A Vehicle-to-Microgrid (V2M) Framework with Optimization-Incorporated Distributed EV Coordination for a Commercial Neighborhood

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Abstract—An improved vehicle-to-microgrid (V2M) framework is proposed for a commercial locality operating as a hybrid alternating-current (AC) / direct-current (DC) microgrid, which optimally coordinates electric-vehicle (EV) storages in a distributed manner. An aggregator model is proposed that solves the economic dispatch problem of parked EV storages in a centralized fashion and generates power references in real-time for the designed EV storage controllers. Unlike the conventional EV storage controller, the proposed optimization-incorporated distributed EV storage controller (ODC) can switch from decentralized to distributed control mode or vice versa based on situations and utilizes a sparse vehicle-to-vehicle (V2V) communication network. The power flow between the AC and DC subgrids is managed by interlinking converters (IC). The IC control structure is augmented by combining voltage- and power-based droop-control schemes in the power control loop. This modification enables simultaneous AC and DC bus voltage regulations. Case studies are carried out to validate the efficacy of the developed framework with a real commercial network and loads. The results exhibit robust performance of the overall system for generation-demand variability, transitions between islanded and grid-tied conditions, and user-preferred EV disconnections and time delay.

Index Terms—Hybrid AC/DC microgrid, economic dispatch, interlinking inverter, electric vehicles, distributed cooperative control.

I. INTRODUCTION

THE concept of a direct-current (DC) power distribution network is gaining momentum due to the increased number of photovoltaic (PV) installations along with the rapid growth in electric vehicles (EV) as promising energy storage systems (ESS). The DC distribution system can provide a cost-effective solution to integrate DC technologies such as light-emitting diodes (LED), DC motors, data centers etc. with minimum conversion losses. Commercial buildings, that consume nearly 61% of the total electric energy in the United States, are emerging as zero-net-energy (ZNE) buildings by adopting DC distribution systems [1]. As a result, islanded DC distribution systems or inter-tied DC microgrids are possible by expanding the capacities of rooftop PV and ESS in

commercial buildings. However, the installation of a DC-only distribution system is unlikely in the near future due to the AC-dominated legacy electric system. Therefore, an intermediate solution would be hybrid AC/DC microgrids [2], [3]. Hybrid microgrids combine the aptness of both AC and DC systems. They facilitate the connection of both the AC and DC types of loads and sources due to the existence of individual buses of different nature. Moreover, there are other advantages such as minimum AC/DC conversion loss, increased efficiency, and reduced voltage synchronization effort, to ensure improved connectivity for AC and DC technologies [4], [5]. However, this microgrid structure has convoluted network and control topologies. Due to the intricate nature of their structures and control methodologies, hybrid microgrids are well suited for commercial neighborhood rather than residential localities.

Contemporary commercial buildings are equipped with state-of-the-art technologies such as smart EV parks, intelligent power-electronic-interfaced variable-speed drives (VSDs), four-quadrant inverters and smart high-voltage air-conditioning (HVAC) systems. Utilizing these technologies, commercial buildings can contribute to both electric power grids and the electricity market by providing ancillary services [6]. However, coordination among multiple technologies such as EV storages is a difficult task, particularly when these buildings are operating as autonomous microgrids. Furthermore, peak load for commercial areas occurs during mid-daytime; therefore, parked EV storages in commercial neighborhoods can be utilized to provide ancillary services during office hours, which typically range between 9:00 am to 6:30 pm [7], [8]. Considering the above-mentioned possibilities of vehicle-to-microgrid (V2M) (i. e. islanded operation) and vehicle-to-grid (V2G) (i. e. grid-tied operation) application in commercial vicinities, several pieces of literature have explored this research area. In [9], an economic analysis is presented to show the feasibility of using EV storages in commercial-building microgrids. An energy-management system (EMS) for a building with PV units and EV storages is presented in [10], designed to minimize the operating cost considering different charging and discharging profiles. A real-time peak-shaving model to reduce high peak demand combining demand response and load control is presented in [11]. A four-stage optimization algorithm is proposed in [12] for a PV-assisted EV charging station in a commercial building to minimize operation costs associated with customer satisfaction by the optimal scheduling of EV storages. However, all the

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optimization approaches to coordinate EV storages for V2M operations follows either the hourly or the daily forecasting methods. As a result, these approaches are only suitable for the planning purposes of the V2M. Conversely, a dynamic framework to ensure EV coordination in conjunction with the real-time optimization technique can provide both technical and economic optimality.

The V2M connection can be achieved by centralized, decentralized or distributed approaches for AC, DC or hybrid AC/DC microgrids. The centralized structure provides improved controllability with reduced scalability. The decentralized structure ensures modularity, however, optimal operation cannot be guaranteed due to the limited information exchange among units. Conversely, a distributed structure combines the advantages of both centralized and decentralized structures. As a result, distributed control in microgrids with EV storages is gaining momentum. Distributed controllers are developed for AC microgrids [13], [14], for DC microgrids [15]–[17] and for hybrid AC/DC microgrids [8], [18]. The application of distributed control for ESS is presented in [19]–[23] to achieve voltage control, state-of-charge balancing and power-sharing considering time delays and uncertainties in PV output power generation. However, these analyses do not specifically concentrate on commercial-grade V2M applications, and the concept of incorporating a solution for the EV economic dispatch problem in their real-time control has not been explored. Some recent work [24], [25], has attempted to unify optimization-based economic dispatch with real-time distributed control for DC microgrids. However, their feasibility and efficacy for hybrid-microgrid operations are not explored. Moreover, from a realistic point of a view, an EV aggregator would like to have a certain control over the EV storages under its operational vicinity, but at the same time, EV storages are parked in a spatially dispersed form. Therefore, from the perspective of an EV aggregator and EV owners, a combination of the centralized and distributed control framework would be an optimal approach for commercial-grade V2M operation.

Addressing all the above-mentioned issues, this paper presents a novel V2M framework suitable for commercial neighborhoods. The hybrid AC/DC microgrid structure is adopted due to its suitability for commercial operation. An improved control framework is proposed to integrate EV aggregators, which involves three core components: (i) a centralized EV economic-dispatch optimizer, (ii) a distributed EV storage controller and (ii) an enhanced interlinking converter (IC) with modified control topology. The optimizer generates the reference power for each EV storage as a function of the incremental cost (λ) by solving an economic dispatch problem. Later, it adjusts the power reference accordingly, which ensures proper power management within the microgrid through a cost-effective and distributed V2M operation. The IC is responsible to control the power flow between the AC and DC subgrids. The IC control topology is augmented by combining the voltage-based droop [26], [27] and power-based droop-control techniques. This augmentation enables simultaneous AC and DC bus voltage regulation without affecting the power-sharing capabilities of the converter. Overall, the salient features of this paper can be summarized as follows:

- 1) An aggregator model is developed that provides a centralized solution for the EV economic dispatch problem considering a bounded EV output power. The aggregator/ EMS generates a reference power signal for the designed distributed controller. A generalized mathematical expression of the optimal reference power is presented as a function of the optimal incremental cost, defined by the slope of the cost function. This augmentation ensures that EV storages will operate economically providing maximum profit for EV owners.
- 2) A distributed EV storage controller is designed that can operate in both decentralized and distributed manner based on a situation-aware signal. The designed controller communicates with other neighboring EV units through a sparse communication network with a spanning tree to exchange output-power information. Later, it utilizes a local voting protocol for dynamic averaging.
- 3) In order to ensure voltage regulation and to maintain power flow between the AC and DC subgrids, a modified IC control strategy combining power- and voltage-based droop techniques is developed. This enhancement ensures simultaneous AC and DC bus voltage regulations for the hybrid microgrid. Moreover, the transient performance of the IC is further enhanced by utilizing a proportional-derivative (PD) controller within the power-control loop of the IC as proposed in [8]. This approach facilitates a smooth transition between islanded and grid-tied microgrid operation.

The remainder of the paper is organized as follows: Section II presents the concept and configuration of a typical commercial hybrid AC/DC microgrid. Section III presents the proposed V2M control framework, which includes a description of the optimizer operating as a centralized EV aggregator, the distributed EV storage controller and the IC controller. Case studies are presented in Section IV, for a commercial hybrid AC/DC microgrid with four EV storages operating under one aggregator, for various scenarios. Moreover, a concluding discussion based on the results is provided in this section. Section V concludes the paper.

II. COMMERCIAL HYBRID AC/DC MICROGRID

Fig. 1: A general commercial hybrid AC/DC microgrid.

A general configuration of a commercial hybrid AC/DC microgrid is illustrated in Fig. 1. All AC-type sources such as diesel generators, EV AC chargers, doubly-fed induction generators (DFIG), etc. along with AC-type loads are connected to

the AC bus forming the AC subsystem. Similarly, all DC-type sources such as community storages, EV DC fast chargers, etc. along with all DC-type loads are connected to the DC bus forming the DC subsystem. Both AC and DC subsystem are interfaced through ICs ensuring balanced power flow between two subsystems. The AC subsystem is also connected to the utility grid through intelligent bypass switch (IBS). This configuration enables the microgrid to operate in both grid-tied and islanded operations. Each of the generating components has local controllers to regulate their output power. All of these local controllers are controlled by an energy management system (EMS) which can operate either in a centralized or distributed manner utilizing neighbor-to-neighbor information sharing. The EMS also sends the signal to the IBS to initiate grid reconnection or islanding as per system requirements. The proposed V2M control framework presented in later sections describe how the EMS/aggregator is optimizing the EV output power by interacting with the local controllers of EV storage to ensure stable system operations in both islanded and grid-tied scenarios through V2M and V2G modes respectively.

III. PROPOSED V2M CONTROL FRAMEWORK

A. EV Aggregator Problem Formulation

During V2M operation within a hybrid AC/DC microgrid, EV units operate as dispatchable sources. With a view to minimizing the generation cost of EV units while preserving all other flexibilities, the optimization problem can be formulated as similar to that of a conventional power system [24], [28], [29]. Now let us consider that the aggregated cost function, $C(p, t)$ of N EV storages operating in V2M mode is a quadratic function of their corresponding output powers with coefficients of α , β and γ . Therefore, the optimization problem for EV economic dispatch can be presented as follows [24]:

$$\begin{aligned} \min \quad & C(p, t) = \sum_{n \in N} \alpha_n + \beta_n p_n + \gamma_n p_n^2 \\ \text{s.t.} \quad & G = \sum_{n \in N} p_n = P_{total}^{load} - P_{total}^{gen}, \quad n = 1, 2, \dots, N., \\ & H_1 = -p_n + p_n^{min} \leq 0, \\ & H_2 = p_n - p_n^{max} \leq 0 \end{aligned} \quad (1)$$

where, inequalities H_1 and H_2 are $2 \times N$ constraints,

$P_{total}^{load} = \sum S_{AC}^{load} + \sum P_{DC}^{load}$,
 $P_{total}^{gen} = \sum S_{AC}^{gen} + \sum P_{DC}^{gen}$,
 $\sum S_{AC}^{load}$ = the aggregated demand of the apparent power by AC loads,
 $\sum P_{DC}^{load}$ = the aggregated demand of the active power by DC loads,
 $\sum S_{AC}^{gen}$ = the aggregated apparent power generated by dispatchable AC sources,
 $\sum P_{DC}^{gen}$ = the aggregated active power generated by non-dispatchable DC sources,
 p_n^{max} and p_n^{min} = the allowable maximum and minimum power of the n th EV storage respectively.

Therefore, the economic-dispatch problem can be formulated as a Lagrange function with Lagrange (λ) and

Karush–Kuhn–Tucker (KKT) multipliers (μ_1 and μ_2 which are vectors of R^N) for each EV storage:

$$L(p_n, \lambda, \mu_1, \mu_2) = C(p, t) + \lambda G + \mu_1 H_1 + \mu_2 H_2 \quad (2)$$

The solution of the aforementioned optimization problem is a stationary point where the partial derivative of $L(p_n, \lambda)$ is zero with respect to all variables. Now, for the time being, if we neglect the EV output power constraints H_1 and H_2 then

$$\begin{aligned} \frac{\partial L}{\partial p_n} &= \frac{\partial C(p, t)}{\partial p_n} - \lambda = 0 \\ \implies \lambda &= \frac{\partial C(p, t)}{\partial p_n} = \beta_n + 2\gamma_n p_n \end{aligned} \quad (3)$$

In order to achieve optimality, it is necessary that the Lagrange multiplier or the incremental cost (λ) of each EV storage converges to the optimal incremental cost (λ^*). This convergence can be achieved only when all EV storages generate the optimal power (p_n^*). Considering small perturbations of both AC and DC load demands, the optimal output power of each EV storage can be obtained with simple mathematical manipulation of (3), as below [30]–[32]

$$\begin{cases} \lambda^* = \frac{\Delta P + \sum_{n \in N} \frac{\beta_n}{2\gamma_n}}{\sum_{n \in N} \frac{1}{2\gamma_n}} \\ p_n^* = \frac{\lambda^* - \beta_n}{2\gamma_n} \end{cases} \quad (4)$$

where, $\Delta P = P_{total}^{gen} - P_{total}^{load}$. Moreover, by considering the output power constraints, the necessary minimum-cost operating condition can be extended to represent the reference power for the distributed EV storage controller.

$$p_n^{ref} = \begin{cases} p_n^* & \text{for } p_n^{min} \leq p_n \leq p_n^{max} \\ p_n^{min} & \text{for } p_n \leq p_n^{min} \\ p_n^{max} & \text{for } p_n \geq p_n^{max} \end{cases} \quad (5)$$

B. Optimization-Incorporated Distributed Control (ODC) for EV Storages

Let us consider a commercial neighborhood operating as a hybrid microgrid with N V2M-capable EV storages. Additionally, all active EV storages communicate through a sparse communication network with each other. The interaction among active EV storages can be represented via a weighted directed graph (digraph). The interconnection nodes can be represented by $\mathcal{G} = (\mathcal{V}_G, \mathcal{E}_G, \mathcal{A}_G)$, where $\mathcal{V}_G = \{\mathcal{V}_1, \mathcal{V}_2, \mathcal{V}_3, \dots, \mathcal{V}_N\}$ is the set of all nodes, $\mathcal{E}_G \subset \mathcal{V}_G \times \mathcal{V}_G$ is the set of pairs of nodes also known as edges, and $\mathcal{A}_G = [a_{ij}]_{N \times N}$ is the weighted adjacency matrix of dimension $N \times N$ that gives information regarding the interconnectivity of nodes. The communication between node i and node j can be presented as follows:

$$a_{i \times j} = \begin{cases} 1 & \text{if } (i, j) \in \mathcal{E}_G \\ 0 & \text{otherwise} \end{cases} \quad (6)$$

The in-degree matrix is defined as $D_G^{in} = \text{diag}\{d_i^{in}\}$, i.e. the diagonal matrix of $d_i^{in} = \sum_{j=0}^n a_{ij}$. Likewise the out-degree matrix is defined as $D_G^{out} = \text{diag}\{d_i^{out}\}$, i.e. the diagonal matrix of $d_i^{out} = \sum_{i=0}^n a_{ji}$. The Laplacian matrix $\mathcal{L}_G$, defined

Fig. 2: Proposed control topology. (a) ODC for individual EV storage. (b) Single-line circuit diagram of each IC. (c) IC control structure with voltage-based droop.

as $\mathcal{L}_G = D_G^{in} - \mathcal{A}_G$, provides useful insights regarding the stability of the communication network. For an undirected communication network with bidirectional information flow, $D_G = D_G^{out} = D_G^{in}$, which results in $\mathcal{L}_G$ being *balanced* for this particular case [33].

All EV storages are designed with the local voting protocol shown in Fig. 2a. This protocol uses local information of the n th EV storage and the information observed from its neighbors to converge to an average output power u_p^n , given by

$$u_p^n(t) = p_{EV}^n(t) + \psi_p b_p \sum_{j \in N} a_{n \times j} \left(p_{EV}^j(\tau) - u_p^n(\tau) \right) d\tau \quad (7)$$

where p_{EV}^n = measured output power of n^{th} EV storage, ψ_p = acknowledgement signal for the distributed operation which is governed by the need-based distributed coordination strategy (NDCS) [8],

b_p = coupling gain of the cooperative control loop.

Even though the aggregator generates necessary dispatch command for individual EV storages, the distributed EV storage controller is the part that is monitoring and controlling the EV charging and discharging by considering EV related constraints. The controller is governed by the NDCS algorithm

which takes three EV related constraints into account, i.e. storage capacity based on state-of-charge (SOC), converter capacity, and user preference.

The local voting protocol ensures that the output power of all EV storages for any step changes will converge at an average value of the neighboring units at $t \rightarrow \infty$, considering a spanning tree is present and the communication delay (T_d) satisfies the condition [34]

$$T_d \leq \frac{\pi}{2 \max(\text{eig}(\mathcal{L}_G))} \quad (8)$$

Now by introducing an uniform time delay of T_d in (7), the following relation can be obtained

$$u_p^n(t) = p_{EV}^n(t) + \psi_p b_p \int_0^t e^{-T_d \tau} \sum_{j \in N} a_{n \times j} \left(p_{EV}^j(\tau) - u_p^n(\tau) \right) d\tau \quad (9)$$

Example: let us consider that the output powers of four EV storages for any instant are 20 kW, 15 kW, 25 kW and 30 kW – represented by EV-1, EV-2, EV-3 and EV-4 respectively. A ring-structured communication network is used in this paper.

Fig. 3: Convergence of output powers with the distributed controller for various time delays. (a) Time delay, $T_d = 0$ s. (b) Time delay, $T_d = 0.3927$ s. (c) Time delay, $T_d = 1.5$ s. The dotted lines are the outputs measured from the distributed controller.

This network can be mathematically presented as follows:

$$\mathcal{A}_G = \begin{bmatrix} 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \end{bmatrix}; \mathcal{D}_G = \begin{bmatrix} 2 & 0 & 0 & 0 \\ 0 & 2 & 0 & 0 \\ 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 2 \end{bmatrix};$$

$$\mathcal{L}_G = \begin{bmatrix} 2 & -1 & 0 & -1 \\ -1 & 2 & -1 & 0 \\ 0 & -1 & 2 & -1 \\ -1 & 0 & -1 & 2 \end{bmatrix}.$$

Therefore, the output power of all EV storages will converge to an average consensus value of 22.5 kW following (7) as long as the time delay T_d is less than 0.3927 s, calculated using (8). The results of this example are presented in Fig. 3, where Figs. 3a, 3b and 3c represents the performance of the distributed controller for $T_d = 0$ s, 0.3927 s and 1.5 s respectively. By differentiating (7) and taking the Laplace transformation with zero initial conditions, we can obtain a generalized model for the cooperative power controller:

$$\mathbf{U}_p = s(s\mathbf{I}_{N \times N} + G_{TD}\psi_p b_p \mathcal{L}_G)^{-1} \mathbf{P}_{EV} \quad (10)$$

where the cooperative control output, $\mathbf{U}_p = [u_p^1 \ u_p^2 \ \dots \ u_p^N]^T$, the measured output powers of EV storages, $\mathbf{P}_{EV} = \text{diag}\{p_{EV}^n\}$, and $G_{TD} = \frac{1}{1+T_d s}$. $\mathbf{I}_{N \times N}$ represents an identity matrix of dimension $N \times N$. Overall, the general formulation of the voltage references, $\mathbf{V}^{\text{ref}} = [v_1^{\text{ref}} \ v_2^{\text{ref}} \ \dots \ v_n^{\text{ref}}]^T$ for the optimization-incorporated distributed EV storage controller can be expressed as

$$\mathbf{V}^{\text{ref}} = \left[\mathbf{P}^{\text{ref}} \left(\mathbf{I}_{N \times N} + \mathbf{G}_{pi(P)}^{\text{EV}} \right) - \mathbf{U}_p \mathbf{G}_{pi(P)}^{\text{EV}} \right] \mathbf{I}_{EV}^{-1} \quad (11)$$

where $\mathbf{G}_{pi(P)}^{\text{EV}} = \text{diag}\{G_{pi(P)}^{\text{EV}}\}$, $\mathbf{P}^{\text{ref}} = \text{diag}\{p_n^{\text{ref}}\}$ and $\mathbf{I}_{EV} = \text{diag}\{i_{EV}^n\}$ considering $G_{pi(P)}^{\text{EV}}$ to be the transfer function of the proportional-integral (PI) controller in the power-control loop of the ODC and i_{EV}^n is the output current of the n th EV storage.

Overall, the design procedure of the proposed ODC can be summarized as below:

Step 1: From smart meters collect load and generation data then check output powers of active EV storages.

Step 2: Find values of α , β and γ for all EV storages.

Step 3: Calculate p_n^{ref} using (5).

Step 4: Calculate $\mathbf{V}^{\text{ref}}$ using (11).

Step 5: Repeat the process until $|p_n^{\text{ref}} - p_{EV}^n| \approx 0$.

C. Power-Flow Control between Subgrids via IC

The objective of the IC is to ensure accurate active and reactive power flow between the AC and DC subgrids to maintain the bus voltages and the frequency stability. The single-line circuit diagram of the IC is shown in Fig. 2b. The IC controller consists of three control loops, i.e. power, voltage and current-control loops with bandwidths (BW) of 2-10 Hz, 400-600 Hz and 1.5 kHz or above respectively as illustrate in Fig. 2c. The voltage and current controllers are designed utilizing a conventional decoupled topology with voltage and current feed-forward techniques, whereas the power-control loop is extended with the combined voltage- and power-based droop techniques proposed in [8]. This augmentation improves concurrent DC and AC bus voltage regulation and coordination among AC and DC subgrids. The algebraic expression of the inverter voltage references in $d-q$ reference frame (v_{id}^* and v_{iq}^*) and the input angle θ for the $d-q$ to abc converter can be presented as below

$$\begin{cases} v_{id}^* = v_{od} - \omega L_f i_{lq} + [\{V^* - D_Q(Q - Q^*)G_{pd} - v_{od}\}G_{pi}^V \\ \quad - \omega C_f v_{oq} + F i_{od} - i_{ld}]G_{pi}^I \\ v_{iq}^* = v_{oq} + \omega L_f i_{ld} + \{\omega C_f v_{od} + (v_{oq}^* - v_{oq})G_{pi}^V \\ \quad + F i_{oq} - i_{lq}\}G_{pi}^I \\ \theta = \frac{1}{s} \{\omega^* - D_P(P - P^*)G_{pd}\} \end{cases} \quad (12)$$

where P and Q are the filtered output active and reactive power whereas P^* and Q^* are the respective references. v_{ldq} and v_{odq} are the inverter filter input and output voltages, i_{ldq} and v_{odq} are the inverter filter input and output currents in the $d-q$ reference frame. D_P and D_Q are active and reactive power droop coefficients. V^* is the output of the voltage-based droop-control loop [8] and F is the feed-forward gain. ω is the angular frequency measured from the phase-locked loop (PLL). L_f and C_f are the inductance and capacitance values of the LC filter. G_{pd} , G_{pi}^V and G_{pi}^I are the transfer functions of the PD controller of the power-control loop, the PI controllers of the voltage and current-control loops respectively. Considering V_{DC} to be the measured DC bus voltage, finally, the pulse-width modulation (PWM) generator of the IC generates the modulation index in the natural abc reference frame as follows:

$$\mathbf{M}_{abc} = \frac{2}{V_{DC}} \mathbf{T}_{dqo-abc}(\theta) \mathbf{V}_{idq}^* \quad (13)$$

where $\mathbf{M}_{abc} = [m_a \ m_b \ m_c]^T$, $\mathbf{V}_{idq}^* = [v_{id}^* \ v_{iq}^*]^T$ and $\mathbf{T}_{dqo-abc}(\theta)$ is the $dq-abc$ transformation matrix.

IV. CASE STUDIES

The designed commercial hybrid AC/DC microgrid is illustrated in Fig. 4, and consists of four V2M-capable EV storages parked at the parking area with individual capacities of 24 kWh, one rooftop solar PV unit with a rated capacity of 30

Fig. 4: Single-line circuit diagram of the test hybrid AC/DC microgrid.

kW and four 17 kVA dispatchable-power electronic-based AC sources. EV storage models are realistically recalibrated to the specification of Mitsubishi Outlander storage model. The microgrid model presented here is the extended and modified version of the university-based microgrid presented in [7], [8]. All the EV storages and the PV unit are connected to the DC bus of the microgrid. The PV unit is designed to provide maximum power, whereas the EV storages are equipped with the designed ODC. The dispatchable AC sources are connected to the AC bus via four-quadrant inverters, which are controlled by decentralized droop control scheme as presented in [35]. It should be noted that due to large-value inductors present at the inverter terminals, commercial localities usually have a higher X/R ratio. Thus, decentralized $P-f$ and $Q-V$ droop-control schemes are adopted. Both the AC and DC buses are interfaced through a bidirectional interlinking converter, which is controlled by the combined voltage- and power-based droop-control scheme.

Three case studies are carried out to demonstrate the efficacy of the proposed V2M framework. The first case study demonstrates the voltage-regulation and power-sharing capabilities of the proposed scheme considering irradiation and load variability. The second case study provides insights on the performance of the framework during and subsequent to grid reconnection. The final case study is performed to show the effects of a sudden V2M service disruption due to the disconnection of particular EV storages. This case study also explores the effects of time delay on the output powers of the EV storages. Parameters relevant to the design of the system are depicted in Table I. The load and solar irradiation data are obtained using OSI PI software which gathers sensor data from the smart meters installed at the university premises.

A. Case A: Variable Solar Insolation and Commercial Load-ing

For Case A, the designed V2M framework is tested considering PV generation and commercial load variability. The main objective of this case study is to assess the robustness of the developed framework. Real-time irradiation profile for the solar farm and the commercial load data are obtained using the OSI PI software installed for monitoring smart meter data for the Griffith University microgrid model [7], [8]. Concurrent PV power and load variabilities ensure genuine conditions that the controller needs to withstand. EV storages

TABLE I: System Parameters

Energy nodes			
PV	30 kW	DG-(1,2,3,4)	17 kVA
EV-(1,2,3,4)	24 kWh		
Line parameters			
Nominal V_{AC}^{RMS}	240 V	L_f	20×10^{-3} H
V_{DC}^*	600 V	C_f	200×10^{-6} F
Frequency	50 Hz	R_c, R_G	0.03Ω
C_{DC}	130×10^{-4} F	L_c, L_G	3.5×10^{-4} H
R_f^I	0.1Ω	r_d	0.65Ω
r_1, r_2, r_3, r_4	0.02Ω	$r_{12}, r_{23}, r_{34}, r_{45}$	0.05Ω
Control parameters			
Power controller		Voltage controller	
ω_c, ω_e	31.42, 314.16 rad/s	F	0.19
ω^*	314.16 rad/s	K_p	0.11
D_P	3.14×10^{-4}	K_i	2.2
D_Q	1.36×10^{-3}	Current controller	
K_p	2×10^{-5}	K_p	0.16
K_d	2×10^{-7}	K_i	200
EV storage controller			
Power control loop		Voltage control loop	
K_p	1.3	K_p	0.03
K_i	6	K_i	1.1
b_p	1.5		
Cost functions of EV storages			
EV-1	$120 + 0.80p_1 + 0.017p_1^2$		
EV-2	$80 + 0.65p_2 + 0.012p_2^2$		
EV-3	$90 + 0.60p_3 + 0.010p_3^2$		
EV-4	$100 + 0.90p_4 + 0.018p_4^2$		

communicate through a vehicle-to-vehicle (V2V) communication network illustrated in Fig. 4. As was mentioned before, the designed distributed controller can provide stable operation as long as there exists a spanning tree and the time delay is within a specified limit. The interaction graph among the four EV storages shown in Fig. 4. has one spanning tree. The optimal incremental cost ($\$/kW$) and the dynamic cost for all EV storages for this case are presented in Figs. 5a and 5c respectively. It can be observed from the dynamic-cost profiles of all EV storages that EV-1 and EV-4 require higher incentives to provide V2M operation than EV-2 and EV-3. Therefore, from Fig. 5e, it can be observed that the EV storages with higher dynamic costs discharge less power for V2M operation. As a result, the highest power is discharged by EV-3 and then EV-2 descending from EV-1 towards EV-4. Figs. 5b, 5d and 5f represent electrical parameters such as the AC bus voltage, the normalized DC bus voltage and the system frequency respectively. It can be concluded from the results that the designed V2M framework can provide stable and efficient hybrid microgrid operations in a cost-effective manner.

B. Case B: Effects of Grid Reconnection

Case B is carried out to demonstrate the efficacy of the designed system during and subsequent to grid reconnection. Microgrids can operate in both islanded and grid-tied modes.

Fig. 5: Performance evaluation under variable solar insolation and commercial load profile. (a) Optimal incremental cost in €/kW. (b) AC bus voltage in per unit (p. u.). (c) Dynamic cost of all EV storages. (d) Normalized DC bus voltage. (e) Output power of all EV storages. (f) Frequency of the system.

However, an intentional islanding or grid reconnection have certain effects on the electrical parameters of the concerned microgrid. For this case study, at $t = 2.5$ s the islanded hybrid AC/DC microgrid is reconnected with the grid. During the islanded operational mode, the EV storages provide ancillary V2M services by power sharing and voltage regulation to ensure stable microgrid operation. However, if the microgrid is reconnected with a stiff grid then further V2M operation might not be essential. As a result, EV storages are typically expected to be in charging mode during grid-tied microgrid operation. Furthermore, due to the support of the grid, the operating cost or incentives required for V2M operation are reduced. This phenomenon can be observed in Figs. 6a and 6c, which represent the optimal incremental cost and the operating cost of all EV storages. It can be observed from both Figs. 6a and 6c that the overall cost is steeply reduced due to the

presence of a stiff grid. Therefore, all EV storages enter into charging modes also known as grid-to-vehicle (G2V) mode, for most of the period after $t = 2.5$ s. The negative values of the cost function in Fig. 6c represents the dynamic cost required to charge a vehicle. The output charging or discharging power for all EV storages are shown in Fig. 6e. The electrical parameters such as the AC bus voltage, the DC bus voltage and the system frequency for this case are shown in Figs. 6b, 6d and 6f respectively. Due to grid reconnection, the AC bus voltage and the frequency quickly settle down by tracking the grid-enforced reference values. The DC bus voltage exhibits a dip during the reconnection but quickly settles down due to the efficacy of the designed ODC for EV storage.

Fig. 6: Performance evaluation during and subsequent to grid reconnection. (a) Optimal incremental cost in ¢/kW . (b) AC bus voltage in per unit (p. u.). (c) Dynamic cost of all EV storages. (d) Normalized DC bus voltage. (e) Output power of all EV storages. (f) Frequency of the system.

C. Case C: Effects of EV Disconnection and Time Delay

Case C is dedicated to analyzing the effects of intentional EV service disruption on the system. As EV storages are individually owned, the designed V2M network needs to withstand sudden EV disconnection based on owners' desires. The designed framework should be robust enough to endure dynamic situations where EV owners possess the flexibility of including or excluding EV storages for V2M operations. The load profiles and the solar insolation used in the previous case are kept similar for this case study. At $t = 2$ s, EV-4 is disconnected from the system, emulating a fault at the V2M terminal or a service disruption condition. Figs. 7 and 8 present the dynamic operating cost and the output power profile for all EV storages before and after the disconnection of EV-4. As there is a shortage of supply due to this disconnection, other

EV storages need to cover this additional power requirement to make the system stable. As a result, the output powers of all EV storages have increased after $t = 2$ s. However, active EV storages require higher incentives to supply this additional discharged power. Therefore, it can be observed from Fig. 7 that there is an escalation in the operating cost profile after $t = 2$ s.

Fig. 9 represents the results for the scenario when consecutively two EV storages are disconnected within a short interval. At $t = 1.5$ s EV-1 is disconnected; as a result, other EV storages have increased their output power to meet the demand as expected. However, at $t = 3$ s another EV storage (i.e., EV-3) is disconnected. The microgrid system is now incapable of serving the load requirements due to the loss of two storages. As a result, the grid reconnection is initiated at $t = 3$ s. The operating EV-2 and EV-4 power then become supplemented

Fig. 7: Costs of all EV storages when EV-4 is intentionally disconnected at $t = 2$ s.

Fig. 8: Output powers of all EV storages when EV-4 is intentionally disconnected at $t = 2$ s.

by the grid to meet the load requirements.

The effects of a time delay on the power profiles of EV storages are presented in Fig. 10. A time delay of 30 ms is introduced at the distributed power-control loop. It can be observed from Fig. 10a that the outputs of the distributed controller for all EV storages, i.e. u_p^1, u_p^2, u_p^3 and u_p^4 , converge to an average value of output power with time delay $T_d = 0$ ms. Conversely, introducing a delay of 30 ms deteriorates the controller performance on convergence. However, the response is stable, as T_d is within the specified limit given in (8). As the output powers of all EV storages are driven by the values u_p^n , the discharged output powers from all EV storages are also affected by the time delay as shown in Fig. 10.

V. CONCLUSION

A novel V2M control framework combining the centralized economic dispatch problem with the distributed EV coordination strategy is presented for optimal power-sharing and voltage regulation for a commercial neighborhood to operate as an autonomous electric entity. An aggregator model is developed that generates reference powers for all EV storages utilizing a centralized optimization technique to solve an economic dispatch problem. An EV storage controller is developed that tracks the reference power generated by the EV aggregator and can operate in either decentralized or distributed mode. Finally, a modified interlinking converter is designed that ensures proper power transportation between the AC and DC subgrids of a hybrid AC/DC microgrid intended for a commercial

Fig. 9: Output powers of all EV storages when EV-1 is intentionally disconnected at $t = 1.5$ s, then EV-3 is disconnected at $t = 3$ s. The loss of two EV storages initiates grid reconnection at $t = 3$ s.

Fig. 10: Effects of 30 ms time delay on the system power profile. (a) Output u_p^n of the distributed controllers for all EV storages with time delay (dotted) and without time delay (solid). (b) Discharged power of all EV storages with time delay (red) and without time delay (black).

locality. The developed control framework provides visibility on how the centralized aggregator model will interact with individual EV storage controllers. The proposed structure will offer not only technical efficacy concerning voltage/frequency regulation, and system stability but also provide economic benefits to EV owners and aggregators. Rigorous case studies conducted considering various scenarios such as generation-load variability, intentional EV disconnection, time delay, and grid reconnection solidifies the effectiveness of the overall microgrid system. The future directive of this research is to incorporate additional functionalities such as improved power quality, reduced circulating current [36], [37] and robust

performance during unbalanced weak grid scenario into the proposed V2M framework.

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