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Preemptive Demand Response Management for Buildings

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Abstract—Building energy management system (BEMS) which forms an integral part of a smart grid enables building operators to monitor, manage and control the energy utilized in their buildings, thus reducing the demand and consumption of energy. Building operators are responsible for the day-to-day maintenance and operation of their buildings' heating, cooling, mechanical and electrical systems. This paper proposes an intelligent preemptive demand response management (DRM) using the BEMS to ensure contracted capacity or demand limit (CC/DL) is not exceeded and at the same time reduce energy consumption in buildings. In this paper, dynamic electric vehicle charge scheduling, speed control of air conditioning system's variable speed drive, and priority-based load shedding are considered in the DRM program. The performance of the proposed DRM program to keep the building power demand within the CC/DL and reduce the energy consumption is tested and analyzed using the BEMS.

Index Terms—Demand response, building energy management system, electric vehicle, air conditioning, load shedding.

I. INTRODUCTION

THE rapid urbanization with increasing population and demand for a better quality of living has led to a greater usage of energy. Singapore, being a highly urbanized country, has approximately 17% of the total energy consumed by buildings in 2005 [1]. Instead of increasing the energy production from traditional carbon based sources to meet this growing demand, managing and controlling the energy utilized by buildings through demand response management (DRM) will reduce overall power demand and energy consumption.

Current DRM algorithms such as those discussed in [2]-[4] are intended to alter the level of instantaneous demand through the implementation of dedicated control methods that shed loads in response to market price conditions, demand limits, or a request by the utility. In these algorithms, during peak demand periods, interruptible loads such as lights, water heaters and air conditioning units are shed according to the customer's priority-based load shedding requirements. Time-of-use pricing is another concept introduced in [5] to achieve demand response potential by encouraging customers to shift their loads from peak to off-peak periods. In [6], on-site generation of electricity using conventional generators or energy storage devices is proposed to achieve DRM capability during peak demand periods.

DRM have been studied in depth for residential buildings as discussed earlier. However, research on DRM potential in commercial building sector is relatively immature, even though this sector is one of the main consumers of electricity. Building load curtailment based on demand limit signals sent by the utility

provider to alleviate system constraint conditions is employed in [7]. In [8], a load prediction method is proposed to estimate the amount of load to be shed during a demand response event. Advanced simulation of model-based control using intelligent building energy information system for energy reductions and optimal demand response is presented in [9]. All the above methods provide various approaches for DRM and operate once the constraints are violated. In this paper, an intelligent preemptive DRM program is proposed to ensure the building load demand is always maintained below contracted capacity or utility imposed demand limit. It employs three different techniques, namely, dynamic electric vehicle charge scheduling, speed control of air conditioning (AC) system's variable speed drive (VSD) and priority-based load shedding for demand response in commercial buildings. Precautionary steps taken to reduce the building load demand before the constraints are violated will ensure that the building load demand does not exceed the contracted capacity or utility imposed demand limit. Hence, reducing the energy cost for building operators.

The methods available in literature for control of EV mainly focus on using a single EV available in a residential building as interruptible load (in fixed power charging mode) or flexible load (in variable power charging mode) where the priority of the EV is combined with other residential loads [10]-[12]. The method proposed in this paper for using EVs in DRM focuses on combining several EVs available in commercial buildings to behave as both flexible and interruptible load using fixed power charging mode. Furthermore, the proposed dynamic priority criteria used for EVs participating in DRM is a novel approach which is applicable for managing EV load demand in commercial buildings. The proposed method will also ensure higher degree of fairness to the EV owners as the EV with highest probability to charge before departure is shed first when the DRM for EV is invoked.

Existing methods available in literature for control of AC systems focus on reducing AC system load demand based on dynamic temperature setting or periodic stopping of AC systems. Direct control of AC systems to adjust their power consumption to follow load balancing signals based on outdoor temperature profiles and indoor temperature settings is proposed in [13]. In [14], a dynamic AC chiller load model is developed for demand response application by shedding the chiller load in response to electricity price. The method proposed in this paper focuses on speed control of AC system's variable speed drive to reduce the AC system load demand based on the indoor temperature, occupant level, building load demand and contracted capacity. The proposed method enables a more efficient control of the AC system for optimum energy efficiency and at the same time ensures that building occupant comfort is always maintained. Furthermore, the consideration of building load demand and contracted capacity in AC system speed control allows the AC system to participate in DRM seamlessly.

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II. DEMAND RESPONSE FOR COMMERCIAL BUILDINGS

Commercial buildings in Singapore are treated as non-contestable consumers and charged under High Tension Small Supplies tariff category. The usage charge includes contracted capacity charge, uncontracted capacity charge, peak period charge, off-peak period charge and reactive power charge [15]. The purpose of contracted capacity is to encourage better load management, thus preventing uncontrolled growth of demand. In addition, the consumer is not allowed to change the declared contracted capacity for a period of 5 years [15]. Therefore, it is crucial for building operators to carefully consider the contracted capacity according to the expected maximum demand in order to minimize their annual electricity costs. However, in the event of building's total load demand exceeding its contracted capacity, the building operators have the choice of paying a penalty charge for the uncontracted capacity, or introducing a building energy management system that dynamically performs DRM to shave a portion off the maximum demand.

Building energy management system (BEMS) which keeps track of the building's maximum demand in real time plays a key role in executing the DRM. The DRM controls, influences and generally reduces the building's maximum demand to meet contracted capacity or utility imposed demand limit (CC/DL). It facilitates load control and short-term load reduction in the building during system constraints or peak periods. In this paper, the proposed DRM program takes preemptive measures to keep the load demand below CC/DL by first employing dynamic electric vehicle (EV) charge scheduling when the current building load demand exceeds $x\%$ of CC/DL. Subsequently, speed control of AC system's VSD is engaged to reduce the load demand of the building when the current building load exceeds $y\%$ of CC/DL. Finally, as a last resort, priority-based load shedding is performed to keep the building load demand below CC/DL. However, when the building returns to its normal operation and the current building load demand reduces to less than $z\%$ of CC/DL, the EVs and loads that have been shed previously will be reconnected. The values of x , y and z can be determined by the building operator based on required margin from the CC/DL. Since EVs are considered as non-essential loads, the demand response of EV loads should take place first before other loads, thus the required margin from CC/DL should be larger.

A. Dynamic EV Charge Scheduling

Highly urbanized cities around the world such as Singapore are looking at mass deployment of EVs to achieve a cleaner and greener mobility. However, large-scale penetration of EVs will increase the load demand of buildings. Furthermore, if the additional load due to EVs is not managed properly, it can easily result in the building's total load demand exceeding its CC/DL [16], [17]. Dynamic EV charge scheduling is proposed in this paper to enable a forecasted DRM that ensures EV charging will not result in the building's total load demand exceeding its CC/DL. The dynamic priority criteria used in the proposed EV charge scheduling will enhance the fairness and customer satisfaction compared to the traditional and modified dynamic scheduling methods available in literature [18]-[20].

The EVs in a commercial building will be charged in groups at parking lots with charging stations installed and controlled by the building operator. Furthermore, the EVs are usually charged during fixed working hours. The proposed dynamic EV charge scheduling reduces the possibility of load demand exceeding CC/DL by dynamically scheduling the EV charging at every half-

hour interval. The dynamic EV charge scheduling procedure is shown in Fig. 1. The inputs required for the dynamic EV charge scheduling procedure are the forecasted building load profile, predicted EV charging profile, forecasted output power of distributed energy resources (DERs) such as solar PVs, CC/DL value, EV arrival and departure times, initial state of charge (SOC) at arrival and minimum required SOC at departure. The forecasted building load profile and predicted EV charging profile are derived using the methods developed in [21]. The forecasted total building load demand P_T obtained by considering the forecasted building load profile P_L , forecasted output power of DERs P_{DER} and predicted charging profile of each EV P_{EV} can be expressed as

$$P_T = P_L - P_{DER} + \sum_{i=1}^n P_{EV_i} \quad (1)$$

The average total building load demand $P_{T(ave)}$ is then calculated for the whole charging period as given by

$$P_{T(ave)} = \frac{\sum_{j=1}^{m_{\max}} (P_T)}{m_{\max}} \quad (2)$$

where

$$m_{\max} = \sigma_{\max}(N_{dep})$$

$\sigma_{\max}(N_{dep})$ denotes the departure interval selection process and subscript 'max' represents the propositional formula to select the departure interval of the last EV to depart. For example, if there are 5 EVs connected to the building, namely EV1, EV2, EV3, EV4 and EV5 with specific departure interval numbers of 8, 18, 24, 20 and 16 respectively, the departure interval selection process $\sigma_{\max}(N_{dep})$ will select EV3 as it has the largest departure interval number. Then, an EV's charging status for one particular half-hour interval is determined based on (i) EV's priority (will

Fig. 1. Dynamic EV charge scheduling.

be discussed in Section II-C), (ii) the condition that the additional load due to the EV charging does not exceed $x\%$ of CC/DL, and (iii) the total building load demand in that half-hour interval $P_T(j)$ is within $P_{T(ave)}$. The first constraint ensures fairness to all EV owners while the second constraint is to ensure that the EVs scheduled for charging will not be interrupted by DRM program. The third constraint is required to achieve a smooth valley filling and higher energy efficiency [22]. Therefore, each half-hour interval in the EV charge scheduling (i.e., a total of 48 intervals) will have an optimum number of EV charging. Furthermore, 24-hour scheduling helps to spread the EV load without violating owner's satisfaction and comfort. Dynamic scheduling of EV charging will also ensure that the charging of EVs will not violate CC/DL while maximizing the utilization of DERs and minimizing the total cost of operation. The output of the dynamic EV charge scheduling procedure is the charging schedule (CS) for next 24 hours of all the EVs connected to the building. The CS is a matrix in the form as

$$CS_{n,48} = \begin{bmatrix} x_{1,1} & x_{1,2} & \cdots & x_{1,48} \\ x_{2,1} & x_{2,2} & \cdots & x_{2,48} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n,1} & x_{n,2} & \cdots & x_{n,48} \end{bmatrix} \quad (3)$$

where $x_{i,j} = \begin{cases} 0, & \text{charging not allowed} \\ 1, & \text{charging allowed} \end{cases}$

where $x_{i,j}$ is the control command given to the circuit breaker of the EV charging station by the BEMS to start or stop charging such that j represents one half-hour interval in a day, i is the EV number and n is the total number of EV charging stations installed in the building. i^{th} row of the CS matrix represents the charging schedule of i^{th} EV for next 24 hours. In this scenario, there are n rows which represent n EVs. Each column of the CS matrix represents one half-hour interval, e.g., column 1 represents the interval from 09:30 to 10:00 hours, column 2 represents the interval from 10:00 to 10:30 hours, etc. The CS is updated for every half-hour interval to cater for the arrival of new EVs as well as to reschedule the charging of EVs that are involved in the load shedding process during the previous interval. Also, half-hour intervals are considered to account for the 30-minute electricity pricing system in Singapore.

B. Speed Control of AC System's VSD

About 60% of energy consumed by buildings in Singapore is used for cooling as Singapore experiences a tropical climate throughout the year [23]. According to [24], the power needed to drive the fan used in an AC system is directly proportional to the cube of the speed. Hence, a small reduction in airflow can result in significant energy saving. VSDs connected to the AC system motors can help to achieve significant reduction in AC system power demand. However, to protect the well-being of building occupants, the ambient room temperature is set between 22.5°C to 25.5°C as recommended by Building and Construction Authority of Singapore [25].

The proposed preemptive DRM program includes an enhanced multi-parameter based DRM program to reduce the AC system's power demand based on the room temperature T_R , human occupancy level H_{OL} , current power demand P_{CD} and CC/DL value. The flow chart for the operation and control of the AC system's VSD is shown in Fig. 2. Firstly, the building operator

through the BEMS will specify their comfort preference by setting the maximum temperature $T_{AC,max}$ and minimum temperature $T_{AC,min}$ set points. During normal operation (i.e., P_{CD} is below $y\%$ of CC/DL), if T_R is less than or equal to $T_{AC,min}$, the DRM program will send a control signal to the VSD to turn off the AC system for a period of time by reducing the VSD operating frequency f_{VSD} to 0 Hz. When T_R reaches $T_{AC,max}$, the BEMS will send a control signal to the VSD to turn on the AC system and increase the speed of the VSD to 90% of full load (i.e., by increasing f_{VSD} to 90% of the power system frequency f_s). From $T_{AC,max}$ until the temperature reaches back to $T_{AC,min}$, the speed of the VSD will be decreased by 10% of full load for every 1°C drop in T_R . Under this operating condition, in the case where T_R increases instead of decreasing due to unpredicted circumstances, the DRM program will ensure that the VSD operates at its current speed setting until T_R reaches $T_{AC,max}$ where the speed will be set back to 90% of full load. When T_R is equal to $T_{AC,min}$, the DRM program will turn off the AC system by reducing f_{VSD} to 0 Hz. The time taken for the temperature in the room to rise from $T_{AC,min}$ to $T_{AC,max}$ is when significant energy saving is achieved by not operating the AC system. The normal operating procedure will repeat continuously as long as P_{CD} does not exceed $y\%$ of CC/DL. The DRM program also considers the human occupancy level H_{OL} in the DRM decision. For example, if H_{OL} is less than the high occupancy setting H_{high} , the BEMS will send a control signal to shut down the AC system when T_R is less than or equal to $T_{AC,min}$. However, the DRM program will reduce the speed of VSD to 30% of full load (i.e., by decreasing f_{VSD} to 30% of f_s) if H_{OL} is greater than or equal to H_{high} . This speed setting will ensure that the time taken for the temperature in the room to rise from $T_{AC,min}$ to $T_{AC,max}$ can be prolonged which otherwise will rise quickly due to the high occupant level. The VSD operating frequency f_{VSD} under normal operation condition

Fig. 2. Operation and control of the AC system's VSD.

where P_{CD} is below $y\%$ of CC/DL is given by

$$f_{VSD} = \begin{cases} 0.9f_s, & \text{for } T_R \geq T_{AC,max} \\ [0.9 - 0.1(T_{AC,max} - T_R)]f_s, & \text{for } T_{AC,max} \geq T_R > T_{AC,min}; \\ 0.3af_s, & \text{and } f_{VSD} > 0 \\ & \text{for } T_R < T_{AC,min} \end{cases} \quad (4)$$

$$\text{where } a = \begin{cases} 0, & \text{for } H_{OL} < H_{high} \\ 1, & \text{for } H_{OL} \geq H_{high} \end{cases}$$

However, when the building load demand exceeds $y\%$ of CC/DL, H_{OL} and T_R will have major roles in deciding the speed of the AC system's VSD operating frequency. If H_{OL} is more than or equal to H_{high} , then the DRM program will set the speed of the VSD to 50% of full load (i.e., f_{VSD} equals 50% of f_s) if T_R is greater than or equal to $T_{AC,max}$ and to 30% of full load (i.e., f_{VSD} equals 30% of f_s) if T_R is lower than $T_{AC,max}$. However, if H_{OL} is less than H_{high} , then the DRM program will only allow the AC system to operate when T_R is greater than or equal to $T_{AC,max}$ but the speed will be set to only 30% of full load. The VSD operating frequency f_{VSD} under system constraint condition where P_{CD} is equal to or more than $y\%$ of CC/DL is given by

$$f_{VSD} = \begin{cases} 0.3f_s + 0.2af_s, & \text{for } T_R \geq T_{AC,max} \\ 0.3af_s, & \text{for } T_R < T_{AC,max} \end{cases} \quad (5)$$

$$\text{where } a = \begin{cases} 0, & \text{for } H_{OL} < H_{high} \\ 1, & \text{for } H_{OL} \geq H_{high} \end{cases}$$

The demand response operation of the AC system during periods of system constraint will help to maintain/reduce the building load demand below CC/DL. However, in order to ensure occupant comfort, the AC system will operate at reduced load demand only when T_R reaches $T_{AC,max}$. The value of H_{high} can be determined arbitrarily or by studying how occupancy level affects temperature rise in a building environment. In this paper, the value of H_{high} is taken as 20.

C. Priority-based Load Shedding

Load shedding is one of the most common demand response techniques currently employed to facilitate short-term load reduction. In its simplest form, load shedding involves reducing the electrical load by a certain percentage in response to a request from the utility. In this paper, an automated demand response is considered, where the BEMS will monitor the P_{CD} against CC/DL and then invoke the DRM load shedding program if lower margin from the CC/DL is detected. The proposed DRM program consists of a user defined priority setting for interruptible loads (ILs) as well as an innovative dynamic priority allocation for EVs.

i) Shedding of EV load

In this paper, EVs are considered as the lowest priority load that will be shed first before shedding any other ILs. This is because temporary discontinuity of EV charging will not have significant impact on the EV owner's satisfaction and comfort provided that the owner's required SOC at departure can be achieved. The dynamic EV charge scheduling algorithm ensures that the EV charging will be scheduled dynamically every half-hour in order to ensure the required SOC at departure can be achieved despite EV load shedding during a particular interval.

The load shedding priority of an EV that is being charged during one particular half-hour interval is obtained based on various priority parameters in particular, battery SOC, slack time available for charging (i.e., the difference between the available time before departure and the required time for completion) and completed charging intervals as given by (6)-(8) respectively. The parameters SOC and slack time are related to the possibility of achieving the owner's required SOC at departure. In other words, these parameters are closely associated with owner's satisfaction and comfort. When the values of these parameters are high, it ensures higher possibility of achieving the owner's required SOC at departure. Therefore, higher SOC and slack time will yield lower load shedding priority for a particular EV. This is because even if the EV is shed for demand response, the EV can still be charged up to its required SOC in the subsequent half-hour intervals. The third parameter relates to the amount of charging time already allocated to a particular EV. The load shedding priority of a particular EV will be lower if the EV has been granted higher amount of charging time in order to ensure fairness to all EV owners.

$$\alpha_i = 1 - \left(\frac{SOC_i}{100} \right) \quad (6)$$

$$\beta_i = 1 - \left(\frac{N_{dep,i} - N_{req,i}}{t_{c,i}} \right) \quad (7)$$

$$\delta_i = 1 - \left(\frac{N_{com,i}}{t_{c,i}} \right) \quad (8)$$

where i is the EV number, α_i represents the priority parameter due to battery SOC, SOC_i is the state-of-charge of i^{th} EV in percentage, β_i represents the priority parameter due to slack time available for charging, $N_{dep,i}$ is the number of half-hour time intervals available before departure of i^{th} EV, $N_{req,i}$ is the number of half-hour time intervals required for charging the particular EV up to the desired SOC, δ_i represents the priority parameter due to completed charging intervals, $N_{com,i}$ is the number of half-hour time intervals completed for charging the particular EV, and $t_{c,i}$ is time in half-hour intervals required for charging the EV from its minimum to maximum SOC. Each of the three priority parameters gives different priority preference to different EVs as follows:

1. SOC (equation 6): α_i gives more preference to EVs with lower SOC. The priority value will decrease with increase of SOC, hence EVs with higher SOC will have lower priority value. This means that EVs with higher SOC will be more likely to be shed first compared to EVs with lower SOC. This parameter is essential for ensuring higher EV owners' satisfaction.
2. Slack time (equation 7): β_i gives more preference to EVs with shorter time available to complete charging before departure. This is obtained based on the difference between the time available before departure and the time required to complete charging. The priority value will decrease with increase in slack time, which will enable EVs with longer slack time to have lower priority value. This means that EVs with longer slack time will be shed first compared to EVs with shorter slack time. This parameter is required to ensure higher degree of fairness to the EV owners.
3. Completed charging intervals (equation 8): δ_i gives more preference to EVs which require more charging time to reach

the desired SOC before departure. Although this priority criterion complements β_i , it is required for balancing the fairness among EVs with same battery capacity. The priority value will decrease with increase in the number of intervals used for charging. This means that EVs with higher number of completed charging intervals will be more likely to be shed first compared to EVs with lower number of completed charging intervals.

A linear combination of the priority criteria is used to combine all three priority parameters, in particular, battery SOC, slack time available for charging, and completed charging intervals, with different weightage in order to determine a priority value for each EV. This is because each of the three priority parameters gives different preference to different EVs such that α_i gives more preference to EVs with lower SOC, β_i gives more preferences to EVs with shorter time available to complete charging before departure and δ_i gives more preference to EVs which require more charging time to reach the desired SOC before departure. The priority value of the EV can then be expressed as

$$\rho_i = w_1\alpha_i + w_2\beta_i + w_3\delta_i \quad (9)$$

w_1 , w_2 and w_3 are the weighing factors for the priority parameters which can be determined by the building operator in order to ensure higher degree of fairness and customer's satisfaction. In this paper, w_1 , w_2 and w_3 take the value of 1 in order to give equal weightage for all the three priority parameters. Although a particular EV charging is stopped due to load shedding requirement, its load shedding priority in the next interval will be dynamically allocated based on the possibility for the EV to be charged up to its required SOC before the departure time.

The proposed DRM program will invoke shedding of the lowest priority EV when the building current load demand P_{CD} exceeds $x\%$ of CC/DL. This process repeats for the next lowest priority EV if P_{CD} continues to exceed $x\%$ of CC/DL until all EVs that are being charged have been shed. However, when the building returns to its normal operation and P_{CD} reduces to less than $z\%$ of CC/DL, the EVs that have been shed previously will be allowed to charge based on their priority values. In this case, the highest priority EV among the EVs that are not being charged will be allowed to start charging. The lowest priority EV for one particular half-hour interval j is obtained from the selection of the EV with the minimum priority value from all EVs that are being charged during the interval j . Similarly, the highest priority EV for one particular half-hour interval j is obtained from the selection of the EV with the maximum priority value from all EVs that are not charged during the interval j . The selection of the lowest and highest priority EV can be represented by

$$i = \begin{cases} \sigma_{\min}(\rho_{i,j}), & P_{CD} > x\% \text{ of CC/DL} \\ \sigma_{\max}(\rho_{i,j}), & P_{CD} < z\% \text{ of CC/DL} \end{cases} \quad (10)$$

for $i = 1, 2, 3, \dots, n$ where n is the total number of EV charging stations installed in the building. Equation (10) returns the EV number where $\sigma_{\min}(\rho_{i,j})$ and $\sigma_{\max}(\rho_{i,j})$ denote the selection process of the EV having the lowest and highest priority values respectively, and subscripts 'min' and 'max' represent the propositional formula to select the EV with the minimum and maximum priority values respectively. For example, if there are 5 EVs connected to the building, namely EV1, EV2, EV3, EV4 and EV5 with specific priority values of 2, 4, 3, 6 and 1 respectively, $\sigma_{\min}(\rho_{i,j})$ will select EV5 as it has the lowest priority value and

$\sigma_{\max}(\rho_{i,j})$ will select EV4 as it has the highest priority value. The control signal sent by the BEMS to the circuit breaker at the EV charging station to start or stop charging according to the DRM program is given by

$$x_{i,j} = \begin{cases} 0, & P_{CD} > x\% \text{ of CC/DL} \\ 1, & P_{CD} < z\% \text{ of CC/DL} \end{cases} \quad (11)$$

where "0" and "1" represent the circuit breaker "OFF" and "ON" status respectively, j represents one half-hour interval in a day and i is the EV number.

ii) Shedding of interruptible loads

Other ILs in the building have a priority value ρ_{IL} which is assigned by the building operator through the BEMS. With "1" as the lowest priority and "5" as the highest priority, the building operator can determine with much flexibility which loads in the building are less critical or non-essential such as corridor lightings and assign them with lower priority "1" and which loads are critical loads such as surveillance systems where the building operator can assign them higher priority "5". When P_{CD} exceeds $y\%$ of CC/DL, the DRM program will automatically shed lower priority loads, starting from "1". Loads with highest priority "5" will not be shed under any circumstances. For example, if "corridor lightings" have priority "1" setting, they will be shed first when P_{CD} exceeds $y\%$ of CC/DL. The same process is repeated for priority "2" loads if P_{CD} continues to exceed $y\%$ of CC/DL after priority "1" loads have been shed. When P_{CD} is less than or equal to $z\%$ of CC/DL, the loads that were previously shed will be reconnected automatically. By setting priority levels for various loads, DRM can be performed to shave a portion of the maximum demand to meet CC/DL.

In this paper, electronic information display units, corridor lightings, car park ventilation fans and storage tank water pumps are considered as ILs. The IL with the lowest priority during the load shedding process is obtained from the selection of the IL with minimum priority value from all ILs as given by (12) which returns the IL unit number ℓ holding the minimum priority value.

$$\ell = \sigma_{\min}(\rho_{IL}), \quad IL = 1, 2, 3, \dots, q. \quad (12)$$

where σ denotes the IL selection process, subscript 'min' represents the propositional formula to select the IL with the minimum priority value and q is the number of ILs that participate in the load shedding process. The control signal sent by the BEMS to the load control module (LCM) of a particular IL during the load shedding process is given by

$$LCM_{IL,\ell} = \begin{cases} 0, & P_{CD} > y\% \text{ of CC/DL} \\ 1, & P_{CD} < z\% \text{ of CC/DL} \end{cases} \quad (13)$$

where "0" and "1" represent the LCM "OFF" and "ON" status respectively.

III. LOAD MODEL FOR DRM

The DRM program proposed in this paper considers the EVs, AC system's VSD and ILs as the loads that participate in the demand response. Load models are developed to allow the analysis on the capability of the proposed DRM program to reduce the building's overall power demand.

i) *EV load model*

The power demand of one EV charging is based on the estimated charging demand of the EV and the charging station circuit breaker ON/OFF status, and is given by

$$P_{EV,i} = P_{CS,i} \cdot x_{i,j} \quad (14)$$

where i is the EV number and $x_{i,j} = \{0,1\}$ represents the circuit breaker "OFF" and "ON" status of the EV charging station for one particular half-hour interval j . $P_{CS,i}$ is the estimated charging power demand of the i^{th} EV in the next interval. It is obtained by using the current SOC of the EV, time period of the next interval and the predicted charging profile of the EV. Data mapping with current SOC as the identification parameter is used to determine the starting point in the predicted charging profile. The number of data points equal to the number of minutes in the next interval (30 minutes in this case) is extracted to calculate the value of $P_{CS,i}$. The load model for predicting the charging profile of the EV using initial SOC, final SOC and previous charging profile is described in [21]. The total building's EV power demand is then given by

$$P_{EV,total} = \sum_{i=1}^n P_{EV,i} \quad (15)$$

where n is the total number of EV charging stations installed in the building.

ii) *AC system load model*

The power demand of one AC system load is based on its motor power rating, circuit breaker ON/OFF status and motor operating speed in relation to the VSD frequency as follows:

$$P_{AC,k} = P_{ACmotor,k} \times B_{ACmotor,k} \times \frac{f_{VSD,k}}{f_s} \quad (16)$$

where k is the AC system unit number, $P_{AC,k}$ is the AC system power demand of the k^{th} unit, $P_{ACmotor,k}$ is the AC system motor rated power of the k^{th} unit, $B_{ACmotor,k}$ represents the circuit breaker ON/OFF status of the k^{th} unit, $f_{VSD,k}$ is the VSD operating frequency and f_s is the supply frequency. The total building's AC system power demand is then obtained by

$$P_{AC,total} = \sum_{k=1}^r P_{AC,k} \quad (17)$$

where r is the total number of AC system loads installed in the building.

iii) *IL model*

The power demand of other ILs is based on the load rated power and the LCM ON/OFF status as represented by

$$P_{IL,\ell} = P_{ILrated,\ell} \times LCM_{IL,\ell} \quad (18)$$

where ℓ is the IL unit number, $P_{IL,\ell}$ is the IL power demand of the ℓ^{th} unit, $P_{ILrated,\ell}$ is the IL rated power of the ℓ^{th} unit and $LCM_{IL,\ell}$ represents the LCM ON/OFF status of the ℓ^{th} unit. The total building's IL power demand takes the form of

$$P_{IL,total} = \sum_{\ell=1}^w P_{IL,\ell} \quad (19)$$

TABLE I
PARAMETERS FOR DYNAMIC EV CHARGE SCHEDULING

EV ID (i)	Capacity (kWh)	Initial SOC (%)	Desired SOC (%)	Arrival Time	Departure Time
1	7	68.57	85	8:55	18:47
2	16	52.85	80	8:48	21:37
3	16	73.75	95	8:13	20:18
4	16	59.50	85	8:55	19:05
5	24	65.95	90	9:15	17:50

where w is the total number of ILs in the building.

The building current load demand P_{CD} can then be obtained by the summation of the total EV, AC system and IL power demands. The building current load demand is given by

$$P_{CD} = P_{EV,total} + P_{AC,total} + P_{IL,total} + P_{others} \quad (20)$$

P_{others} is the power demand of other essential and non-essential loads that do not participate in the DRM program. P_{others} is used as the control variable in the DRM analysis to increase P_{CD} to $x\%$ and $y\%$ of CC/DL.

IV. RESULTS AND DISCUSSIONS

In order to assess the performance of the proposed DRM program, individual case studies are conducted to study the capability of the proposed DRM program to ensure that P_{CD} is always maintained below CC/DL. In order to evaluate the accuracy of the developed mathematical models, the analytical results obtained using the mathematical models presented in this paper are compared with the simulation results obtained using the computer simulation models of the Building Energy Management System (BEMS). In the case studies the values of x , y and z parameters are considered as 80%, 90% and 50% respectively. For the forecasted DRM using EV charge scheduling, the case study presented uses a specific EV charge schedule derived based on the EV profiles given in Table I which is obtained based on a normal distribution with an average travel distance of 55 km and a standard deviation of 10 km [26]. Assuming that the working hours of the EV owners in a commercial building are from 08:30 to 18:00 hours, the arrival and departure of the EVs are varied randomly between 08:30 hours and 18:00 hours in the simulation in order to clearly observe the advantage of the proposed dynamic EV charge scheduling. The output of the dynamic EV charge scheduling at 09:30 hours based on the procedure discussed in Section II-A is given by

$$CS_{5,48} = \left[\begin{array}{cccccccccccccccccccc} 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & \dots & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & \dots & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & \dots & 0 \\ 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dots & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dots & 0 \end{array} \right] \left. \begin{array}{l} \text{EV 1} \\ \text{EV 2} \\ \text{EV 3} \\ \text{EV 4} \\ \text{EV 5} \end{array} \right\} \text{EV ID}$$

09:30 10:30 11:30 12:30 13:30 14:30 15:30 16:30 09:00
Time (hours)

It can be seen that during the half-hour interval from 09:30 to 10:00 hours, EV 4 and EV 5 are allocated time for charging as the values of $x_{4,1}$ and $x_{5,1}$ are equal to 1. This is because based on the departure time of all the EVs, EV 5 actually has a shorter slack time available for charging compared to other EVs. On the other hand, EV 4 which has a longer slack time available for charging compared to EV 1 is allocated charging time during this interval as it has a larger charging requirement to fulfill before the departure time compared to EV 1. Also, it can be observed that EV 2 which arrived earlier than EVs 1, 4 and 5 is given the

lowest priority for charging due to its smaller SOC requirement and longer slack time as it will depart last. It can also be seen that at most only three EVs are allocated charging time during one particular interval in order to ensure that the total building load will not exceed $x\%$ of CC/DL. However, the dynamic EV charge scheduling ensures that all five EVs are charged to their required SOC before their departure time.

Figs. 3 and 4 show the capability of the dynamic EV charge scheduling DRM program to respond swiftly to unexpected lower and higher building load demand compared to the predicted load profile respectively. It can be observed that the analytical results obtained using the developed load models correspond well with the simulation results. P_{others} is used as the control variable in the DRM analysis to decrease and increase P_{CD} to $z\%$ and $x\%$ of CC/DL respectively. As shown in Fig. 3, with the decrease in P_{CD} to less than $z\%$ (in this case 50%) of CC/DL (i.e., 25kW) at 09:46 hours, the EV load is increased in steps taking into consideration the conditions that the additional load due to the EV charging does not exceed $x\%$ of CC/DL (in this case 80%) and $P(j)$ is within $P_{T(ave)}$. It can be seen that only one EV is allowed to start charging at 9:46 hours without violating the conditions. In the event when other load demand P_{others} is reduced further at 9:52 hours, two more EVs are scheduled to start charging. This ensures proper resource utilization and higher charging efficiency as EVs are charged during low load period. The response can also be related to a scenario when the outputs of DERs such as solar PVs

Fig. 3. Dynamic charge scheduling of EVs during low load period.

Fig. 4. Dynamic charge scheduling of EVs during high load period.

installed in the building are available, thus reducing the total amount of power supplied from the grid. Similarly, as shown in Fig. 4, with the increase in P_{CD} to more than $x\%$ of CC/DL (i.e., 40kW), the EV load is decreased accordingly to maintain P_{CD} below $x\%$ of CC/DL. This can be clearly seen in Fig. 4 at 09:38 hours where an increase in other building load causes P_{CD} to exceed $x\%$ of CC/DL which triggers the DRM program to reduce EV load demand by sending a signal to stop the charging of one EV. This is sufficient to bring P_{CD} below $x\%$ of CC/DL. Subsequently, at 09:43 hours, another violation of P_{CD} exceeding $x\%$ of CC/DL occurs and further reduction of EV load demand can be observed. However, after 09:44 hours when all EVs have been stopped from charging, the continual increase in P_{others} causes P_{CD} to exceed $x\%$ of CC/DL. This will trigger the DRM program to activate the subsequent DRM program to reduce the AC system's power demand through VSD control and finally priority-based load shedding in order to ensure that P_{CD} is always maintained below CC/DL.

The proposed DRM program consists of a multi-parameter based AC system's VSD speed control function which ensures reduction in AC system's power demand while considering the building occupant comfort. In this case study, the capability of the proposed DRM program to facilitate load reduction based on room temperature T_R , human occupancy level H_{OL} , current power demand P_{CD} and CC/DL value as discussed in Section II-B is

Fig. 5. Speed control of AC system's VSD under normal condition.

Fig. 6. Speed control of AC system's VSD during high load period.

demonstrated. The AC system motor rated power $P_{ACmotor}$ and high occupancy setting H_{high} are taken as 7.5kW and 20 respectively. It can be seen from Figs. 5 and 6 that the analytical results correspond well with the simulation results. As shown in Fig. 5, during normal operation when P_{CD} is below $y\%$ (in this case 90%) of CC/DL (i.e., 45kW) and H_{OL} is less than H_{high} , the AC system does not operate if T_R is less than $T_{AC,min}$ (in this case 20°C). The AC system will only start operating when the temperature rises to $T_{AC,max}$ (in this case 25°C). It can be observed that at 15:21 hours, when T_R reaches 25°C and H_{OL} is less than H_{high} , the AC system starts to operate at 90% of full load (i.e., $f_{VSD} = 0.9f_s$) which corresponds to about 6.75kW AC power demand. Subsequently, for every 1°C drop in T_R , the AC system's VSD speed is reduced by 10% of full load until T_R reaches the preset $T_{AC,min}$ where the AC system will stop operating at 16:08 hours. During this period, every 10% reduction in AC system's VSD speed corresponds to about 0.75kW reduction in AC power demand. Furthermore, the time duration taken for the temperature to rise from $T_{AC,min}$ to $T_{AC,max}$ is when significant energy saving is achieved by not operating the AC system. The AC system's VSD speed control operates differently when H_{OL} is higher than H_{high} as the increase in temperature will be much faster due to human presences and activities. In the case when H_{OL} is higher than H_{high} , it can be observed from Fig. 5 that when T_R rises from $T_{AC,min}$ to $T_{AC,max}$ during the time period from 16:21 to 17:22 hours, the DRM program will operate the AC system at 30% of full load (i.e., $f_{VSD} = 0.3f_s$) which corresponds to 2.25kW instead of turning off the AC system completely. When T_R reaches $T_{AC,max}$ at 17:37 hours, the AC system starts to operate at 90% of full load and subsequently, for every 1°C drop in T_R , the AC system's VSD speed is reduced by 10% of full load until T_R reaches the preset $T_{AC,min}$ where the AC system will operate at 30% of full load until T_R reaches $T_{AC,max}$ again. This will help to prolong the time taken for the temperature in the room to rise from $T_{AC,min}$ to $T_{AC,max}$, thus ensuring continuous occupant comfort.

Meanwhile, as shown in Fig. 6, during high load operation when P_{CD} is above $y\%$ of CC/DL and H_{OL} is less than H_{high} , the

Fig. 7. Overall demand response capability of the proposed DRM program.

AC system is only allowed to operate at 30% of full load (i.e., $f_{VSD} = 0.3f_s$) when T_R is equal to $T_{AC,max}$ at 9:35 hours. As the cool air starts to blow into the room, T_R will not rise but maintain at $T_{AC,max}$ for sometime before decreasing to 24°C at 10:10 hours. Then, the DRM program will send a signal to the AC system's VSD to stop operation. If the high load condition persists, the AC system will be operated again at 30% of full load when T_R rises back to $T_{AC,max}$ at 11:35 hours. However, during high load operation when P_{CD} is above $y\%$ of CC/DL and H_{OL} is equal to or higher than H_{high} , the AC system will be allowed to operate at 50% of full load (i.e., $f_{VSD} = 0.5f_s$) when T_R is equal to $T_{AC,max}$ as observed at approximately 11:35 hours in Fig. 6. When T_R slowly decreases to 24°C at approximately 14:05 hours, the DRM program will reduce the AC system's VSD speed to 30% of full load. This speed setting will continue until any of the conditions where T_R equals to or less than $T_{AC,min}$, T_R equals to or higher than $T_{AC,max}$, or P_{CD} is below $y\%$ of CC/DL is satisfied.

Fig. 7 shows the overall demand response capability of the proposed DRM program. In this case study, H_{OL} is set to 10, H_{high} is set to 20, and T_R is set to 25°C. $T_{AC,min}$ and $T_{AC,max}$ are set to 20°C and 25°C respectively. ILs in the building are given load shedding priorities and power demands as defined in Table II. Other building load demands P_{others} are intentionally increased to analyze and test the applicability of the proposed DRM program to achieve demand response capability. It can be observed from Fig. 7 that when P_{CD} is increased to more than $x\%$ (in this case 80%) of CC/DL (i.e., 40kW) at 9:32 hours, the reduction in EV load is triggered by the DRM program to reduce P_{CD} below $x\%$ of CC/DL. As the building load demand continues to increase due to increase in P_{others} , the charging of other EVs are stopped accordingly as it can be seen at 9:36 and 9:47 hours. After all the EVs have been stopped from charging, at 09:54 hours, when the building load demand exceeds $y\%$ (in this case 90%) of CC/DL (i.e., 45kW), the DRM program reduces the power demand of the AC system, which represents the largest power consumer in the building. In this case, before the DRM program sends a control signal to the VSD, the AC system at each floor is operating at 90% of full load which corresponds to 6.75kW. However, when the total building demand exceeds $y\%$ of CC/DL, the AC system's VSD speed is reduced to 30% of full load which corresponds to 2.25kW. This constitutes to a reduction of 9kW (for 2 AC systems) in P_{CD} . Concurrently, the shedding of the lowest priority IL, in this case the electronic information display unit load, will take place when P_{CD} is above $y\%$ of CC/DL. This reduces P_{CD} by another 2kW. As P_{CD} is increased further and exceeds $y\%$ of CC/DL at 10:03 hours, the shedding of next higher priority load (i.e., priority 2 IL) can be observed where the corridor lighting load is shed at 10:03 hours. Since the corridor lighting load demand is only 0.45 kW which is insufficient to lower the P_{CD} below $y\%$ of CC/DL, the priority 3 IL, car park ventilation fan load, is subsequently shed at 10:04 hours to ensure P_{CD} is below $y\%$ of CC/DL. Finally, when the P_{CD} exceeds $y\%$ of CC/DL again at 10:07 hours, the storage tank water pump load (i.e., priority 4 IL) is shed.

V. DRM COST AND BENEFIT ANALYSIS

In order to analyze the feasibility of the proposed DRM system, this section aims to study the cost and benefit of deploying the proposed DRM system in commercial buildings. Based on the load demand profile of an office building in Singapore, the peak demand periods occur from 10:00 to 12:00 hours at 1,350kW and from 13:00 to 16:00 hours at 1,400kW. Assuming that the contracted capacity is 1,300kW, the building

TABLE II
LOAD SHEDDING PRIORITY AND POWER DEMAND

Interruptible Load	Priority	Power Demand (kW)
Electronic Information Display Unit	1	2
Corridor Lighting	2	0.45
Car Park Ventilation Fan	3	1.2
Storage Tank Water Pump	4	4.5

owner will be required to pay for the uncontracted capacity charge incurred when the load demand exceeds the contracted capacity of 1,300kW. In order to avoid paying this additional cost, the building owner has an option to deploy diesel generators to carry out peak shaving tasks. In this paper, this option is considered as the reference of comparison to the proposed DRM system. The cost of a 125kW Cummins diesel generator is S\$23,272.80 [27]. Considering an installation cost of S\$10,000, the total initial cost of the diesel generator is S\$33,272.80. The power to be supplied by the diesel generators for the period from 10:00 to 12:00 hours is 50kW and for the period from 13:00 to 16:00 hours is 100kW. According to [28], the diesel generator fuel consumption F_{DG} can be represented as

$$F_{DG} = 0.01356C_{DG} + 0.2265P_{DG} \quad (21)$$

where C_{DG} is the rated capacity of the diesel generator and P_{DG} is the output power of the diesel generator. Then, the fuel consumption of the diesel generator is 13.02ℓ/hr for an output power of 50kW and 24.35ℓ/hr for an output power of 100kW. Therefore, the annual fuel cost of the diesel generator for peak energy reduction of 400kWh per day [(50kW x 2hr) + (100kW x 3hr)] is S\$43,250.32 considering a diesel cost of S\$1.2/ℓ [29]. According to [30], the average maintenance cost of a diesel generator is \$5,000/year. The cost components of the diesel generator are given in Table III.

On the other hand, the annual cost savings from the peak energy reduction of 400kWh per day is about S\$37,098.60 based on the electricity tariff of S\$0.2541/kWh for High Tension Small Supplies consumer category in Singapore [31]. In addition to the cost savings in reduction of peak demand, the building owner will also avoid paying the uncontracted capacity charge incurred when the load demand exceeds the contracted capacity of 1,300kW. The uncontracted capacity tariff is S\$12.03/kW for High Tension Small Supplies consumer category in Singapore [31]. The annual uncontracted capacity charge is about S\$14,436.00 (100kW x S\$12.03/kW x 12months). Therefore, the total cost savings that can be achieved is S\$51,534.60 (S\$37,098.60 + S\$14,436.00). It is assumed that the project duration is 20 years, the annual fuel escalation rate is 5% and the annual inflation rate is 5%. The payback period for the diesel generator system is 8.12 years. The peak shaving using diesel generator will yield a profit of S\$80,754.94 by the end of 20 years.

In order to determine the payback period for the building owner to recover the investment in the proposed DRM system, an estimation of the implementation cost based on the experience of implementing the proposed DRM system in the laboratory prototype and administration building in campus is shown in Table IV. The total initial cost is estimated at S\$65,500 for a building with 5 air conditioning system's variable speed drives and 50 load control modules. However, it is to be noted that the initial cost for the building owner will vary according to the size of the building and amount of control required. Hence, a large building with a sophisticated control requirement will incur more

TABLE III
DIESEL GENERATOR COST FOR BUILDING OWNER

Type	Component	Cost
Initial Cost	Cummins 125kW Diesel Generator	S\$23,272.80
	Installation	S\$10,000
Annual Cost	Diesel Fuel	S\$43,250.32
	Maintenance	S\$5,000

TABLE IV
DRM INITIAL COST FOR BUILDING OWNER

Component	Quantity	Cost
BEMS Software with DRM	1	S\$20,000
Programmable Logic Controller	1	S\$8,000
Smart Meter	1	S\$2,500
Variable Speed Drive	5	S\$30,000
Load Control Module	50	S\$5,000

investment cost. It is estimated that the proposed DRM system will incur an annual operational and maintenance cost of 15% of the total initial cost. Similar to the benefit analysis of the diesel generator, only the direct cost savings in reduction of peak demand and uncontracted capacity charge are considered to quantify the benefit of the DRM system. Therefore, the total annual savings that can be achieved using the proposed DRM system is S\$51,534.60. It is assumed that the project duration is 20 years and the annual inflation rate is 5%. The payback period for the proposed DRM system is 1.56 years. The peak shaving using the proposed DRM system will yield a profit of S\$1,382,626.13 by the end of 20 years.

It can be seen that although the initial cost of the DRM system is higher than the diesel generator, the annual operation and maintenance cost is much lower as it does not require fuel to operate. The shorter payback period and higher return offered by the proposed DRM system compared to using diesel generator clearly indicates the economic feasibility of employing the proposed DRM system for reducing electricity cost while improving energy efficiency in commercial buildings.

VI. CONCLUSION

This paper has proposed a preemptive DRM program for commercial buildings to ensure contracted capacity or utility imposed demand limit is not exceeded. The DRM program utilizes building energy management system to execute three different demand response techniques, namely, dynamic EV charge scheduling, speed control of air conditioning system's variable speed drive and priority-based load shedding. The proposed dynamic EV charge scheduling considers the forecasted building load profile, predicted EV charging profile, building contracted capacity or demand limit and EV data as the base for scheduling the EV charging. Furthermore, the novel dynamic priority calculation method varies the priority of each EV dynamically after every half-hour interval based on battery SOC, slack time available for charging and completed charging intervals. This ensures fairness to all EV owners while maximizing customer's satisfaction. The enhanced multi-parameter based DRM program to reduce the air conditioning system power demand based on the room temperature, human occupancy level, current power demand and building contracted capacity or demand limit enables the building operator to reduce the power consumption of their air conditioning systems without affecting occupant comfort. The automated load shedding DRM program which consists of a user defined priority setting for interruptible loads as well as an innovative dynamic priority

allocation for EV charging has been proposed to ensure building current power demand does not exceed building contracted capacity or demand limit. The performance of the proposed DRM program to keep within the contracted capacity or demand limit has been successfully tested and analyzed using the building energy management system.

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