A Testbed for Automated Energy Storage Management in Microgrids

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Abstract—This paper presents a grid-tied microgrid testbed for development and verification of automated energy storage management systems. Different assets in the microgrid including renewable generation, programmable load and a battery unit are introduced. Structure of the communication network to monitor and control the assets is also described in details. Based on the microgrid configuration, a centralized real-time management system for energy storage operation is designed and tested. Case studies show the effectiveness of the management system in response to dynamic changes in the microgrid while realizing long-term cost savings for the users.

Index Terms—Distribution network, Microgrid, Energy storage, Management systems.

I. INTRODUCTION

Energy storage application to reduce electricity cost for energy consumers is an emerging market in the energy industry. Dynamic electricity tariffs and incentives for small scale renewable energy installations have provided an opportunity to expand battery applications in buildings beyond conventional backup services. The unique feature of batteries which can quickly switch between charge and discharge modes can be used to smooth supply and demand variations at the distribution network level, thus helping utilities for a more reliable and efficient operation of the distribution system. End-users can also benefit from this feature by storing electricity in a battery during low electricity cost periods for later use during periods of high electricity cost.

To facilitate the adaption of energy storage units in buildings it is necessary to develop automated management systems which control charge and discharge cycles of a unit based on energy optimization objective and operational points of other energy assets in a building. The management system should be capable of realizing electricity cost reduction for battery owners without the necessity of user intervention. Current technology requires the battery owners to define battery charge and discharge schedules in advance according to their estimation of future events such as utility tariffs which might not be an easy task for non-expert users. Also, time-based battery operation based on static schedules is not an optimal strategy because it is insensitive to unexpected dynamic changes in generation, demand, or other parameters in the system. Management of distributed energy storage units can also be carried out by the utility directly or indirectly through an aggregator. However this approach might not be in the best interest of customers as the utility management objective could be sometimes different from a customer’s objective of electricity cost reduction.

This paper presents a grid-tied microgrid (MG) testbed at NEC Labs America (NECLA) which is currently being used for development and test of automated energy storage management systems. The MG is designed in a way to resemble electric systems of common buildings so that the management system can be employed with minimum changes in available infrastructure of buildings. Main features of the management system which were considered during the development stages are as follows:

- Cost-aware operation: To increase electricity cost savings from energy storage utilization for users.
- Compatible with different electricity tariffs and profiles: To provide plug and play features.
- Technology agnostic: To allow customer’s choice of energy storage technology.
- Robust real-time control: To respond effectively to contingencies.

The paper is organized as follows: Section II describes the MG layout including devices and hardware connections. Details of the MG communication network for the purpose of monitoring and control is explained in section III. Section IV presents the control strategy for management of energy storage units. Experimental results of applying the management system to MG is presented and discussed in Section V, followed by conclusions in Section VI.

II. TESTBED LAYOUT AND ARCHITECTURE

The testbed is a 208v MG consisting of a 6kW photovoltaic (PV) system, a 48v 246Ah valve-regulated lead-acid (VRLA) battery, two 3kW programmable AC loads, and a connection to the utility grid. A phasor measurement unit (PMU) is also installed on the utility connection bus to measure the power flow between the MG and the grid. MG devices are only coupled with each other and the grid on the Ac side inside a distribution panel. All devices are equipped with individual power converters to convert between DC and AC power. Internal or external metering modules are also provided for all equipments. Fig. I shows the schematic of MG testbed. The PV system is a non-dispatchable generator which delivers the maximum output power of solar panels to the MG based on internal MPPT control. The battery can be controlled in three different modes:

1) Charge: In this mode the charger unit is on and is charging the battery. Charging profile is usually recommended by the battery manufacturers. The testbed charger unit
applies a constant current (CC) to the battery until the battery voltage climbs to 57v (bulk phase). After that the battery voltage is kept constant by the charger unit which results in a gradual decrease in the battery current (absorption phase). Once the current falls below 1A or the total charging time exceeds 10 hours the charger automatically turns off. Since the battery charging profile can not be changed on the fly, the charger unit can only be turned on or off in real-time by the management system.

2) **Discharge**: The battery can deliver power back to the MG during discharge via a grid-tied inverter unit. The inverter regulates the discharge power based on the target output power. Therefore the management system can turn on or off the inverter and also determine the desired discharge level in watts.

3) **Idle**: When both charger and inverter units are off the battery is in the idle mode. In this mode there is a small discharge into the charger and inverter electronics to keep them operational.

Absorbed power by programmable loads can be controlled during the system operation or it can follow a pre-defined profile throughout the day. This feature helps to emulate various demand profiles such as those of commercial and residential buildings in the testbed.

### III. COMMUNICATION AND MANAGEMENT NETWORK

The MG communication and management network provides the necessary tools for monitoring real-time and historical data about the MG and sending the management system commands to devices. Since the communication protocol for all MG devices are not the same, the network is structured in a way to decouple IO communication application from the management system through a database (DB) layer. The IO communication application is responsible for using device-specific protocols for retrieving data or sending commands to actual hardware. Decoupling IO communication from the management system allows asynchronous operation of the system i.e. running the management system and IO application with different time-steps. DB layer also provides the possibility of monitoring and off-line analysis of MG data on client machines.

Fig. 2 shows the structure of MG communication and management network. It can be seen that IO application, DB layer, and management system all reside on a server computer. IO application communicates with load, PV, and battery at certain time intervals using industry standard protocols. The most recent retrieved data are logged in current and historical tables in the DB. The management system collects real-time data from DB at each control time-step. This data is then used as inputs for the management algorithm which determines the appropriate control commands for the current time-step. These commands are then written back into the DB. The management system also calculates various MG performance metrics such as overall electricity cost and savings at each time-step and writes them into the DB. Finally the IO application reads the control commands from DB and send them to the battery for execution. These steps are repeated continuously to provide constant monitoring and control over the MG operation.

On the client side, a graphical user interface (GUI) is developed which lets the user to view real-time power flow in the MG as well as historical profiles related to generation, demand and battery operations. The GUI also allows the user to bypass the management system commands and initiate a manual charge or discharge on the battery. In this mode the management system only calculates and updates the MG performance metrics in the DB.

### IV. MANAGEMENT SYSTEM

In this paper, the main function of MG management system is defined as balancing supply and demand all the time while reducing the overall cost of electricity for the MG owner on a daily basis. Other parameters such as environmental impacts, efficiency, and transient performance are assumed to have a negligible effect on the management system decision. Since the testbed in this paper is a grid-tied MG one does not need to worry about the balance of supply and demand. This is because...
in grid-tied systems any shortage in the local generation is balanced by the imported power from the grid. Any excess generation in the MG is also feed into the grid. The power flow equation in the MG can be written as follows:

\[ P_{pv} = P_{demand} + P_{battery} + P_{grid} \]  

where \( P_{pv}, P_{battery}, P_{grid}, \) and \( P_{demand} \) are PV, battery, grid, and demand power respectively. \( P_{battery} \) can be positive or negative depending on the charge or discharge mode. Grid power \( (P_{grid}) \) is also positive when power is exported from the MG to utility and negative when power is imported by the MG.

The impact of daily variations in demand and local generation profiles and utility tariffs on the MG performance can be minimized by regulating the charge and discharge of battery. The regulation can be directed toward different objectives such as peak-shaving and electricity cost minimization.

A. Peak-Shaving

In a peak-shaving management strategy it is intended to keep the imported power from the utility to MG below a certain threshold [9]. Since imported power from the utility is assumed to be negative, the peak-shaving criteria can be written as:

\[ P_{peak-shaving} \leq P_{grid} \]  

where \( P_{peak-shaving} \) is the peak-shaving threshold.

To achieve peak-shaving management it is necessary to measure the net demand in MG at each management time-step. The net demand can be defined as the difference between local generation and demand excluding the battery as follows:

\[ P_{net-demand} = P_{demand} - P_{pv} \]  

where \( P_{net-demand} \) is the MG net demand.

If the net demand is positive there is shortage of generation in the system which must be provided either by the battery discharge or importing power from the grid. The management system then adjust the battery discharge power to keep the imported power from the grid less than the threshold value:

\[ P_{battery} = -(P_{net-demand} + P_{peak-shaving}) \]  

Fig. 3 depicts the battery discharge power and imported grid power contributions in a sample MG net demand profile. It is to be noted that the described peak-shaving scenario is insensitive to utility tariffs but responds effectively to any dynamic changes in demand or local generation profiles.

B. Electricity Cost Minimization (ECM)

In this method, the main objective is to discharge the battery when it is cost effective for the end-user. For this purpose, in case of a positive net demand in the MG, the management system compares the real-time utility tariff \( (C_g) \) with the unit price of stored energy in the battery \( (C_b) \). If \( C_b \) is less than \( C_g \) and battery state of charge (SOC) is higher than the minimum value \( (SOC_{min}) \) then the battery is discharges to compensate for the generation shortage in the MG. Otherwise battery remains idle and grid power supplies the difference between local generation and demand in the MG. Battery charging periods are scheduled during times of low utility tariff or high excess PV generation in order to store low-price or free electricity in the battery.

The unit price of energy from battery \( (C_b) \) in dollar per kWh is updated during each charging time-step based on contributions of different generation resources (in this case PV and grid) into the charging power provided to the battery. In this way charging power provided by the PV lowers the unit price of energy from the battery. In an extreme case if only PV charging is allowed by the management system then \( C_b \) is equal to zero because PV renewable energy is free of cost. On the other hand if the battery is only charged by the grid with the utility tariff of \( (C_g) \) then \( C_b \) is equal to \( C_g \). Most charging profiles throughout a day are combination of PV and grid charging which puts the unit price of stored energy somewhere between the two extreme cases mentioned before. During the battery discharge and idle modes of operation \( C_b \) remains constant.

The management steps are repeated in an infinite loop with a time-step of \( \Delta t \) as long as the MG is operational. This strategy works based on comparison of a price signal provided by the utility \( (C_g) \) and a price signal calculated internally in the management system \( (C_b) \) and therefore is not directly dependent on the net demand level of the MG in contrary to the peak-shaving strategy.

C. Intelligent Power Management System (IPMS)

IPMS combines benefits of both peak-shaving and ECM applications. For this purpose, IPMS enters a peak-shaving mode when the net demand is above a predefined threshold. Rest of the time it follows the ECM operation. Battery charging schedule in IPMS is defined in two ways as follows:

- **Time-based:** This includes the over night charging of battery using off-peak utility tariffs. charging period is defined by specifying the beginning of charging time, maximum SOC and maximum charging duration. Time-based charging mode terminates when either the maximum charging duration or SOC are reached. Obviously during this charging period PV generation is equal to zero and does not contribute in charging the battery. If
maximum SOC is set equal to 100% then a full night charge occurs at night.

- **Condition-based**: This charging mode is defined in order to use the excess PV generation during the day to charge the battery. Condition-based charging is characterized by defining a PV charging threshold value. Whenever the difference between PV generation and demand in the MG is greater than the threshold value the charger unit is turned on. The PV contribution in charging the battery is determined based on the threshold level. If the threshold value is equal or greater than the battery charging power then all the charging power in this mode is provided by the PV.

V. RESULTS AND DISCUSSIONS

Based on the discussion in the previous section intelligent power management system (IPMS) was implemented and verified on the NECLA MG testbed. Demand profile of Load1 in the MG was defined based on a scaled-down commercial building load profile with a peak value of 3kW. Load2 was kept on a stand-by mode with a default value of 200W which could be changed during the MG operation. In all experiments IPMS time-step was set equal to 3 minutes and grid electricity price was based on Time-of-Use (TOU) rates as shown in Table I.

<table>
<thead>
<tr>
<th>TOU Rates</th>
<th>Time</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak</td>
<td>12 noon-6 pm</td>
<td>0.165$/kWh</td>
</tr>
<tr>
<td>Partial-Peak</td>
<td>8:30 am-12 noon and 6:00 pm-9:30 pm</td>
<td>0.066$/kWh</td>
</tr>
<tr>
<td>Off-Peak</td>
<td>9:30 pm-8:30 am</td>
<td>0.033$/kWh</td>
</tr>
</tbody>
</table>

A. Case Study I : Sunny Day

This experiment was conducted for a 24-hour period starting from 2 am. The battery was fully charged over night so that no PV charging was necessary in the day. The peak-shaving threshold was set equal to 2400W. Fig. 4 shows daily load and PV profiles and the battery power during the experiment. PV profile indicates a clear sky day with a short period of cloud coverage around 10 am. The battery charging power including both bulk and absorption phases can be seen at the beginning of the day. After the full charge over night the battery remains idle until it enters the peak-shaving mode at 7 am because of a net demand higher than the peak-shaving threshold. The peak-shaving mode ends at 8:20 am when PV generation becomes large enough to bring down the net demand below 2400W. There is no peak-shaving period in the remaining of the day because the net demand does not exceed the threshold value again.

The battery does not enter the ECM-based discharge mode in the morning because this mode is only activated during and after the peak grid price period in the day. ECM-based discharge mode starts at 4:20 pm when PV generation becomes less than the load and ends at 6:40 pm because the battery reaches its minimum SOC (75%) by that time. The battery remains idle for the rest of the day until the next daily operational cycle starts by a new charging period.

Accumulated costs of electricity to supply the MG load for IPMS and peak-shaving management strategies are shown in Fig. 5. It can be seen that at the end of the day IPMS management results in 19% reduction in electricity cost while also keeping the net demand below the peak-shaving threshold all the time. The unit price of energy from battery ($C_b$) in this case is equal to off-peak grid price (0.033 $/kWh) because all battery charging power is supplied from the grid during the off-peak period.

B. Case Study II : Cloudy Day

Case study II investigates the performance of IPMS during a 24-hour period when the sky is cloudy starting from midnight. In this study the battery is charged up to 97% during the time-based charging period at the beginning of experiment. Therefore some battery capacity is preserved for condition-based charging later in the day. PV charging threshold is set equal to zero which means condition-based charging happens as long as there is excess PV generation available in the MG. The peak-shaving threshold was set equal to 2400W similar to Case study I.

Fig. 6 shows daily load and PV profiles and the battery power for Case Study II. It can be seen that the bulk phase charging period up to 97% SOC at midnight is followed by four pulse charging periods to compensate for battery self-discharge during the idle time. The battery enters the first period of peak-shaving around the same time as Case study I (7 am) but in this case this period lasts longer up to 9 am because of a cloudy sky and lower PV generation values. Later on in the morning there are multiple instants of condition-based charging periods as excess PV generation becomes available in the MG. The last instant of condition-based charging fully charges the battery by completing the absorption phase at 1
pm. In the afternoon, the battery starts to discharge whenever PV generation becomes less than the load value. During this period the battery switches multiple times between peak-shaving and EMC modes depending on the instantaneous net demand value in the MG. The battery reaches its low voltage limit at 5 pm and enters the idle mode. There is a short period of discharge at the end of the day in order to equalize the final SOC and initial SOC values and have the battery ready for the next day operation.

Electricity cost curves for peak-shaving and IPMS methods are compared with each other in Fig. 7. Due to the low level of PV generation for most of the day both costs are higher compared to Case study I. Nevertheless, IPMS cost is still 10% lower than the peak-shaving cost in this Case study due to combining peak-shaving and ECM applications together.

VI. CONCLUSION

Automated energy storage management systems can pave the way toward rapid adoption of battery installations in commercial and residential buildings and communities for energy optimization applications. This paper describes a microgrid testbed for design and verification of these systems based on off-the-shelf energy assets such as commercial solar systems and lead-acid batteries and IP based communication protocols. An intelligent power management system (IPMS) is developed and tested for the control of batteries in the testbed to reduce electricity cost and maximum imported power from the grid. Results of two case studies including a sunny and a cloudy day are presented and discussed. It is shown that IPMS can provide more cost savings to the end-users compared to a conventional peak-shaving management strategy. Furthermore the proposed management system can respond effectively to any dynamic changes in the microgrid parameters such as load and generation values and utility tariffs.

REFERENCES