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A Demand Response Implementation Case Study for Islanding of a Building

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Abstract

The power sector is experiencing challenges with a change in load shape from the demand and supply curves from increased penetration of distributed generation (DG) in the form of renewable energy technologies. Microgrids and technological approaches at the building level that respond to these challenges along with providing resilience in the case of grid failure need to be incorporated to strengthen conventional power networks. In this paper, we present a case study with successes and challenges in implementing an intelligent state-of-the-art islanding use case in a 400 m² mixed-use building. We developed a control system that includes an intelligent Demand Response to extend the critical operation of the building, when grid supply is unavailable, using predictions of battery charge and on-site solar PV generation. We present our findings from the performance testing and occupant feedback of this islanding use case. In future, we intend to use machine learning and calibrated models to further improve the predictions.

Key Innovations

- Implementation of demand response control for islanding use case in India
- Testing of prediction of solar energy generation using historical data that can be extended to a machine learning prediction approach.

Introduction

Electricity grids across India are beginning to show signs of strain under the mounting pressure of climate change and fossil fuel dependence. As per Singh, 2022, the central government of India barred 27 distribution companies (DISCOMS) across 13 states from buying or selling electricity in power exchanges citing their non-payment of dues to generation companies (GENCOS). This move would cause power outages more common in the affected states leading to brownouts and blackouts. Due to ever increasing energy demand, the power grid is liable to face several other challenges in the years to come.

India is on the path of major growth in renewable energy. Against the target of achieving 175 GW of Renewable Energy installed capacity by 2022, a total of 114.07 GW renewable energy capacity (excluding large hydro) has been installed in the country as on June 30, 2022 (Spotlight, 2022). The imbalance due to the penetration of renewable energy and the evolving demand is leading to the formation of the 'duck curve', and the problem will become more acute as renewables become more widespread (Soonee, 2015). See Figure 1.

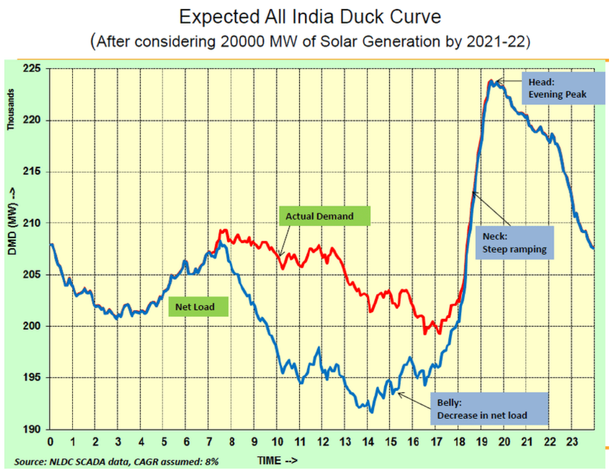

Figure 1 Expected All India Duck Curve

While in developed countries, demand response and storage (DRS) have become an important part of the solution to matching the power supply and demand curves in real time, in countries such as India, blackouts and brownouts can also be dealt with using DRS. Mixed use communities and urban areas can become islands of microgrids where on-site energy sources, storage and demand flexibility can extend critical operations during grid power failure scenarios. This approach also holds promise to reduce the vulnerability of communities during extreme weather events, when power companies force communities into islanding scenarios. Such islanding DRS requires aggressive and intelligent power management along with real time prediction of onsite renewable energy.

This paper presents a comprehensive case of planning, implementing, and testing an islanding use case on a 400 m^2 mixed-use building. This was implemented with an open-source Campus Operating System software to monitor and control the energy and water systems with the 400 m^2 building as a prototype.

About the Building

An educational institution is developing a new campus that embodies experimentation and mainstreaming of zero carbon and resilient urban development. The 400 sq.m prototype building on the campus consists of a 2-storied building occupied by 60 people and is used as an office and an environmental lab. The large conference room is used for meetings, events, and educational sessions. The typical operating hours are from 9 am to 6 pm for five days a week.

The building integrates passive design techniques, a super insulated envelope, and efficient lighting and equipment to reduce energy demand. It has a rooftop 6 kWp photovoltaic (PV) array with a 14.4 kWh battery. About 70% of the building is naturally ventilated operating in free-running mode, while the lab, conference room, and the media room are provided with air-conditioning. The building has a weather station mounted on the roof, and indoor environmental data (temperature, humidity, CO2 and PM2.5/10) are collected with IoT boxes in each room (Figure 2). Energy is sub-metered at the floor level and the end-use level (lights, fans, AC, and equipment plug loads). Energy demand is controlled with relays installed in distribution boards, with a scheme that provides granularity of control at the room and end-use level.

Figure 2 An IoT Box installed at a room level

Methodology

1. **Energy Audit:** We conducted an energy audit of the building to compare and analyse the building loads with the PV generation. It helped us understand the end-use, spatial and temporal energy use in the building. The operational power draw of each equipment was measured, while the rated power was noted from the labels. This information was only used to calculate the total equipment power density. The loads were categorized by end-use and building functions. The comparison of the operational loads to be supported by the PV system gave the demand profile of the building in the absence of grid power.
2. **Critical load scenarios:** After the energy audit we looked at historic solar radiation for a year and binned it into 5 typical days based on the minimum and maximum throughout the year. Using the PV outputs for the 5 typical days, we created load profiles that matched the consumption to the generation. These load profiles defined the critical functionality of the building were used to create 5 operational scenarios to island the building in the absence of grid power. The hours of operation and the operation scenarios were discussed with the administration, facilities managers, and the users. Their inputs were used to adjust the scenarios and to accommodate the battery capacity to the calculations.
3. **Control Architecture:** The architecture to control the system was designed to be distributed with multiple layers (Figure 3). All the sensors and microcontrollers were integrated in the hardware layer, which used Ethernet, Wi-Fi or LORA to communicate with the hardware. All recorded data is passed through cleaning scripts and then published to the Kafka framework at the local server. The central server is maintained for high computational processing like AI modeling and analytics.

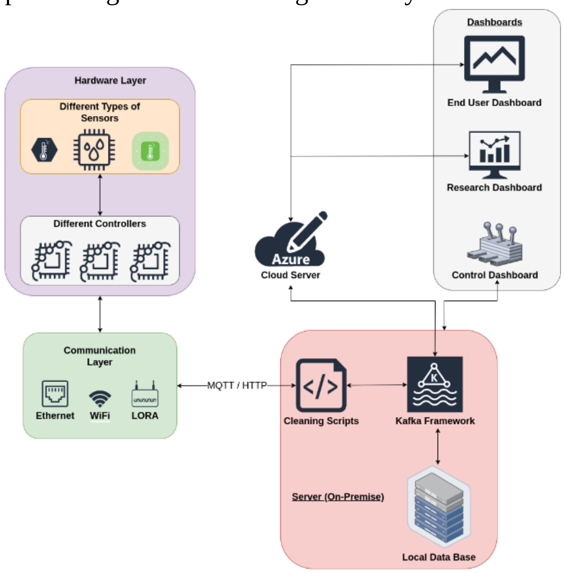

Figure 3 Control Architecture of the system

4. **Software Integration:** The next step was to plan the control and relay architecture to match the scenarios and integrate them with the operating software. We worked on developing the user interface and the open-source software. At this point, all the building controls were functioning from the OS.
5. **Testing:** The last step in this process was to test the islanding use case after integrating it with the OS. We had setup protocols to test the functionality and

validate the correctness of the output at an hourly level. To test this out, grid power was shut down intentionally and the Campus OS was allowed to take over and decide the operational scenario that the building would in based on the predicted solar energy available on that day. The testing included if the various relays were being activated based on the cycling schedule, and if the users were able to continue critical functions through the day.

Results

This section describes the results for each step described in the methodology section.

1. **Energy Audit:** From the energy audit, we found out that the building operations need more energy than that generated by the solar PV array. A typical winter afternoon will have a power draw of about 6 kW, while the generation will be about half of that at 3.0 kW. A typical summer afternoon will have a power draw of about 8 kW, while the generation will be less than half of that at 3.0 kW. If the lab was running an experiment, the typical winter afternoon power draw will be 8.7kW and that for a summer afternoon will be 10.3 kW. These results helped us identify the need to do intelligent Demand Response (DR). The audit also revealed that equipment plug loads had the largest energy consumption.
2. **Critical load scenarios:** Five bins of daily solar generation based on radiation data were created. These ranged from less than 15kWh to 35kWh. Based on these ranges, five scenarios were created, namely, blue, green, yellow, orange and red. The Red scenario was designed for very low generation days and only included the energy supply to the IT and IoT control equipment, along with some mission critical refrigeration in the lab and kitchen. Users would not be able to occupy the building in Red scenario. The other scenarios were designed to successively provide more energy to more end uses and users. While air-conditioning was not available in any of the scenarios, ceiling fans were made available to provide thermal comfort. The consumption of plug load equipment, which largely consisted of laptop computers was managed by cycling the power available to the outlets. The solar radiation data of a typical year showed that the blue scenario would be in effect for about 47 days in a year, while the red scenario for 9 days. See Table 1 for the load range and number of days in a typical year for each scenario. Figure 4 shows a graph comparing the PV output, building load and battery charge from one of the tests done at site.

Table 1 Load Range for the 5 scenarios

	Red	Orange	Yellow	Green	Blue
Load Range (kWh)	<15	15-20	20-25	25-30	30-35
No. of days	9	23	93	193	47

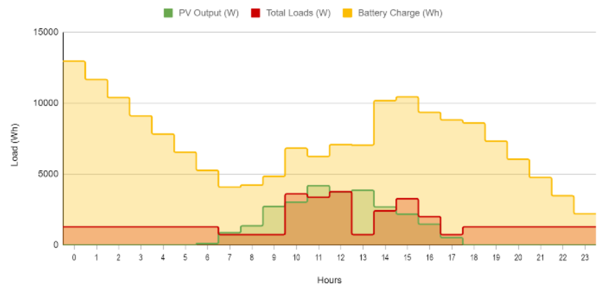

Figure 4 Operation Scenario during a testing

3. **Control Architecture:** A distributed architecture helped us take edge decisions independently at the local server level and without the interference of the central server. Apache Kafka and MQTT proved to be a good combination for many IoT use cases. This allowed us to process data in motion and not just restrict it to a sub/pub messaging level. This overall approach and the use of open-source technology has made the system scalable and extremely cost-effective.
4. **Software Integration:** Initially the relays were envisioned at the level of individual equipment so that the granularity of control would match the granularity of the energy audit done at an equipment level. This did not appear to be scalable, so we planned the relay architecture to enable control at floor, room and endues levels. This required us to set up frequency of cycling of loads for the 5 scenarios enable power sufficiency for each typical solar day until midnight. Figure 5 depicts the user-interface that also shows granularity of the controls developed to operate the scenarios.

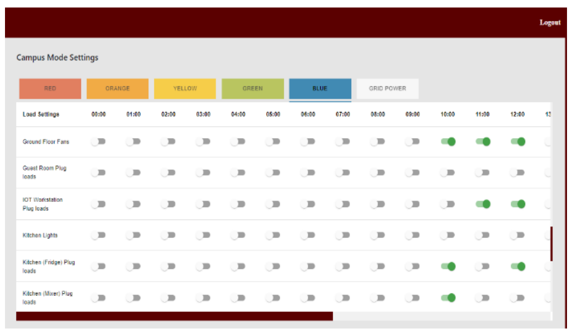

Figure 5 UI of the Campus OS to operate the scenarios

5. **Testing:** The testing proved that when the islanding use case was tested it allowed the functions of the building to last for an entire working day. The Campus OS was able to shift the building into a "green mode" where equipment functioned on cycling basis for various teams/spaces. A combination of PV generation and battery was able to sustain the building functionality throughout the day. This was also a validation for all our controls and their functionality. The testing was done at an hourly level where our made a log every hour to check if all lights and equipment were working as per the scenario chosen by the Campus OS.
Our testing also confirmed that the forecasted prediction was not always aligned with the actual situation on that day. The historic data showed that it will a cloudy day, leading to low PV generation, while it was a bright sunny day, and the PV system could produce much more and help sustain more than just the critical functions of the building. This helped us understand the unreliability of historic data to predict PV production at an hourly level. The testing also involved getting feedback from the occupants of the building. The occupants had been experiencing power outages during office hours which made working conditions difficult. With the implementation of the islanding use and distribution of power supply as per what can be generated on a certain day, power became more widely available to a variety of user groups. The implementation of the islanding use case was appreciated by the occupants of the building.

Conclusions

The design and implementation of the DR for an islanding use case helped us demonstrate that it is technologically possible to combine PV prediction, battery storage and demand management using off the shelf relays and our Campus Operating System. Air-conditioning was not a major load since this islanding use case was implemented in a temperate climate, and with passive strategies, user operated fans and daylight, the biggest load was equipment plug loads.

To make this solution scalable, controls with relays need to be done at room/zone level, and not at level of a workstation, or a bank of workstations since furniture arrangements may change in the future. This will help to optimise the number of relays and complexity of controls. However, large power consuming equipment must be controlled individually.

There were initial concerns by users about an automated takeover of building controls, especially plug loads. During testing, users realised that a planned switch to PV supply in a grid power failure scenario is better than an unpredicted power outage. This approached to DR is more aggressive than found in literature where we aimed to control and cycle power available to outlets for users. In an islanded scenario, initial results say that this level of DR seems acceptable to users, however more rigorous user acceptability testing needs to be done.

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