

# Real time Power Capping with Smart Circuit Breaker to maximize Power Utilization of Local Generator

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**Abstract**—Effective energy management and control is an important and urgent issue in the emerging and developing countries, so as to achieve their sustainable growth, because of poor quality of power supply by their electric power companies. In order to come up with the frequent electric power outage by the power company, most of buildings in developing and emerging countries install a power generator. Although because of poor control system in the premises, utilization factor of output capability of power generators is typically low except at peak periods. To improve the utilization factor of power generator, we propose a system, which can manage power segments in the building using SCB (Smart Circuit Breaker). SCBs are connected by wireless technologies with battery backup, and set their power capping based on the indication issued by central manager. The central manager computes power capping threshold of each SCB using the proposed algorithm, in real-time fashion. Experimental results show that the proposed algorithm can optimize the required capacity of the local power generator and that we need a feedback-looped adaptive threshold calculation algorithm.

**Keywords**—Smart Buildings, Power capping, Green ICT.

## I. INTRODUCTION

Most of commercial and residential buildings in emerging and developing countries have on-the-premises backup power generator against the outage of power supply by electrical power company. These power generators runs with fossil energy sources, that leads to larger carbon foot print, investment and maintenance costs. Though renewable energy sources like solar energy system is widely considered as the alternate backup power source, the recent studies, e.g., [4], reveals that the penetration ratio of renewable energy sources are very low, because of large initial investment. Therefore, conventional generators shall be a primary systems at least for next four or five years. This means that the efficient and smart use of power generators minimizes the total carbon foot print and operational costs of power generators. Traditionally, the capacity of power generator is determined as the summation of total breaking capacities/thresholds of edge circuit breakers in a building. For example, in a 220V system, if the threshold of each breaker is 10 Amps and 100 circuits are existing in a building, 1000 Amps and 220kVA output is simply required for the capacity of local power generator. Generally, the demand is lower than circuit breakers capacity, except at peak periods. If generator was not planned against for the peak demand of building, the power supply system in the building is getting unstable. In other words, unless we schedule or power capping the loads of the system components during peak period, we cannot guarantee the stability of power system in the building.

Main contribution of this research is to improve utilization factor of power generator in a case of power outage caused by electric power company, by the combination of dynamic power capping to Smart Circuit Breaker (SCB) system installed in the building. We propose that the conventional circuit breakers should be replaced by SCB in this paper. SCB can dynamically define its power capping level, according to the control indication message by the central manager, when the building is in power outage. Here, the proposed SCB system can also work in a peak demand period. SCB based power capping system has an effective feedback system among central manager, SCB and end users in a building. Since the proposed system can run both in power outage and peak period, we can reduce the capacity of power generator or can reduce the amount of power generation to improve its operational performance, as a result. Rest of the paper is organized as follows. Section II describes related works regarding power capping and demand control. Section III introduces the requirements and design of proposed SCB-based power system. Section IV describes the calculation algorithm of power capping level at every SCB. Section V gives the results of experimentation. Finally, section VI concludes the paper.

## II. RELATED WORKS

Power management capping is an evolving research area especially in computer data centers [11], [13] and [5]. Many data centers use some specific actuators such as UPS and CPU clock speed control to enable power capping, that is sometimes called as DCIM (Data Center Infrastructure Management). Power capping in a chip and in a fabric level is also well investigated, e.g. [12] and [8]. However above researches mainly focus on a computer domain and it is difficult to apply these frameworks for commercial and residential buildings.

There are many researches to improve the operational efficiency of generated power in Smart Grid area. Well designed and sophisticated system based on state-of-the-art technologies try to reduce power consumption, try to improve power supplying efficiency or try to improve the operational reliability of power system in a building. Smart Device and Smart Power Strip are two recent findings to reduce energy consumption in a building. As discussed in [10] and [14], massive deployment of smart power strips can significantly reduce the power consumption. Here, the functionality of smart plug strip is to control power supply of conventional device by the computer networks, so as to achieve Demand Response (DR), within a building. Many researchers, such as [7], [3]

TABLE I: Comparison between SCB, Smart Device and Smart Power Strip to make Power capping system

	Smart Device	Smart Power Strip	SCB
#Devices in Home	Under 200	Under 200	Under 5
#Devices in Commercial Building	Around 1000 to 10000	Around 1000 to 10000	Around 10 to 100
Battery	Not considered	Not considered	Considered
Fineness	High	Medium	Low
Deployability	Low	Medium	High

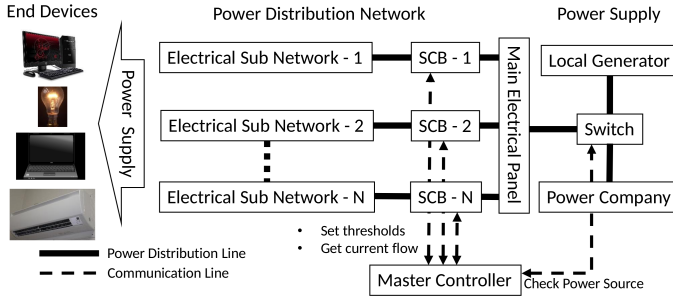


Fig. 1: Proposed power capping system architecture

and [2], are working on designing communication and control protocols for DR using Smart Devices.

Their research objective is decreasing power consumption in a building for ordinary operation. On the contrary, our research purpose is to maximize the operational efficiency of on-site power generator in a building. One circuit breaker accommodates one circuit and around 10 devices under the circuit in a typical configuration. A typical power distributing panel may accommodate about 30 circuits. This means that a single SCB manages around 300 devices. Number of batteries for SCB system discussed in this paper is less compared to the other approaches using Smart Device and Smart Power Strips. TABLE I shows the comparison of the proposed system, against similar conventional researches.

### III. POWER CAPPING ARCHITECTURE

This section describes the proposed power capping system. Fig. 1 shows the overview of the proposed system. Main electrical panel is connected with both power company's power supply and local power generator, so as to select and switch the appropriate power source for the building. All electrical sub networks in a building are connected to main electrical panel to be fed the power. Every sub network is monitored and controlled by SCB, where all SCBs receive data from the master controller using an available network, such as WiFi and ZigBee. Master controller monitors the power sources, i.e., power company and local generator and the current flows on each SCB. Based on these electrical power status, the proposed system decide the power capping threshold of every single SCB. Master controller runs power capping algorithms to calculate the threshold value of each SCB, so as to guarantee the current flow to every single sub networks in the building.

#### A. Requirements for the proposed SCB system

The following four are the requirements that the proposed SCB system must satisfy for the proposed system.

1) *Latency of Response*: The latency of response against the change of system status must be less than ten seconds. Because the recent power generator automatically, without any indication by human-being, starts the power supply within the order of few seconds[6]. The system must complete all the configuration of SCBs in this time limitation.

2) *Human activity*: The system should be able to influence the residents' activity and should be able to refer to the residents' activity for control. Since the power consumption in a building is strongly related to human activity, the system should have a feedback-loop so as to be referred the status of building by the residents, so that the residents react to control their power consumption in the building. SCB-based power system proposed in this paper does not care about residents and their activity to calculate the power capping threshold values of SCBs, but only visualizes the status of building and sub networks. Also, the calculation algorithm of power capping threshold values of SCBs should be transparent to all the residents in the building, so that the resident can realize how the threshold values are determined. For example, the residents may be able to inform to the system operator which sub networks are critical or important and which sub networks are not of critical. This means that the residents can inform to set the priorities of each SCB and the system operator can refer this priority into the threshold value calculation algorithm.

3) *Island mode of SCB operation*: Each SCB in the building must work correctly even if the SCB loses network connectivity. In the power outage time, there is a possibility of network failure due to the lack of power supply to routers and switches. The system must work and keep power capping functioning even during the failure of network system.

4) *Power backup*: SCB must have a power backup capability in order to come up with the situation where threshold of power capping by the SCB is indicated by the central manager ("Master Controller" in Fig. 1) during the power outage.

#### B. Protocol and Interface Design

We adopt connectionless communication, rather than connection oriented communication with master-slave periodical polling discipline to the communication protocol between the Master Controller and each SCBs, in order to save the electricity consumption on SCB. Since the clock synchronization and maintenance of accurate clock management at SCB is not easy, we adopt the periodic polling by master node (Master Controller). Although, we adopt the polling methodology, the slave node (SCB) can let sleep (i.e., turn off) it's network interface for long period and can let wake up (i.e., turn on) it's network interface so as to wait the reception of polling message from master node. Since large number of SCB are accommodated in the building and the ratio of data transmission period versus the data transmission interval is enough small, the period, where the network interface can be turned off, can be enough long.

Fig. 2 shows the common packet format among SCBs and Master Controller. The size of packet is not fixed, but is variable length, which is shown in the second byte field. The first one byte represents the start of packet and the third byte represents the type of packet. The last byte in the packet is the checksum value, calculated by XOR excluding initial byte

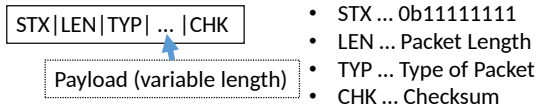


Fig. 2: Common Packet Format for Smart Circuit Breaker

Notification Payloads	Query	P Mode Config 1 ...  Config N	Configuration (Config)
	Ack.	Empty	TH1 SW1 TH2 SW2 TH3 SW3
Status Information Payloads	Query	Empty	Information (Info) Config layout is same as above
	Ack.	SCB Mode P Mode Info 1 ...  Info N	Config(6 vals) Ave. Max Dive.

Fig. 3: Payloads for 4 types of messages of the SCB system

(0xFF). As shown in Fig. 3, we define four types of packet messages. These are query and corresponding acknowledgment messages for notification and status reporting functions. Query message is generated by the Master Controller and acknowledgment message is returned from SCBs to the Master Controller. The key point of this design is the information for SCB is in the notification query.

Notification message is to set the power capping threshold and the switch states (open/close) of the SCB. Query message has two fields; power grid status field (P Mode in the Fig. 3) and configuration fields (Config). Configuration field indicates the number of circuits. When the SCB has two circuits, the content of the configuration field is two. These six values are stored in the memory on SCB as three pairs of threshold values and switch states. These three pairs are referred by three important events which are the first pair for the present time, the second pair for the power outage and the third pair for the time out. SCB changes threshold value and switch state immediately and the first pair, when SCB receives a notification query. Similarly, SCB changes to the second and the third pairs when a power outage and network time out event occurs respectively.

Status information message is for the Master Controller to calculate the threshold values and the switch states for each SCB depending on their recent states. Payload of status information query is empty as shown in Fig. 3. Status information acknowledgment has three kinds of fields; the SCB mode, the power grid status (P Mode, same as notification message) and the circuit information (Info). In the circuit information field, there are eight values; three pairs of threshold values and the switch states along with the maximum and average current in RMS (Root Mean Square). Master Controller calculates threshold values and determine the switch state for each SCB based on the acknowledgment against this message. The current RMS values are reset when SCB sends the status information acknowledgment message. Master Controller sends the status information query every five minutes and expects the message of maximum current flow every five minutes.

Periodical polling saves a lot of energy consumption on slave devices, i.e., SCB. Slave device sends data only when it receives a query message from the Master Controller. Moreover we can control power supply for a wireless unit because of the polling frequency is static. Here, we show the Master Controller skeleton design in Fig. 4. The update function includes the algorithms to decide new threshold values

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1: procedure CONTROLLER( $update, \vec{SCB}, Interval$ )
2:    $\triangleright update$  is user defined function
3:   while 1 do
4:      $Info \leftarrow getStatusInformation(\vec{SCB})$ 
5:      $New\vec{Status} \leftarrow update(Info)$ 
6:      $sendNotification(\vec{SCB}, New\vec{Status})$ 
7:      $Sleep(Interval)$ 
8:   end while
9: end procedure

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Fig. 4: Controller skeleton: algorithm is given as  $update$  function and  $\vec{SCB}$  is a set of SCBs.

for every single SCBs. In this paper, we implemented two types of update algorithms which are called as "Simple" and "Simple + Adaptive" for evaluation purpose. Algorithms are described in detail in next section. Finally we support the requirements in the starting of this section with below statements.

1) *Latency of Response*: The completion of threshold value calculation at the Master Controller and the configuration setting of power capping value at SCB is unsynchronized. When a power outage happened, the threshold value and switch state for power outage timing is already stored on SCBs inherently from notification message. SCB simply changes its own threshold value and switch state immediately based on the second values in the configuration field.

2) *Human activity*: In the current proposed system, the human activity is not considered in the calculation of threshold values for every SCB. However, the proposed system has the visualization function of system status and behavior, so that the residents may correctly and adequately react against the current status of their building. And, one of other important reaction by the residents is to avoid exceeding smaller threshold value in SCB. The resident can inform inappropriate threshold value setting to the system operator, so that a better parameters can be configure in the threshold value calculation.

3) *Island mode of SCB operation*: Master Controller can recognize the threshold values and the switch states of unreachable SCBs. Since each SCB has a timeout field and the threshold values, which are set by Master Controller, and these information are shared with Master Controller, Master Controller can control the reachable SCB based on these information so that the system can be operated safely.

4) *Power backup*: Since the SCB system adopts the master-slave periodical polling discipline, the SCB system can run with low energy consumption because the communication unit in SCB can be off in most of time, except the given timing of polling by Master Control node.

#### IV. MATHEMATICAL MODELING AND CONTROLLING ALGORITHMS

SCB operates using communicated threshold values from the controller. Threshold is decided by the controller from the data analysis algorithms on the monitored values of the circuit. Threshold can be calculated in different ways, but the algorithm developed in our implementation is explained with mathematical expressions in the following subsections.

$$P_g = (1 + \alpha)P_C \quad (1)$$

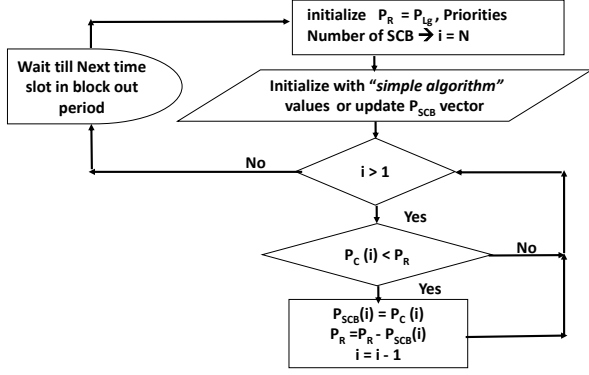


Fig. 5: Flow chart for priority based Simple + Adaptive algorithm

$$P_g > P_C \geq \sum_{i=0}^N p_c(i) > P_{Lg} \quad (2)$$

$P_C$ ,  $P_g$  and  $P_{Lg}$  are maximum values of connected load, power company, power generator respectively and  $\alpha$  is the percentage reserve of the system shown in Eq. 1 and 2. It is assumed that power company supports maximum values of connected load in the building and power generator capacity is less than  $P_g$  and  $P_{Lg}$  shown in the Eq. 2.  $P_{SCB}(1)$ ,  $P_{SCB}(2) \dots P_{SCB}(N)$  are threshold values of  $N$  networks respectively.  $p_c(1)$ ,  $p_c(2) \dots p_c(N)$  are individual maximum values of connected loads of same  $N$  networks respectively meeting individual constraints of each SCB shown in the Eq. 2. Objective of the proposed SCB system shown at Eq. 3 is to minimize the overall threshold of the building without violating constraints on each individual network as well as total capacity of the generator. Threshold of each SCB can be decided with different methods like *load forecasting*, *simple maximum value* and *machine learning methods*. The simplest of all the methods is *Simple* which considers  $L$  immediate past values of the network before power outage and computes the maximum from it. The method does not consider any load variations in the network during power outage period. *Simple* method is experimented on our prototype system and it is observed that loads in the network are frequently switching ON/OFF due to addition of extra loads. Extra loads in the power outage period for a sub network will exceed the threshold decided during power from company.

$$\begin{aligned} \min \quad & \sum_{i=0}^N P_{SCB}(i) \\ \text{s.t.} \quad & P_{Lg} > \sum_{i=0}^N P_{SCB}(i) \\ & P_{SCB}(i) < p_c(i), \quad i = 1, \dots, N. \end{aligned} \quad (3)$$

$$P_1 > P_2 > P_3 \dots \dots \dots > P_N \quad (4)$$

Another method, *Simple + Adaptive* is proposed in this paper to counter some of the instability issues in *Simple* method. This method considers the max value in *Simple* and predefined priority of each sub network. Priorities of each networks are

assigned as integer number according to essential and non essential loads during power outage period shown in Eq. 4.  $P_1$ ,  $P_2$ , ...  $P_N$  are priorities of  $N$  networks or SCBs. In this priority based method, thresholds are modified in real time according to the load variations in each sub network and the priorities. Detailed flow of the second algorithm is given in the flow chart shown in Fig. 5. The algorithm starts with initialization of all SCBs with max value during normal operation and prioritizing them. Threshold of higher priority SCB is set first and depending on  $P_R$  other SCB thresholds are assigned.  $P_C$  is the observed demand on each network in previous time slot and  $P_R$  is the residual capacity of the generator after master controller allocate SCB a threshold value shown in the Fig. 5. Above *Simple + Adaptive* method is implemented in our prototype and it is observed that load instability issue due to new incoming loads on priority networks is effectively handled shown in Fig. 8 and 9. Detailed discussion of above algorithm and experimentation details are followed in next subsections.

## V. IMPLEMENTATION OF THE SYSTEM AND EXPERIMENTATION

A prototype system is developed to evaluate our proposed system. We carried out some experimentation scenarios on the prototype with Simple max value (i.e., Simple) and Simple + Adaptive controller algorithms.

### A. Implementation

A SCB with two ports is developed for the experimentation shown in Fig. 6. Two CTs (Current Transformer; U\_RD CTL-10-CLS) are connected to ADC (Analog Digital Converter) ports. MCU (Micro Computing Unit; ATMEL ATmega328p) captures ADC values every 1msec. using the internal timer and calculate the RMS values every 100ms. MCU checks the computed RMS values to apply the power capping against electrical flow of each SCB based on their threshold values. Two SSRs (Solid State Relay; SHARP S202S02) are used as the power switching devices and each SSR connected to the MCU is controlled by it. MCU is also connected to the XBee module (XBee-ZB S2, 2.4GHz ZigBee Model) via UART (Universal Asynchronous Receiver Transmitter) port. According to the threshold values set by Master Controller. SCB controls SSRs. SCB also updates maximum/average/divergence values on their memory for the sending status information acknowledgment. MCU continuously checks for data from XBee on UART port. MCU processes the data and sends an acknowledgment message to the Master Controller using XBee if the data is available on UART port. A 40mAh battery and a charge controlling IC are integrated into the MCU power line to support during power outage time. The battery keeps working for one hour. Master-slave periodical polling system saves energy consumption and contributes that tiny battery is sufficient even for one hour power outage.

A prototype of SCB-based system is shown in Fig. 6 and 7. As shown in Fig. 7, power source board, electric panel board with SCBs and end circuits board are placed from right to left. Controller PC has two USB devices which are connected to power outage detector to recognize the status of a power company and a XBee to communicate SCBs. In the prototype system, power is supplied from two power sockets. We defined that left side socket is for local generator and right side is for

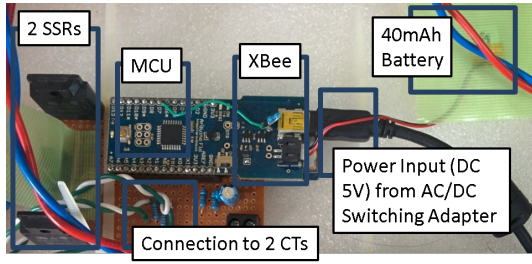


Fig. 6: Two ports type Smart Circuit Breaker

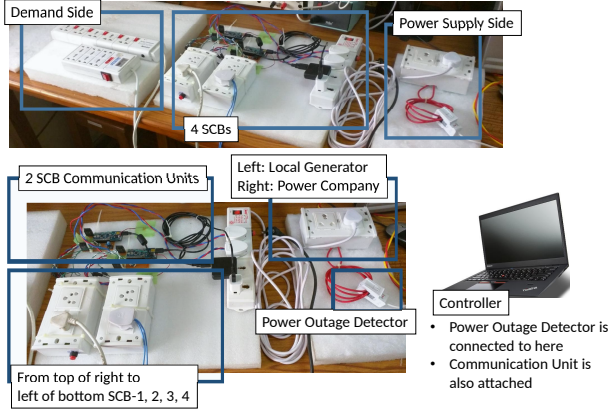


Fig. 7: Prototype of SCB-based Power System: Upper image shows over whole deployment and lower image shows more detail information and each components

power company. A CT is attached to the main cable to detect the power outage which we termed as power outage detector. Power outage event is detected when the main cable does not have current flow in it. The SCB board has four SCBs, each SCB pair has one MCU board. We named these SCBs as SCB-1, SCB-2, SCB-3 and SCB-4 from top of right to bottom of left. In real deployment, all of SCBs are in an electrical panel.

Visualization system is also implemented on Master Controller computer. We customized a third party software namely InfluxDB[1] and Grafana[9]. InfluxDB is a kind of database system and designed to store huge time-series data and Grafana is a visualization system worked on web browser for time-series data. Residents can monitor the real time threshold values that can be configured SCBs through this visualization system interface.

### B. Experimentation and Results

Developed system was evaluated with following experimental scenarios. The load devices for the scenarios are lighting, Air cooler (AC), Outlets1 and Outlets2. Outlets1 has an UPS and a desktop computer connected to the UPS and Outlets2 has a laptop computer. Outlets1 and Outlets2 are given highest priority, where lighting is given the second highest and finally the lowest priority to AC during power outage. Output capacity of the local generator is assumed 2A. Scenarios carried for experimentation are listed as below.

- 1) Power is provided from a power company and we can use all devices. Whole current is around 2.3A.

- 2) Power outage on the power company is happened and power is down for 30 seconds.
- 3) Local generator is turned on and power is resumed. The output capacity is 2A.
- 4) After some seconds, we try to add new load, a filament bulb, to Outlets2.

Fig. 8 shows time series events of controlling algorithms *Simple* and *Simple + Adaptive* respectively. Violet time series line shows the actual demand current from a load device and Blue time series line shows a threshold value for power outage timing. Area covered with blue shows the first events of our scenario, where area in red is power outage (the second event), yellow shows the local generator time (the third event) and violet shows the adding new load (the fourth event). Power capping value is shown in Fig. 9 and it is observed that both algorithms satisfy the specification of power capping to 2A. A detailed discussion of this result is given in next subsection.

Two algorithms shows the same controlling actions until a new device is added to the system. The power consumption is over the threshold and *Simple + Adaptive* way reallocates the threshold values from lower priority to higher priority and *Simple* way does not change the threshold values. With the *Simple* controller, the threshold value is determined according to the occurring of power outage and does not take care of changes in load during power outage. Therefore, when residents try to add new device to Outlets2, Outlets2 is tripped even Outlets2 is at high priority. *Simple + Adaptive* controller enables reallocation of threshold values based on the priorities when some load devices requires more electricity. You can see the reallocation when user insert new device to Outlets2 in violet area. Outlets2 has higher priority than Lighting. The controller reallocate threshold value from Lighting and added to Outlets2 which is shown in Fig. 8. In addition, after some time period, when higher priority UPS is charged enough, the Master Controller allocates this residual threshold value to Lighting shown at orange area in Fig. 8(4'). Eventually, *Simple + Adaptive* algorithms enables four devices working after the forth event. *Simple + Adaptive* algorithm allows larger number of devices and improve utilization of local generator far efficiently than *Simple* algorithm.

### C. Discussions

We compared two algorithms and conventional circuit breaker, assuming that threshold value of the breaker is statically 1A. Lighting and AC circuits should be turned off because the output capacity of the generator is 2A. TABLE II shows whole current flow on each events on our experimental scenario. We use the same data on *Simple + Adaptive* to evaluate a case of conventional breaker. After the forth event, the utilization factors are 50%, 55% and 65% for conventional static, *Simple* and *Simple + Adaptive* respectively. Moreover, *Simple + Adaptive* algorithm achieves 90% utilization factor after 1 minute. This is 40% higher than conventional static. This result shows that our proposal system is far better than conventional system.

As shown above, we show the proposed SCB system works well, as we expected, with the established experimental scenarios. However, the experimentation is only with four SCBs in the prototype system. A full scale system with at

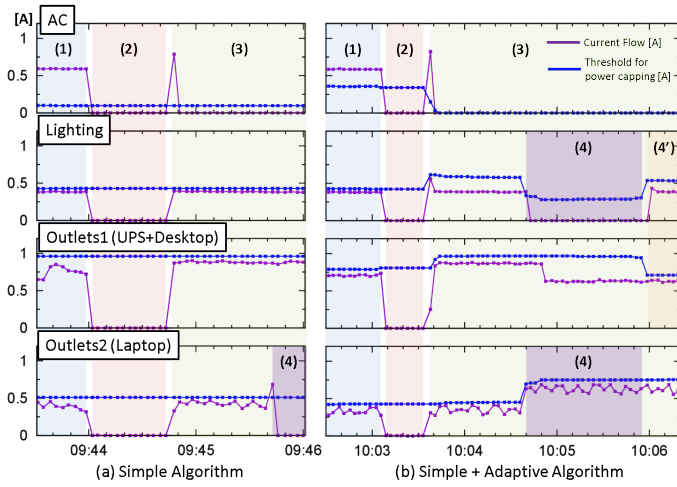


Fig. 8: Result of experimentation from 2 types of strategies: (a) Simple strategy, (b) Simple + Adaptive strategy; Thresholds are reallocated from free area or low priority area to another in violet and orange area in (b).

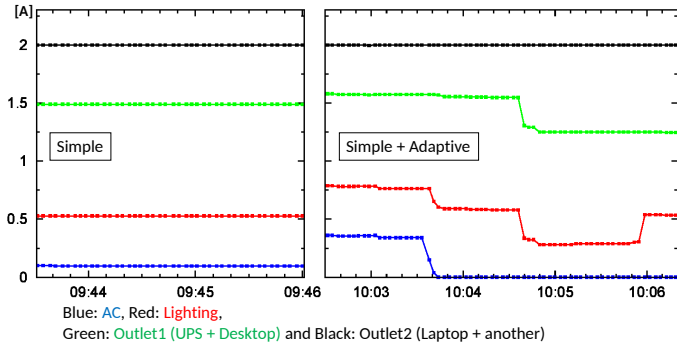


Fig. 9: Result of power capping

least 30 SCBs controlling real time loads in each room of the building is planned to confirm that the proposed system works efficiently for the most of the scenarios/events. Wireless communication networks which is backbone for our prototype system is deployed with ZigBee. We may want to carry out the same experiments using different communication technologies like PLC (Power Line Communication), WiFi or Wi-SUN to evaluate the QoS when network scales is getting larger. Since the SCB is connecting to power lines, the use of PLC would be also a good option. WiFi environment in commercial building is generally with battery backup and it works even in power outage time. Investigation on available wireless technologies and coming up with efficient and economical option is also future scope of our research.

TABLE II: Comparison of current flow between conventional static threshold, *Simple* and *Simple + Adaptive*; unit is A.

Event No	Conventional breakers (threshold is static 1A)	SCBs and Simple	and	SCBs and Simple + Adaptive
1	2.3	2.2		2.3
2	0	0		0
3	0.8	1.4		1.55
4	1.0	1.1		1.3, 1.8 (after I <sub>min</sub> )

## VI. CONCLUSION

In this paper, a novel on-the-premises micro grid system using Smart Circuit Breaker (SCB) with local power generator is proposed so as to improve the utilization factor of the generator focusing on the operation during the power outage event. The proposed system contributes to the improvement of operational efficiency and quality of service, even for the demand response against peak power usage in the existing buildings. We define the sub networks with SCB in the building, while dynamically configuring the power capping threshold value for every single SCB by the central controller in real-time fashion. Experimental operation with *Simple* and *Simple + Adaptive* algorithms shows that the proposed system works well and will be able to improve the operational efficiency of local power generator installed in the building. The system is evaluated with prototype implementation. The evaluation result, with the best scenario, the proposed system achieved 40% higher utilization factor compared to the conventional circuit breaker system with the static threshold value setting.

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