Solid State Transformer (SST) as an Energy Router: Economic Dispatch Based Energy Routing Strategy

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***Abstract*— The Solid State Transformer (SST) is a revolutionary technology being developed by the authors. It has a tremendous number of features, which include power management, fault management and energy management. Its autonomous and distributed power management capability enables large-scale integration of distributed energy resources (DER) into the power grid. Specifically, it supports AC or DC connected Energy Cells: a combination of DERs, energy storage devices and loads. The SST can achieve real-time power flow regulation via the Energy Cell, therefore forming the foundation of its capability to become a real-time Energy Router. This paper introduces an economic based energy routing strategy that utilizes energy storage to reduce consumption of grid power. Predictive photovoltaic and load forecasting are used to optimize charging and discharging of energy storage. This rule-based algorithm is implemented and demonstrated in a SST enabled 380 V DC Energy Cell.**

Keywords—energy management system, DC microgrid, optimization, storage device, renewable energy, distributed system

I. Introduction

A microgrid, or Energy Cell as defined in this paper, is a localized group of sources and loads that is tied to the central electricity system. It can operate connected to the grid in grid-tied mode, or independently, in islanded mode. In the case of a DC Energy Cell, the use of the solid state transformer (SST) as a grid connection interface is needed [1-2]. Typically a microgrid integrates loads, energy resources, and storage devices, which prioritize use of local generation to supply the demand [3]. However, integration of distributed energy resources (DERs) such as photovoltaic (PV) generation and smaller loads, like those found in a single residential home add uncertainty to microgrid operation. Generation and load forecasting are often needed to mitigate this challenge. Additional smart methods such as economic dispatch and demand response have been proposed to balance supply and demand and meet microgrid objectives, such as lowering operational cost and/or enabling net zero energy consumption [4].

Microgrid control consists of three basic types: centralized, decentralized, and hierarchical control [1]. Centralized control manages each device in the system via communication from a central controller. Data typically passes between the device and the central controller during grid operation. Decentralized control bypasses the need for potentially complicated or unreliable communication networks. Each module in the system is controlled based on the circuit itself, through local quantities such as voltage and frequency [5]. This type of control is often implemented through droop control. Hierarchical control acts as a hybrid type, which capitalizes on the strengths of the first two methods [1]. It is broken down into an advisory layer and a real-time layer. Together the two layers accomplish two main tasks: (1) Optimization of energy management by determining daily "long term" control strategies and (2) Satisfying operation constraints in real time by maintaining the microgrid bus voltage and therefore, power flow [4]. With two layers, hierarchical control has the potential operate a more efficient and optimal microgrid than the centralized and decentralized types.

Previous works [1, 5-6] have demonstrated microgrid voltage and frequency control via droop control, ensuring quality of power and reliability [3]. To meet long-term energy goals, a strategy for economic dispatch should be implemented over the droop control layer. One strategy for receding horizon economic dispatch is presented in [3], but a more detailed implementation plan is needed. Another strategy is proposed in [7], but needs to be scheduled on a faster time scale. As described as the tertiary layer in [1], managing battery SOC is one concern that requires energy management. This paper proposes a dispatch algorithm developed from a rule-based list that schedules charging and discharging of energy storage for one day, depending on utility energy prices, and generation and load forecasts. The implementation of this algorithm is unique in that it is housed in the SST module and uses the power flow regulation capability of the SST to provide a voltage reference signal to control the microgrid bus. Power management capability embedded in the SST module puts it at an advantage over traditional microgrids [8] and demonstrates the decentralized control type, which is both distributed and autonomous.

II. System Configuration and Setup

The SST enabled DC microgrid testbed pictured in Fig. 1 will be used to study this economic dispatch problem and demonstrate its implementation via SST's autonomous and distributed control capability. It contains a lithium-ion battery

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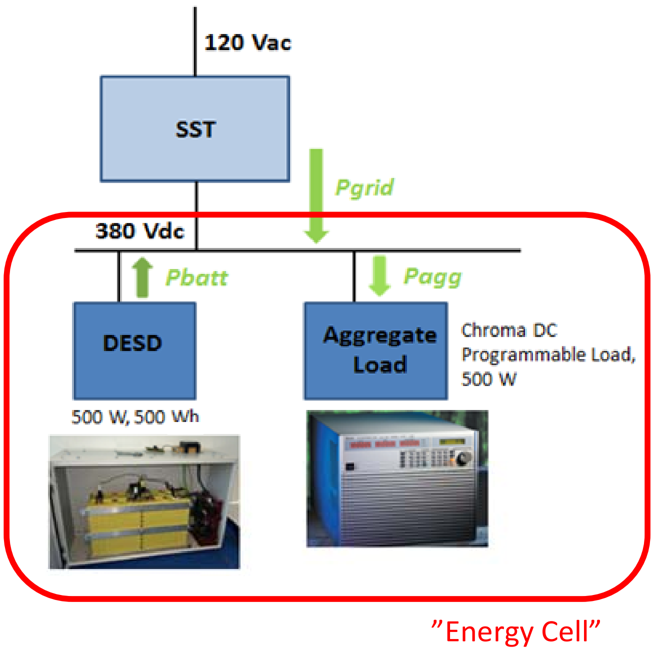

Fig. 1. SST "Energy Router" and the DC Microgrid "Energy Cell" Configuration

based energy storage device, housed in an energy storage system developed in the lab. This distributed energy storage device (DESD) charges and discharges according to the DC bus voltage [9]. A smart algorithm for economic dispatch is located in the SST. The SST will then set the reference for the SST DC bus voltage via a power flow regulation control loop. A programmable load device serves as the aggregate load, and represents the summation of generated PV power and demand for the Energy Cell.

III. MICROGRID "ENERGY CELL" DISPATCH STRATEGY

As briefly described, the microgrid bus voltage can be used to dispatch the energy storage device shown in Fig. 1. By this method, the SST enabled bus serves as a communication link as well as a power transmission link. Here, the SST serves as an Energy Router, directing power from one microgrid to another [10]. In the future, this smart transformer capability will allow the customers of one Energy Cell to buy power and sell power to other Energy Cells, enabled by the SST. In order to route energy, the SST must regulate power flow bi-directionally from the utility grid to its microgrid. In this work, power flow regulation at the SST level has been developed and demonstrated. Economic dispatch will be implemented as a power flow reference to the SST.

In Fig. 2, the power reference is compared to the measured power, P. A proportional-integral (PI) controller with upper and lower limits determines the V_{dc} reference for the DC bus voltage control. Once the V_{dc} reference is set, current control is used to control the DC bus voltage, which communicates charging and discharging commands to the DESD via droop control.

Droop control is detailed further in Fig. 3 and Fig. 4. According to the droop curve in Fig. 3, the battery can be charged and discharged according to the bus voltage. The DC/DC converter interface in the battery storage unit will generate current references for charging and discharging based on the curve. The zero current range from 375 to 385 V serves as standby region for protection and stability. The power rating of the storage determines the slope of the curve. The open loop test is also shown in Fig. 4. Here the DC bus voltage is changed to observe the performance of the DESD dispatch. The current is positive (discharging) when the DC voltage is in the lower range and negative (charging) when the DC voltage is in the upper range. This control method allows the SST to estimate the battery state of charge (SOC), based on coulomb counting. This calculation and test will be the future work.

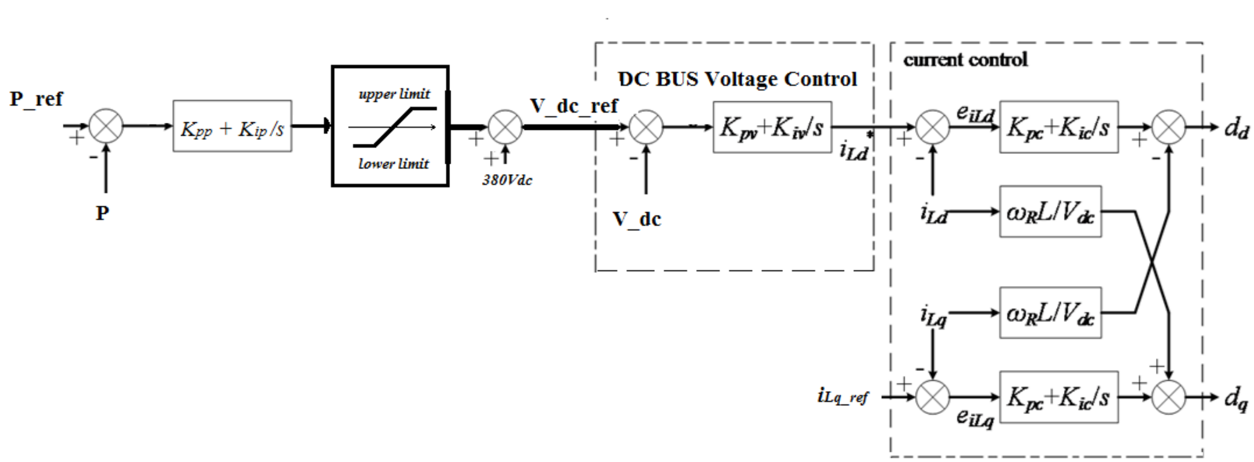

Fig. 2. Control Diagram for SST Power and Voltage Control Loop

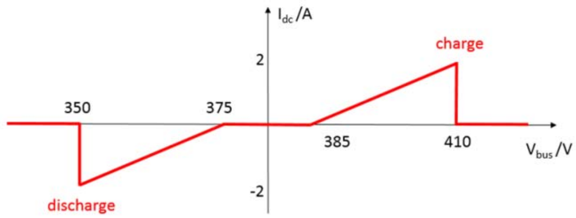

Fig. 3. Battery Droop Control

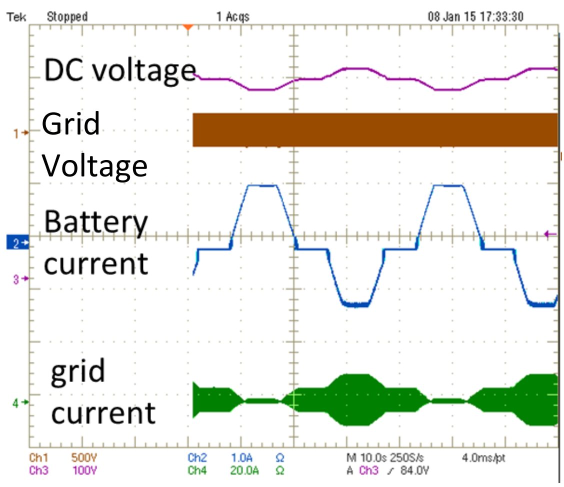

Fig. 4. Open Loop Test Results

IV. ECONOMIC DISPATCH ALGORITHM

For economic dispatch, the proposed Energy Cell can be modeled according to Fig. 1. The three components, (SST, battery, and aggregate load) participate in the following power balance equation

$$P_{grid} = P_{aggregate} - P_{battery} \tag{1}$$

The aggregate load can be broken down into a renewable source like PV and a load

$$P_{aggregate} = P_{load} - P_{pv} \tag{2}$$

Given that these components have already been sized and belong to the load customer, economic dispatch would minimize power purchased from the grid, since power from the battery or PV are essentially "free". Just the operating costs are taken into account in this work. Advanced design will consider the battery life cycle cost, although this algorithm does limit charging and discharging times that do not directly reduce overall energy cost. Given some forecasted PV curve, load curve, and energy prices for the day (in this case, Time Of Use (TOU) rates), this algorithm minimizes energy cost to the load from the grid. SOC starting and ending goals for the day will also play a role in energy scheduling.

Previous works [11-13] utilize bidding strategies to optimize operation of storage. Each time increment has an energy price, and the prices are sorted so that a bid is placed to discharge during high market prices and charge during low market prices. Often, two time increments were paired up so that each discharge time is assigned a previous time to charge. The method to find these pairs depends on the work, ranging from dynamic programing to genetic algorithms. Here, a rule-based method is introduced to sort the time increments according to energy price and aggregate load and then schedule charging and discharging during each increment for the battery over the course of one day.

The procedure for the algorithm is given in Fig. 5. The overall optimization goal is

$$\min J = \sum_{t=0}^{T} C_{grid}(t) P_{grid}(t) \tag{3}$$

where the objective function, J, is to minimize the cost of power, $C_{grid}(t)$ purchased from the grid, $P_{grid}(t)$. After the Aggregate Load is calculated and sorted into price categories (highest to lowest load in each category), the correct time is stored with each data point. In this case, the data is stored in 15-minute increments for a total of 96 points in one day. Fig. 6 shows the optimization flow chart, which then finds the highest load requirements at the highest price and searches for the closest preceding opportunity to charge at the lowest price. If successful, the battery will then be scheduled to discharge during the high priced period, saving the owner money. The

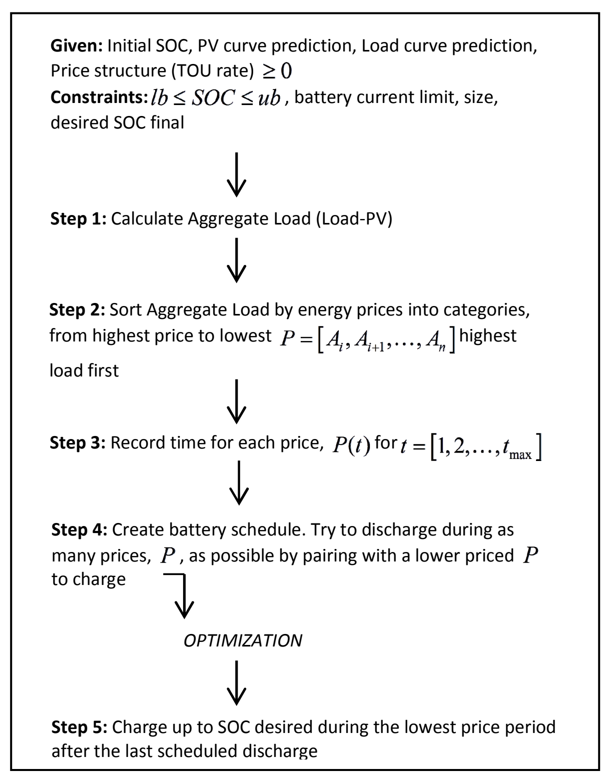

Fig. 5. Economic Dispatch Algorithm Outline

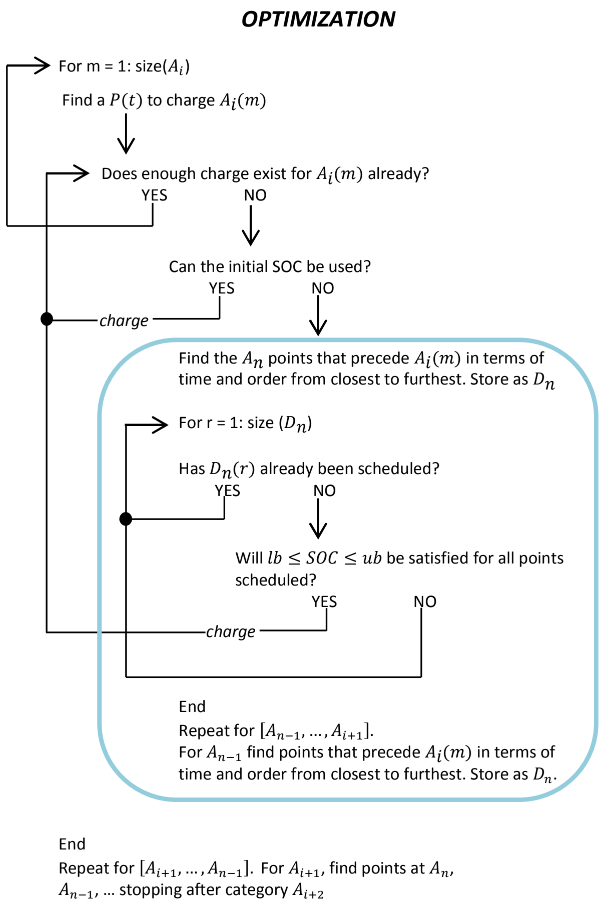

Fig. 6. Optimization Flow Chart

algorithm is capable of recalculating during the day as PV and load predictions change. Future work should account for the prediction errors in the calculation.

Based on the testbed in Fig. 1, a case was simulated involving a typical 3 kW peak load curve for a single home, a typical 1.5 kW peak solar curve, and a 1.5 kWh battery with a 1.5kW power limit. The initial SOC and final desired SOC were set to 40%, with the lower limit and upper limit at 30% and 70%, respectively. The TOU price structure was adopted from [3], where the off-peak price was \$0.033 per kWh from midnight to 8 a.m. and 9:15 p.m. to midnight, the mid-peak price was \$0.068 per kWh from 8:15 a.m. until noon and 6:15 p.m. to 9 p.m., and the on-peak price was \$0.171 per kWh from 12:15 p.m. to 6 p.m.

Following Step 1, the Aggregate Load was calculated in Fig. 7. In Step 2 and 3 the Aggregate Load was sorted into four price categories. The categories followed the three TOU prices, except for where Aggregate Load was negative (due to large generation of PV) and was sorted into a fourth price category with zero cost to the consumer, as shown in Fig. 8. Fig. 9 shows the final results of the optimization in Step 4. The calculated battery schedule is plotted against the PV, Load, and Aggregate Load Curves. The battery charges in the first off-peak period in order to discharge during the mid-peak period.

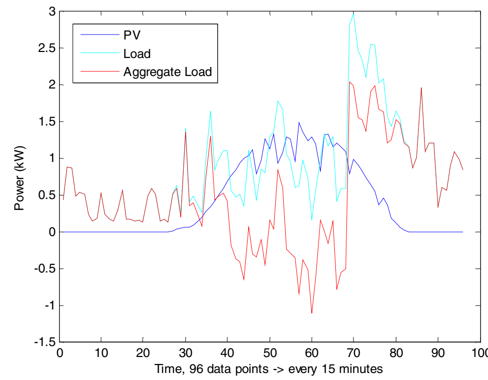

Fig.7. The Aggregate Load is the Load minus PV

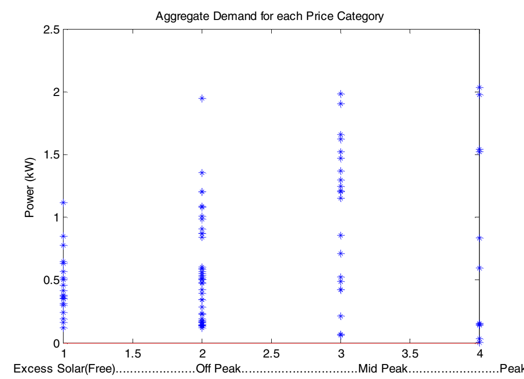

Fig. 8. Four Price Categories Determined

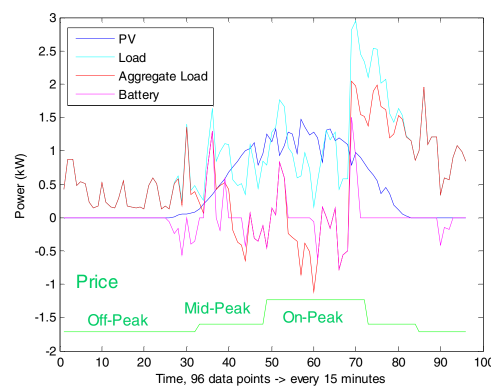

Fig. 9. The Final Battery Curve

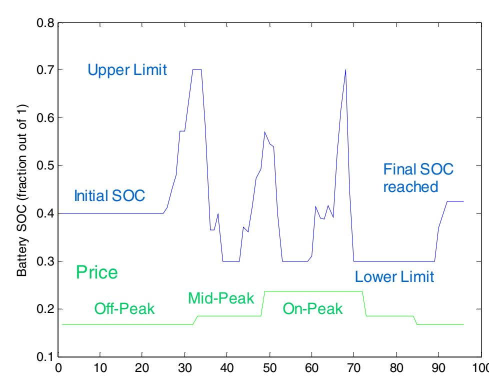

Fig. 10. Expected State of Charge (SOC)

Later, charging occurs when there is excess solar and fully discharges before the on-peak period is over. Fig. 10 displays a calculation of the expected SOC from the battery schedule. About three charging and discharging cycles are expected for the day. These cycles tend to occur as the price is changing. According to Step 5, the battery is charged to its desired final SOC during the last off-peak period at the end of the day.

Intelligent scheduling of battery storage and dispatch has substantially reduced the grid demand during the mid-peak and on-peak time blocks, thus reducing the consumer's electricity bill. The total bill for the day was calculated to be \$0.742, with a savings of \$0.204 from smart cycling of the battery.

V. DEMONSTRATION

The detailed power schedule for the battery calculated from the economic dispatch algorithm was implemented in a 380 V_{dc} SST enabled testbed. As described in the microgrid "Energy Cell" dispatch strategy, the desired battery power was achieved by setting the SST power reference and implementing power flow regulation on the DC bus. To demonstrate this concept, a fluctuating aggregate power curve was programmed into a DC Programmable Load (Fig. 1). The curve is shown in Fig. 11. For the first minute of operation, power flow regulation was demonstrated, as the grid power passing through the SST was held constant at 100 W. During this time, the battery balanced the power and was therefore autonomously controlled by the SST. The experimental results are shown in Fig. 12. After one minute of power flow regulation, various power reference values from the dispatch algorithm were implemented in the SST to show a variety of energy management cases, showcasing its Energy Router capability. As seen in Fig. 11, the grid power is regulated at a negative value around the two-minute mark, followed by regulation at zero power for a brief period. The battery current in Fig. 12 closely follows the expected battery power in Fig. 11. The DC voltage fluctuates within range to charge and discharge the battery according to droop control. Lastly, islanding is demonstrated in the last minute. If a fault occurs at the SST level, the grid voltage goes to zero, but the battery discharges to maintain the DC bus and satisfy the load.

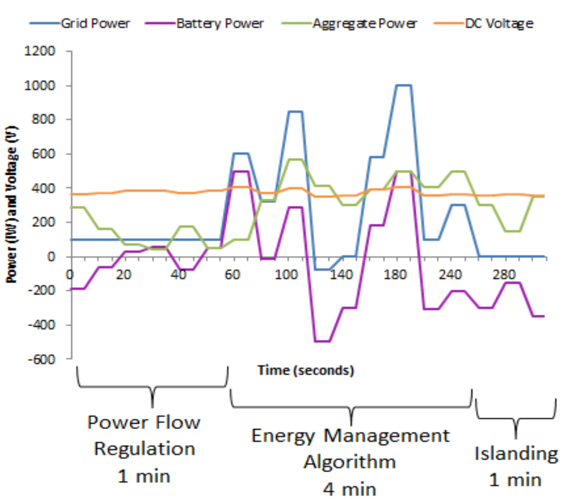

Fig. 11. Demonstration Plan

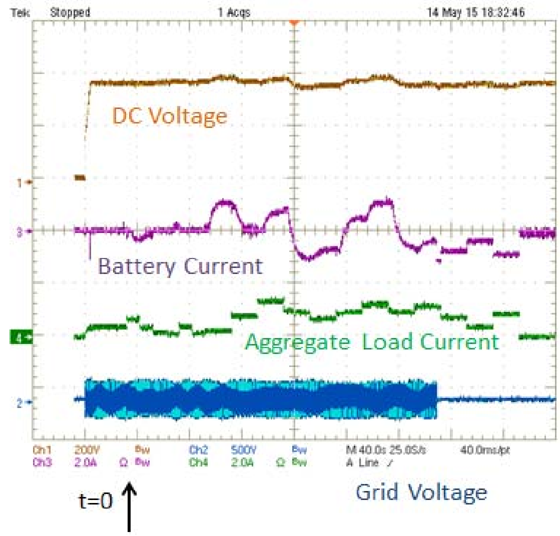

Fig. 12. Experimental Results

VI. CONCLUSION AND FUTURE WORK

In this paper an economic dispatch energy routing strategy has been proposed for energy management and cost savings for a consumer load connected to a smart SST based Energy Cell. Using battery droop control to communicate charging and discharging through the DC bus voltage, a rule-based algorithm can be implemented to provide an optimal voltage reference. SST provides this reference by directing power flow as an Energy Router, operating via autonomous and distributed control. This method of decentralized control reduces the need for complicated or potentially unreliable communication networks.

Future work should test the implementation of the entire algorithm over the course of one day. Further development and testing of the algorithm is needed to account for errors in PV and load predictive curves, battery efficiency and initial cost, and SOC calculation. A more sophisticated interface to the testbed will be developed to program the economic dispatch algorithm and monitor current and voltage. Various optimization methods of economic dispatch will be compared along with different pricing structures and categories. Utilization of SST as an Energy Router will continue to be a key technology to efficient and real-time implementation of smart energy dispatch at the microgrid level.

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