solve most practical home energy management optimization problems.

6. **Baseline estimation for consumer demand:** Demand baseline estimation (BE) is essential in assessing the impact of a demand response event implemented by the utility. While many such BE techniques exist in literature, these may either be inaccurate, computationally expensive, or provide only point estimates of the baseline demand. This project resulted in the development of a novel similarity-based baseline estimation tool ideal for tropical and wet climates that exists in countries like Singapore. This technique was tested using data obtained from the Singapore Energy Market Company and proved to be consistently more accurate than those conventionally implemented by utilities.

7. **Conceptualization of a multi-microgrid distribution system**: Having developed the architecture and control techniques for managing a single residential microgrid, this project visualizes the entire power grid as a collection of such microgrids, i.e., a multi-microgrid. Each microgrid is interfaced to the distribution using an inverter, and therefore, a multi-microgrid can be synonymously considered as a multi-inverter system. With this concept,

additional analyses were performed to mathematically and experimentally study the stability of such systems under contingencies.

8. **Handling contingencies in multi-inverter systems:** The stability of a multi-inverter system depends on the voltage and frequency droop constants, the network parameters, as well as the number of interconnected inverters. The damping of the critical modes of oscillation can change frequently in real-time, and a distribution management system (DMS) maintains the grid stability through supervisory control. During contingencies or periods of low damping, communication from this DMS to the various inverters is vital in restoring the system damping to the minimum required levels. Through this project, a novel method was developed to grade the impact of supervisory control inputs using a new sensitivity measure. This sensitivity is used for assessing the criticality of the various communication links, evaluating resource placement options, or for determining optimal contingency response sequences. The evaluation of the sensitivity values for a given system does not entail computationally expensive eigenvalue calculations and can therefore be augmented into existing DMS systems at no significant additional burden.

9. **Hardware implementation of a multi-microgrid:** A hardware multi-inverter system was constructed in the lab. It consists of three inverters, each capable of being controlled individually. These inverters are connected to each other using distribution lines represented by lumped impedances. Control architectures for these inverters were implemented using the LabView software. The proposed supervisory control scheme was implemented for this setup, and experimentation showed that the proposed damping-recovery scheme is indeed effective in efficiently regaining stability of the multi-inverter system after contingencies.

10. **Attack-resilience of microgrids:** Security analysis of microgrids is essential as we propose more and more such systems to be interconnected in reality. In this line, a novel stealth cyber-attack detection strategy for DC microgrids was proposed. While the detection of conventional cyber-attacks has been well-studied, stealth attacks can bypass the conventional observer-based detection theory. Therefore, the focus was on the formulation and associated scope of instability from stealth attacks to deceive distributed observers realizing the necessary and sufficient conditions to model such attacks. A novel cooperative vulnerability factor was introduced for each agent in the system, which identifies the attacked agent under various scenarios. To facilitate detection under even the worst cases, the cooperative vulnerability factor from the secondary voltage control sublayer was strategically cross-coupled to the current sublayer, which provided a clear norm for triggering defense mechanisms.

6. Impact Summary

From the project findings, we determined that power-sharing among multiple residential microgrids, such as a group of apartments, could result to instability in the system. The main cause is the droop-controlled inverter interfaces and the electromagnetic dynamics of the power lines. This is an issue that has recently drawn significant academic and industry attention.

7. Project Outcome Summary

This project studied the operation of residential apartments as microgrids are capable of operating either in isolation, or in connection to the power grid. Operating such microgrids could potentially increase the efficiency of residential energy consumption. By intelligently coordinating the various local generation and storage, while incentivizing consumers to flexibly use certain appliances such as washing machines, dryers, and dishwashers, the microgrid operator could ensure lowering of energy costs, and reduce overall emissions from the power grid.

Specifically, to allow for residential buildings to be operated as microgrids, local generation sources such as solar photovoltaic generation, battery storage, and loads in the residences must be controlled in a coordinated fashion. This project focused on developing topologies and the associated control philosophies for ensuring that such operation is possible in a stable manner. Mathematical modelling and studies were performed in both the Matlab/Simulink and RTDS platforms to validate that coordination between these resources is possible while ensuring a low cost of infrastructure, and that stability of the system is maintained at all times. To ensure that the proposed control is feasible even when scaled to larger systems, a decentralized approach was adopted, wherein each agent in the system operates only based on locally available information such as voltage and current measurements at its own terminals. Such a design is further resilient to communication failures.

Next, consumer-behavior models were developed to generate the residents' load profiles under business-as-usual conditions. These models were subsequently applied to assess the available flexibility in shifting certain loads in order to improve the consumption efficiency. Novel baseline estimation algorithms were then developed to allow us to assess how much a resident contributes to this increase in efficiency by changing his/her energy consumption behaviors.

Finally, when multiple microgrids are connected together—like multiple buildings in a block connected to each other—theories were developed to understand how such a system may lose stability when disturbances occur in the system. To quantify the impact of the critical parameters on the stability, a scalable sensitivity criterion was derived, which has the advantage of low computational complexity, while retaining its accuracy. Based on this criterion, a method to regain the stability of the system in case of real-time contingencies was designed and demonstrated in this project.

To test the accuracy of our mathematical models and control method, a scaled-down hardware test bed was developed in our laboratory. Experiments showed the close correspondence between the theory and experimentation, proving the accuracy of the modelling process and envisioned performance.

8. Future Plans

The analysis of multi-inverter systems in the project has led to the identification of several interesting and previously unstudied phenomena related to their stability. For instance, it is observed that the simple removal of the real and reactive power cross-coupling is insufficient to guarantee the stability. Systematic analysis of this effect would lead to the theoretical quantification of the as-yet-identified instability effects. Further, suitable control modifications could also be realized from such analysis that supersede empirical design procedures used in the past. Another avenue of study is to analyze the impact of non-uniform R/X ratios of the distribution system on the stability.