Frequency Regulation Support from District Cooling System and V2G Facility in Cluster of Buildings

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***Abstract*—District Cooling System (DCS) is capable of providing cooling power in large capacity to the cluster of buildings. It could be a potential resource to supply the frequency regulation services to operate the power system smoothly. In order to provide high-quality regulation services and maximum revenue from the market, accurate forecasting of the building's electrical consumption and regulation capacity is imperative. Inaccurate forecasting of regulation capacity has two major disadvantages, first, the performance score could be poor, and second, the building's thermal discomfort may rise. As the DCS has a complex thermodynamics model and cooling power demand, the forecasting of regulation capacity becomes more stochastic. This paper addresses the above challenges and proposes a deep reinforcement learning-based regulation capacity strategy. To maximize the revenue, two agents are considered, one represents the DCS and the second vehicle-to-grid facility in the building cluster. First, a combined revenue-earned model for building clusters has been developed on the basis of its performance score and regulating capacity. Second, a markov decision process (MDP) has been formulated to offer a strategy for regulation capacity. On the basis of the above formulation, a deep-determined-policy-gradient method has been executed to evaluate the strategy in MDP, which gives us optimum results. As a result, various case study has been done, which shows the revenue earned by the system in different situation.**

***Index Terms*—Frequency Regulation, District Cooling System, Vehicle to Grid, Deep Reinforcement Learning.**

I. Introduction

Low carbon emission and Net-Zero carbon facilitates the reformation of the power system, which leads to more penetration of renewable energy sources (RES) in future power utility [1]. The uncertain and irregular pattern of power availability from RES requires regulation capacity in high bandwidth to maintain the power balance between demand and source [2]. District Cooling System (DCS), which is used to supply the cooling demand of a number of buildings in large capacity, is a very flexible load for the power system. It could be very fruitful for the regulation services to the utility [3]. As the thermal inertia of the buildings is quite high, it allows the DCS to operate at lower consumption with lower thermal discomfort in buildings [4], [5]. Apart from the DCS, Vehicle to Grid (V2G) facility could also be available to contribute to the regulation market [6], [7]. It denotes that in building cluster DCS and V2G are two resources that can be flexible resources to execute the demand response to contribute to frequency regulation.

As per the literature, if we use only DCS as a regulation resource, there could be a difference between market signal and contributing power. This leads to being penalized by the market [8] Therefore, to avoid the penalty and perform better in the regulation market, the capacity being offered by the DCS should be more accurate. Although this task is quite challenging with the following aspects:

- Complex modelling of DCS: As the DCS is a cooling source with a large and complex network with multiple buildings covering the area in kilometres [9]. Due to this large network, the thermodynamics of the system also becomes very complex, which leads to the modelling as less accurate, which reflects not to use of the traditional methods to calculate the regulating capacity by DCS.
- Uncertainty in cooling demand and RES: The power utility is integrated with the RES, which depends on the weather to generate the electrical power. Apart from this, as the weather changes, there is a change in the cooling demand of the building, and depending on the activity of the building, the cooling power demand varies.
- Uncertainty in V2G availability: V2G facilities in public places have multiple constraints. The first and most important constraint is the willingness of the Electric Vehicle (EV) owner to participate as a power through V2G facility. Second, the availability of EVs for V2G at discharging/charging stations at a time when there is a need for power regulation.

Research contributions

To counter the above issues, a Deep Reinforcement Learning (DRL) based control method is proposed in this paper, including the intrinsic property of the system. The main contributions of this paper are summarised below:

1) A DRL-based capacity offering policy is developed for a cluster of buildings connected with DCS and

V2G facilities to provide the regulation services. The objective is to achieve the maximum revenue with minimum thermal discomfort in the connected buildings. To counterbalance the uncertainties in thermal load or electrical load demand of the building, V2G support is considered, which also helps to improve the revenue of the system.

2) A novel model-free operational strategy is proposed for a cluster of buildings for energy-efficient operation of the DCS plant and V2G facility, which also support the utility for regulation services in a smart grid scenario.

Different parts of the proposed system have been modelled and presented in sections II and section III, including the problem formulation. Controlling algorithms and system flow-chart, including the prototype of the proposed methodology on a laboratory scale, have been discussed in section IV while section V elaborates on the experimental setup outcomes in a different scenario.

II. System Modeling

In this section, the modelling of the different parts of the DCS has been done, which shows the thermodynamic behaviour of the system and electrical power consumption accordingly. The calculation of the performance score of the system and the revenue earned has also been presented by following the rules of the PJM regulation market. Further, it formulates the regulating capacity offered by the device for the services.

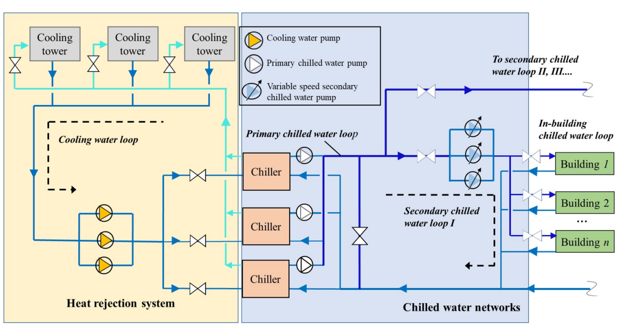

Fig. 1. Considered building cluster and its AHU geometric.

A. District Cooling System and air conditioning zone

1) Thermodynamics of DCS: The schematic of the DCS has been presented in Fig.1, which shows that there could be more than one chiller plant connected centrally as one cooling power source, a number of cooling towers to release the heat from the chiller plant, a water piping network for the chilled water supply and return water from the buildings, various water pump to regulate the water supply, and the connected number of buildings with it. According to thermal energy balancing, the thermal and electrical power of the chiller plant can be formulated as:

$$\dot{Q}^t_{chlr} = \dot{M}^t_{chlr} * c_p * (T^t_{chlr,r} - T^t_{chlr,s}), \quad \forall t \tag{1}$$

$$\dot{P}^t_{chlr} = \frac{\dot{Q}^t_{chlr}}{COP}, \quad \forall t \tag{2}$$

$$\dot{M}^t_{chlr} = \sum_{j=1}^{n_m} \dot{M}^t_{build,j}, \quad \forall t \tag{3}$$

Where $\dot{Q}^t_{chlr}$, $\dot{P}^t_{chlr}$, and $\dot{M}^t_{chlr}$ are the cooling power supply by the chiller plant, electrical power of chiller plant in kW, and chilled water flow rate from the chiller plant (in kg/s) respectively. COP denotes the coefficient of performance, c_p is the specific heat capacity of water $(kJ/kg \deg C)$. The water flow rate in the piping network $\dot{M}^t_{chlr}$ (kg/sec) is the summation of chilled water flow to the buildings $\dot{M}^t_{build,j}$ while n_m denotes the number of buildings in the cluster. Eq.1 reflects that the temperature difference between the supply and return water $(T^t_{chlr,r} - T^t_{chlr,s})$ imposes the cooling load demand on the chiller unit.

2) Required thermal load of a building: The required cooling power in a particular zone can be formulated as:

$$\dot{Q}^{req}_{zone,i} = \dot{M}_{zone,i} * c_p * (T^t_{zone,i} - T^{set}_{zone,i}) \quad (kJ/sec) \tag{4}$$

$\dot{M}_{zone}$ depends on the volumetric flow rate of air which varies with the size of the air conditioning zone and the required air change rate (ACH). It can be calculated by the equation5:

$$\dot{M}_{zone} = V_{zone} * ACH * \rho_{air}/3600 \quad (m^3)/sec \tag{5}$$

Where $V_{zone}(m^3)$ is the volume of the air conditioning zone and ACH (per hour) is air change per rate (as per ASHRAE standard, it should be between 6 to 20 for a classroom,) while ρ_{air} represents the air density. The cooling power demand of a particular building could be found out by adding all the cooling demands of air-conditioning zones of the building, and it is expressed as:

$$\dot{Q}^{req}_{build,j} = \sum_{i=1}^{n_j} \dot{Q}^{req}_{zone,i} \tag{6}$$

where n_j is the number of zones in j^{th} building.

B. Regulation Capacity offered in market

The process and steps for the resources to provide the regulation services are presented in Fig.2. In the PJ market, the day ahead market used to be closed a day before the operating day at the time $02:15$ PM. Meanwhile, the resources have to bid for services with some power. To be more accurate in available power capacity for the regulation services, the change in offering regulation capacity and modulation in the numbers of available capacity is allowed before 60 min prior to the operating hour when the hour-ahead market closes. The PJ market determines the capacity of all the resources in a one-time slot before the operating time hour [8]. At the time the building cluster finishes the services at $t+1$ hour, it receives an hourly revenue r^{build}_t by the market, which is formulated as:

$$r^{build}_t = C^{build}_t * s^{build}_t * p^{PJM}_t, \quad \forall t, \tag{7}$$

$$C^{build}_t = C^{DCS}_t + C^{V2G}_t, \quad \forall t, \tag{8}$$

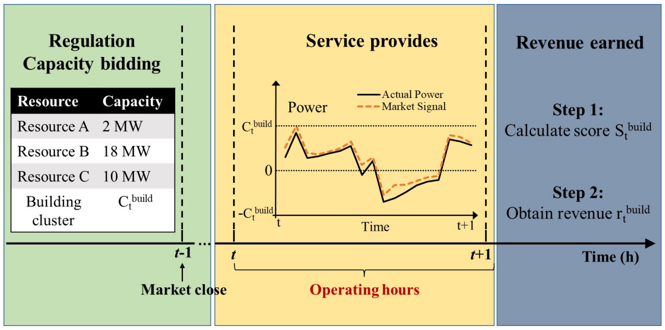

Fig. 2. Procedure of regulation services in PJ Market.

Where C_t^{build} (MW), and $s_t^{build} \in [0,1]$ are the hourly regulation capacity and performance score of the building cluster, respectively, while p_t^{PJM} is the market price. The building cluster regulation capacity C_t^{build} is the cumulative sum of DCS capacity C_t^{DCS} and V2G capacity C_t^{V2G}. It is very uncertain and depends cumulatively on the market participators. As the building cluster's capacity is insufficient to govern the market, it is assumed to be a price-taker only in the market. The performance score s_t^{build} of any resource is the evaluation of the quality of the regulation provided by that particular resource, which is the difference between the actual regulation and regulation signal received by the market. It is evaluated with three aspects on the same weightage: 1) precision, 2) correlation, and 3) time delay:

$$s_t^{build} = \frac{s_t^{pre}}{3} + \frac{s_t^{corr}}{3} + \frac{s_t^{delay}}{3}, \quad \forall t \tag{9}$$

To maximize the building cluster's revenue, it must maintain a high-performance score.

As the regulation capacity is time bounded, the objective of the building cluster is to maximize the revenue from the market during the day. It could be formulated as:

$$\max_{C_t^{build}} r_t^{build} = \sum C_t^{build} * s_t^{build} * p_t^{PJM} \tag{10}$$

$$s.t. : s_t^{build} \geq s^{min}, \left|T_{zone,i}^{t} - T_{zone,i}^{set}\right| \leq D, \tag{11}$$

$$SOC_t^{V,i} \geq SOC^{min}$$

Where $\left|T_{zone,i}^{t} - T_{zone,i}^{set}\right|$ is the thermal discomfort level in a particular air conditioning zone of the buildings

III. Online Regulation Capacity Offered by DRL

In this section, a DRL-based framework has been proposed to determine the regulation capacity of the buildings cluster. First, an MDP has been formulated to maximize the revenue from the regulation market for the building cluster with a good performance score.

A. Capacity Offering based on MDP

To make the system model-free, it needs to design a mathematical model for an MDP explaining the building cluster system and its regulations sources which contributes to capacity offering. It needs a state space containing the necessary information about the DCS and V2G facility within the building cluster. In this work, the state variable contains information about the operation of DCS (e.g. electrical power demand, indoor temperature, and set discomfort level), operation of V2G (e.g. number of vehicles available for V2G), and historical data of regulating market (e.g. regulating signals, marginal price).

An MDP can be explained with tuple (S, A, R, γ) for the regulation capacity offering problem. Where S is state space, A presents the action, R express the reward function, and γ denotes the discount factor. These can be expressed as:

1) Action: The action or decision variables of each agent at time t are defined in terms of the capacity offered by the building cluster to the regulating market, $a_t = [C_t^{build}]^T, \forall t$. It is a continuous variable and satisfies the minimum and maximum regulating capacity. As the market signal σ_t^s has the value of $[-1, 1]$, the power regulation range of the system also has the range of $[-a_t, a_t]$. On the other side, it reflects that the regulation could be both up and downside.

2) State: State space is the condition of the considered system with an action done by the agent, and that is also an input for the agent. In the considered building clusters, the observed state space is described as:

$$s_t = [t, P_t^{DCS}, p_{t-1}^{PJM}, P_{t-1}^{V2G,i}, D_{t-1}^{j}, \sigma_t^s], \quad \forall t$$

In the state space variable, such type of variable should be chosen which has higher relevance information to take the final decision. Here, t is the operating time, P_t^{DCS} is the electrical power consumption of the DCS system, p_{t-1}^{PJM} is the marginal price in the market for the last hour, $P_{t-1}^{V2G,i}$ is the power support available from V2G facility at the previous operating hour from $i_t h$ building, and D_{t-1}^{j} is the thermal discomfort level in j^{th} building in the previous hour.

3) Rewards: The rewards function has been formalized to achieve the maximum revenue from the market. As the performance score is the first constraint, a performance satisfaction factor comes into the picture, and it is denoted by p_t. If it is the condition of $s_t^{build} \geq s^{min}$, the p_t value is "1", failing the above condition, it becomes "0". It is formulated as follows:

$$R_t = \alpha_1 p_t C_t^{build} s_t^{build} p_t^{PJM} - \alpha_2 (1 - p_t) \frac{C_t^{build}}{s_t^{build}}, \quad \forall t \tag{12}$$

$$p_t = (1 + \frac{s_t^{build} - s^{min}}{\left|s_t^{build} - s^{min}\right|})/2, \quad \forall t \tag{13}$$

In Eq.12, there are two-part. The first part denotes the positive reward earned from the market, while the second term expresses the penalty imposed by the system if there is a violation of the constraint limit.

B. Proposed strategy for Capacity Offering

The proposed strategy for the capacity offering by the building cluster considering its flexible load DCS and V2G is shown in Fig.3. It collects the historical data for the training and testing of the system to get the new state interacting with the environment of the building cluster. In this work, some samples of air conditioning units have been scaled up and used for the training and testing of the system. In this proposed work, first, the regulation capacity is being offered on the basis of DCS operation only. Second, while providing the regulating service to the market, depending on the difference between the market signal and regulating signal, agent 2 reacts. If DCS is not capable of regulating as per the market signal, the V2G facility will provide the support so that the performance score of the building cluster as a resource could be better and earn more revenue from the market.

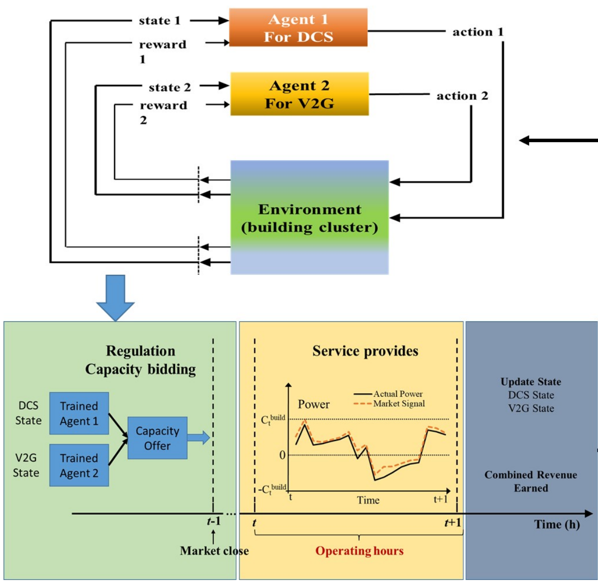

Fig. 3. Framework for proposed strategy.

IV. CASE STUDIES

In considering building clusters, ten buildings have been considered with different cooling demand sizes and various types of buildings some are educational buildings, some are commercial buildings, and some are hospitals. As per the DCS technical guideline, in a building cluster, some electrical and thermal parameter has been set and mentioned in Table I. Table II describes the considered performance score in case one (regulating capacity with DCS only) and case two (regulating capacity with DCS and V2G). The marginal price and market regulation signal regA from PJM is shown in Fig. 4. As per the PJM rule, the capacity offered by any demand resources should not be less than 1 MW, and the performance score should be greater than 0.75.

Assumption for V2G

In considering building clusters, for educational and hospital type of buildings, ten charging/discharging station has been considered, while with commercial buildings, it is fifteen. The power rating of one converter that is connected to one charging point is 20 kW. It is also assumed that the converter connected to the charging station is a bi-directional converter. The supporting vehicle for the V2G has an instantaneous SOC between 50-90 %.

TABLE I
PARAMETER SETTINGS OF THE BUILDING CLUSTER.

Symbols	Definitions	Values
COP	Coefficient of performance	5
c_p	specific heat capacity	4.2 kJ/C
T_t^{set}	Indoor set temperature	$24 - 26°C$
D_t^{perm}	permissible thermal discomfort level	1°
$T_t water$	Supply water temperature	6° C
$C_t^{build,min}$	Minimum regulation capacity	0 MW
$C_t^{build,max}$	Maximum regulation capacity	10 MW

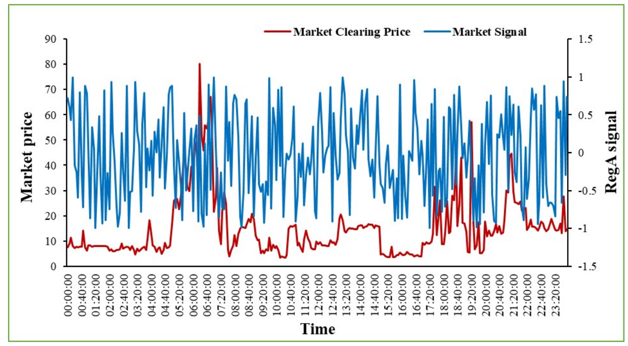

Fig. 4. Marginal price and regulation signal from PJM for one day.

TABLE II
PERFORMANCE SCORE OF THE SYSTEM.

Score:	Case One	Case Two
Accuracy score:	0.92	0.92
Delay score:	0.93	0.93
Precision score:	0.75	0.87
Performance score:	0.87	0.91

V. CONCLUSION

This work proposes a strategy for the capacity offering by the cluster of buildings to maximize the revenue earned from the power market. First, it is offered with DCS only. Second, to counterbalance the uncertainty in the RES power generation and cooling demand from the different buildings of the cluster, V2G facilities also support providing frequency regulation. From the case study discussion, it could be seen that the revenue earned in case one is 117.7 $ while in case two, it is 123.12 $.

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