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Optimal Day Ahead Scheduling for Plug-in Electric Vehicles in an Industrial Microgrid based on V2G System

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***Abstract*— With the increasing amount of electric vehicles (EVs), Vehicle to Grid (V2G) technology has attracted enormous attention from researchers and industries. The major benefit of using V2G is to enable the interaction between EVs and grid. For example, EV batteries can work as responsive sources to provide auxiliary support to a power grid. This paper presents an optimal day-ahead scheduling strategy for a fleet of EVs plugged-in to the grid using V2G operation. Here, lithium-ion EV batteries are managed to reduce peak load constrains in a microgrid and to reduce energy bill. The proposed scheduling scheme is computed based on a linearized model of the lithium-ion battery with an optimization approach considering battery and grid constraints. A case study with an industrial microgrid application is carried out by simulations, to prove the advantages of the proposed technique.**

Keywords— Energy Management System; Smart Grid; Electric Vehicle, Vehicle to Grid, Industrial Microgrid, Day-Ahead Optimal scheduling.

I. INTRODUCTION

In the past decade, strong incentives have been provided by many countries over the world to develop electric vehicles due to its zero emission feature and it is considered as a possible solution to the environmental pollution and sustainability problems [1]. Conventionally, power plant operators conservatively estimate the peak demand that results in a high cost of energy. The V2G technology that uses EV batteries as responsive loads will be playing an important role in the future smart grid to reduce the generator standby capacity, to relieve the peak load pressure, and to enhance voltage and frequency stability of the grid [2-3]. The normal operation of the V2G integrated power grid requires EV batteries to support the grid during peak-time by feeding power into the grid and at off-peak time, the grid will charge those batteries. The V2G technology enables the peak shaving features in the power system such that the cost of energy can be significantly reduced. Furthermore, peak shaving strategies can also be applied in the renewable energy integrated micro grid to increase its capacity.

This paper presents a day-ahead optimal energy management strategies for an industrial microgrid with V2G system to optimize the electric energy cost, which can provide peak shaving service. The V2G system with EV batteries introduce the extra flexibility for industries to improve the cost-effectiveness by the bidirectional energy flow between the EV batteries and grid based on the price of electricity. The optimal scheduling is realised by solving the optimisation problem with the approach in [4]. Specific constraints of EV battery technology and the grid constraints inside the inner energy management are taken into account in the study [5, 6]. Several economics saving sources are investigated, including the penalties (i.e. Extra cost when a non-compliance happens) by reducing the peak load and energy market.

II. DESIGN OF AN OPERATIONAL PLANNING FOR OPTIMAL VALUATION IN THE MARKET

A. Presentation of the framework

As shown in Fig. 1, the proposed work aims to design a day-ahead energy management schedule for power grid based on V2G system; grid and EV battery constraints are taking into account. The current price in the energy market and the energy availability are two important factors that affects the planning of the charging and discharging modes for plugged-in EVs. A power profile of the EV batteries will be generated based on the day-ahead algorithm and can be written as

$$\begin{cases} P_1 &= \left[P_1\ \left(T_1^{ini}\right) P_1\ \left(T_1^{ini} + T_{step}\right) \ldots\ldots\ P_1\ \left(T_1^{fin} - T_{step}\right)\right] \\ P_2 &= \left[P_2\ \left(T_2^{ini}\right) P_2\ \left(T_2^{ini} + T_{step}\right) \ldots\ldots\ P_2\ \left(T_2^{fin} - T_{step}\right)\right] \\ & \vdots \\ P_n &= \left[P_n\ \left(T_n^{ini}\right) P_n\ \left(T_n^{ini} + T_{step}\right) \ldots\ldots\ P_n\ \left(T_n^{fin} - T_{step}\right)\right] \end{cases} \quad (1)$$

where

-$P_i(t)$ is the EV battery power at a time step (T_{Step}) in the following day, as Fig. 2 shows;

-n is the number of EVs;

-T_i^{ini} denotes the time when the ith EV is arrived at (plugged into) the ith charging station;

-T_i^{fin} stands for the departure (plugged out) time of the ith EV from the ith charging station.

The price profile is used as the input and represented by

$$£ = \left[£(1)\ \ £\left(1 + T_{step}\right) \ldots\ldots £(N)\right] \quad (2)$$

where $N = 24/T_{step}$.

The information of Sate of Charge (SOC) is required and can be represented by

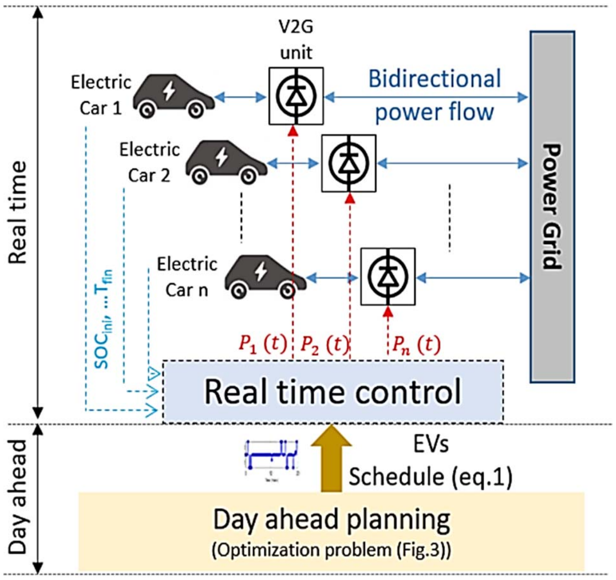

Figure 1. Schematic diagram of industrial microgrid connecting with a fleet of EVs

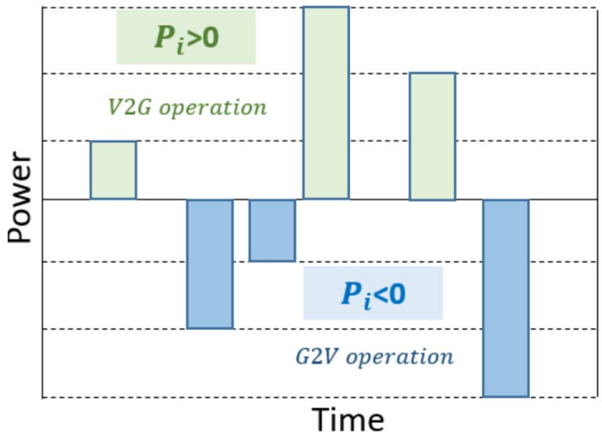

Figure 2. A generic power profile between EVs and a microgrid

$$\begin{cases} S_1 = \left[s_1\left(T_1^{ini}\right) s_1\left(T_1^{ini}+T_{step}\right) \ldots\ldots s_1\left(T_1^{fin}\right)\right] \\ S_2 = \left[s_2\left(T_2^{ini}\right) s_2\left(T_2^{ini}+T_{step}\right) \ldots\ldots s_2\left(T_2^{fin}\right)\right] \\ \vdots \\ S_n = \left[s_n\left(T_n^{ini}\right) s_n\left(T_n^{ini}+T_{step}\right) \ldots\ldots s_n\left(T_n^{fin}\right)\right] \end{cases} \quad (3)$$

At the time $t = T_i^{ini}$, the ith EV is plugged in with the initial SOC that equals $s_i(T_i^{ini})$. When the ith EV is plugged out at $t = T_i^{fin}$, the final SOC is $s_i(T_i^{fin})$.

It is assumed that:

- the information of the arrival time, the battery capacity of the EV, and the initial SOC can be obtained by the charging station when the EV is plugged in,

- the departure time and the final SOC value are setpoints given by the EV owners when starting the V2G operation,

- the charge/discharge period of the ith EV, T_i, can be determined by the charging station.

B. *Model of the lithium-ion battery in EV*

The lithium-ion batteries has been widely installed in EVs and the battery management system (BMS) is required to monitor and control the lithium batteries to ensure reliable, safe, and efficient operation. One of the main functions of a BMS is the SOC estimation. Define the energy stored in the battery i^{th} at time *t as*

$$E_i(t) = \int_{T_i^{ini}}^{T_i^{ini}+T_{step}} P_i(t)dt + E_i^{ini} \quad i = 1 \ldots.n \qquad (4)$$

where

-E_i^{ini} is the initial energy of i$^{\text{th}}$ EV at $t = T_i^{ini}$

-$P_i(t)$ is the instantaneous power exchanged between the i$^{\text{th}}$ EV and the grid.

The SOC of battery i^{th} in this paper is represented as the ratio of the $E_i(t)$ and the battery capacity E_i^{max}:

$$s_i(t) = \frac{E_i(t)}{E_i^{max}} \qquad i = 1 \ldots.n \qquad (5)$$

C. *Model of the lithium-ion battery in EV*

By utilising the method proposed in [1], the proposed scheduling scheme is capable of providing the optimal set-points of the power exchanged between the EV batteries and the grid for any time T_i.

The power flow during the V2G operation (discharging operation) is defined in positive sign whereas the negative sign denotes the power flow from the grid to batteries (G2V / charging operation) (see Fig.2).

III. DAY AHEAD OPTIMISATION ALGORITHM OF THE V2G SYSTEM

The deterministic linear programming formulation of the problem for the day-head planning is presented in this section. The optimization problem is formulated to minimize the energy cost of the microgrid with V2G system as follows:

$$\begin{gathered} \min_x \{J(x)\} \\ s.t. \;\; x \in X. \end{gathered} \qquad (6)$$

where

- *J(x)* is the cost function that need to be determined.

- x is the optimal solution vector that belongs to the solution set X.

The above optimization problem will be defined according to the power grid operation constraint, EV owner constraints and EV battery operation constraints.

A. *The objective function*

The objectives of the optimisation strategy are (1) To minimise the energy exchange between the microgrid and power grid at the point of common coupling, and (2) To maximise EV revenue that performs V2G operation for peak shaving service during the parking time.

Thus, the objective function can be expressed as

$$J = \sum_{i=1}^{n} \sum_{t=T_i^{ini}}^{T_i^{fin}} T_{Step}(P_i(t) \times £(t)) \qquad (7)$$

$$\min_{P(t)} J \qquad (8)$$

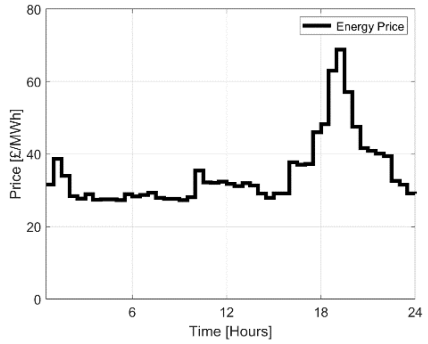

Figure 3. Day-ahead energy price $£(t)$ [8]

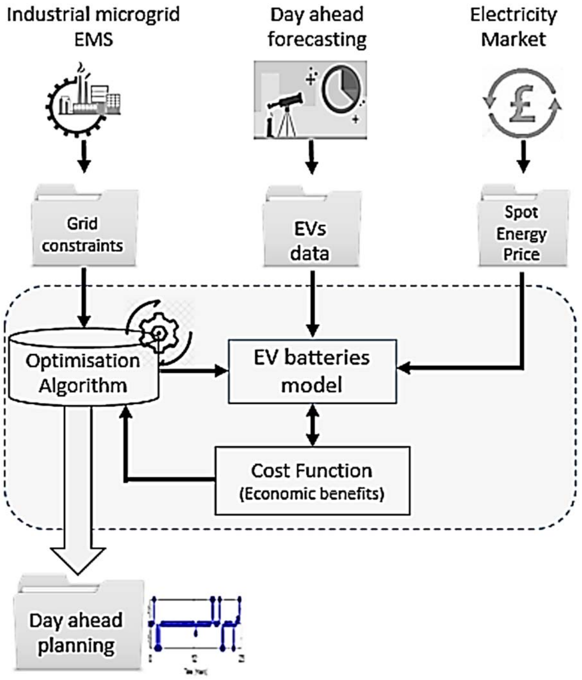

Figure 4. Optimization framework for day ahead planning

The discharge power constrains are given as

$$-P_i^{max} \leq P_i(t) \leq 0 \tag{9}$$

where the range of the charge power is specified as

$$0 \leq P_i(t) \leq P_i^{max} \tag{10}$$

The constrains on the real-time energy are given as

$$s_i(t) - \left(\frac{P_i(t) \times \eta}{E_i^{max}}\right) \times T_{step} \leq 1 \quad \text{if} \quad P_i \leq 0 \tag{11}$$

$$s_i(t) - \left(\frac{P_i(t)/\eta}{E_i^{max}}\right) \times T_{step} \geq 0 \quad \text{if} \quad P_i \geq 0 \tag{12}$$

The constraints on the final energy at the end of V2G operation is given by

$$SOC_i^{ini} + \sum_{T_i^{ini}}^{T_i^{fin}} \left(\frac{\begin{pmatrix} -P_i(t) \times \eta & if \quad P_i \leq 0 \\ -\frac{P_i(t)}{\eta} & if \quad P_i \geq 0 \end{pmatrix}}{E_i^{max}}\right) \times T_{step} = SOC_i^{fin} \tag{13}$$

Since the power grid is limited by its own sizing, it would not be disturbed by the integration of EVs via V2G system. The constraints on the active power flows can be obtained from the limitations of the currents, which can be written as

$$-P_{\max - supply}(t) \leq \sum_{i=1}^{n} P_i(t) \leq P_{\max - load}(t) \tag{14}$$

It suggests that the upper bound of the active power is limited by the total load whereas the lower bound depends on the maximum supply power. Considering those limitations could prevent the system from over power consumption/generation.

$£(t)$ is defined as the spot price of electricity in the day-ahead energy market at the time step t (in £/MWh). The profile of the price variation against time used in this study is shown in Fig. 3. [8].

To solve the optimization problem defined above, the Optimization Toolbox in Matlab is employed [1]. The minimum of the constrained linear/nonlinear multivariable function can be found using "fmincon" function. The minima are returned and stored in the vector (P_i) and the 'fval' would return the optimum of the objective function.

B. *Day-ahead scheduling scheme*

The day-ahead operational planning requires the day-ahead scheduling scheme, in which the EV data (e.g. T_i^{ini}, T_i^{fin}, SOC_i^{ini} etc...) are not available day ahead. The planning of the V2G, namely the schedule of the charge/discharge power for every time step, is based on the historical data and/or statistical information sets, including the forecasted day-ahead energy price, the EV availability statistic data at different time slots, the grid constraints, and the battery model. The optimum of the EV schedules for the next day is generated and presented in Fig. 4. The Day ahead scheduling would minimise the objective function (7) such that energy cost can be minimised.

IV. CASE STUDY OF AN INDUSTRIAL MICROGRID

The diagram of the industrial microgrid with integration of the EVs and renewable energy is shown in Fig. 5. In this case study, the analysis of an industrial microgrid with integration of EVs is conducted to evaluate its energy cost with the V2G and the proposed scheduling scheme.

Fig. 6 shows the PV production and load power of the microgrid, in which the peak industrial load power is 14 MW and the PV with 5 MW power rating was involved into the industrial microgrid [7]. The day ahead scheduling is shown in Fig.7, and the integration of the EV fleets is depicted in Fig. 8.

The penetration capacity is determined by the subscribed rated power, including the fixed monthly costs and the penalties of over exchanging of power (ΔP_{excess}).

The monthly components for subscribed power overruns (MCSPO) is used to represent the monthly cost that needs to be minimized [1]:

$$MCSPO = \sum_{t \in T} \alpha \times k_t \times \sqrt{\sum_{x \in X_t} \Delta P_{excess}^2(x)} \tag{15}$$

where

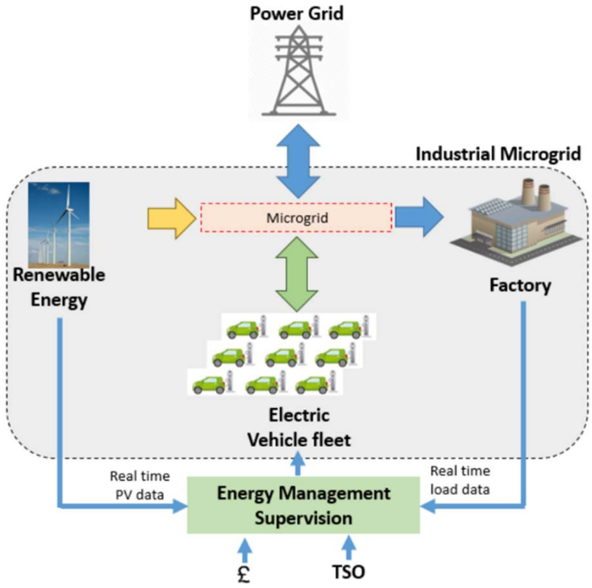

Figure 5. Schematic diagram of industrial microgrid integrating a fleet of EVs

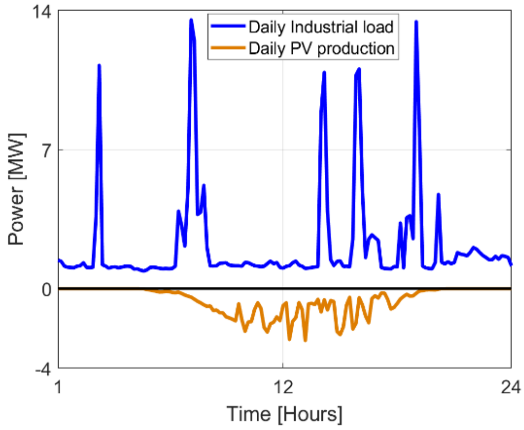

Figure 6. PV power production and Industrial load power [7]

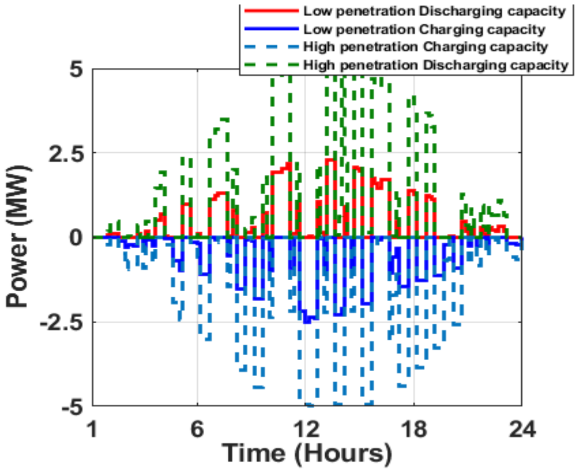

Figure 7. Day ahead scheduling for low and high penetration of EV.

- x is the index set that belongs to each time tariff period t,

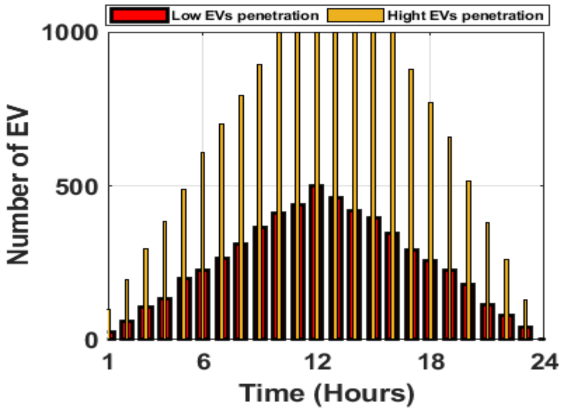

Figure 8. Number of EVs penetration to microgrid (High and low penetrations cases)

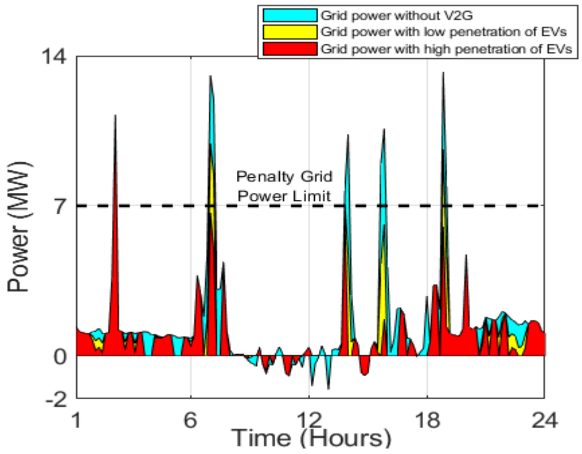

Figure 9. Exchanged power with grid at PCC with and without V2G operations cases of industrial microgrid.

- k_t (%) is a coefficient of the time tariff t,

- the coefficient α is set to be £100/MW.

As Fig. 6 shows, the peak power would cause the over-cost issues to the company and this is the problem that needs to be addressed. In Fig. 7, the estimation of the energy capacity is presented based on the two cases, including the low and the high penetration of electric vehicles (see Fig. 8). Fig. 9 shows the 24-hour operation data of the industrial grid, including the operation without V2G, with low EV penetration (<500 EVs) based V2G, and with high EV penetration (<1000 EVs) based V2G (see Fig.7).

With low EV penetration based V2G operation, the maximum power supplied from the grid has been reduced to 10 MW and it can be further decreased to 7 MW when the EV penetration is high.

The analysis result shows that the operation of the industrial microgrid with EV integration based V2G would save 37% / 69% of the electricity cost for one month (Table.1). But it should be noted that this result cannot be generalized to the operation for the whole year due to the connected EVs uncertainty and meteorological variations. The developed technical economic model would benefit the cost analysis of the power system with V2G technology.

TABLE I. INDUSTRIAL MICROGRID MONTHLY BILL

	Without V2G	Low penetration of EVs	High penetration of EV
Daily energy cost (£)	1,445.8	902.0	467.0
Monthly energy cost (£)	29,916.0	19,040.0	9,340.0
MCSPO (£)	1,583.9	608.5	352.0
Total monthly bill (£)	31,500.0	19,649.0	9,692.0

V. CONCLUSIONS

The cost analysis of the industrial microgrid with EV integration based on V2G technology has been investigated in this paper. The technical economic model has been used to describe the cost of the power system. Linear optimisation has been applied to solve the problem such that a day-ahead schedule can be obtained and the energy cost for the next-day operation can be minimised. The case study of an industrial microgrid has been performed to demonstrate the capability of the day-ahead schedule in planning the EV power penetrations. The results indicate that with the integration of EV into the microgrid and the utilisation of the scheduling scheme, the energy cost has shown to be reduced by 37.62% and 69.23% for both the case of low- and high- penetration of the EVs.

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