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Optimal vehicle to grid planning and scheduling using double layer multi-objective algorithm

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ABSTRACT

Vehicle to grid is a revolutionary technology that allows energy exchange between electric vehicles and power grid for mutual advantages. The implementation of appropriate vehicle to grid energy management system can maximize the potential of electric vehicles to provide grid ancillary services. This paper proposes an optimal vehicle to grid planning and scheduling by utilizing a novel double layer multi-objective algorithm. This optimization algorithm utilizes the grid-connected electric vehicles to perform peak load shaving and load levelling services to minimize the power grid load variance in the first layer optimization. Meanwhile, the second layer optimization minimizes the reactive power compensation for grid voltage regulation and therefore, optimizes the vehicle to grid charger's capacitor sizing. The second layer optimization algorithm utilizes an approximated formula from the simulation of a vehicle to grid charger. The proposed vehicle to grid optimization algorithm considers various power grid and electric vehicle constraints for practicality purpose. With the real time implementation of the proposed algorithm, the optimization results show that the power load curve is effectively followed the preset constant target loading, while the grid voltage is successfully regulated to the predetermined voltage level with minimal amount of reactive power supply from the optimal charger's capacitor.

1. Introduction

In recent years, the deployment of electric vehicle (EV) has become the catalyst in reducing the impact due to climate change, by alleviating carbon emissions of roadway vehicles. The optimization model and analysis has been proposed to determine the best combination of vehicle types to achieve minimal emissions with the lowest investment [1]. It is envisaged that the key findings from the optimization model and analysis shall assist the policy makers and transportation planners to prepare the transportation framework and structure to accommodate future influx of EV [2]. On the other hand, EVs may not be environmental-friendly if EV batteries are charged from the power grid with fossil fuel generation. Despite the contradiction, authors in Ref. [3] have concluded that electrification of roadway transportation is able to reduce fuel consumption and emissions without renewable energy integration. Obviously, the fuel consumption and emissions will be further reduced if renewable energy generations are widely adopted. EVs powered by hybrid solar system can also enhance the reduction of greenhouse gases [4].

The benefits and challenges of EV deployment on the environment, economic and power grid have been reviewed in Ref. [5]. Despite the environmental and economical benefits, EV deployment has brought negative impacts to the power grid as a consequence of EV charging operation. The impact assessment of EV charging to the Swiss distribution grid has been investigated in Ref. [6], where the study indicates that many substations will be overloaded if the EV penetration level is more than 50%. The additional EV charging loads become the bottlenecks where capacity investment is required to solve the overloading problem. The authors in Ref. [7] have examined the power quality impacts of EV charging to the power grid and conclude that the Level 1 EV charging increases the neutral-to-earth voltages which can lead to stray voltage incidents. The authors in Ref. [8] have revealed major impacts of EV charging to the power grid, such as overloading of grid components, voltage drop, harmonics and power loss problems.

Nevertheless, a new opportunity has emerged due to the interaction between EVs and power grid, which is known as vehicle

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Nomenclature

ΔP	grid load variance
n	EV index, $n = 1,2,\ldots,80$
N	maximum EV index
t	time index, $t = 1,2, \ldots,24$
A_n	availability of nth EV
D_n	battery degradation coefficient of$n$th EV
K_n	optimal numbers of EV for V2G application
P_{EV}	total power of EV loads/sources
$P_{\mathrm{EV,charging}}$	EV charging rate
$P_{\mathrm{EV,discharging}}$	EV discharging rate
$P_{\mathrm{EV,max}}$	maximum EV power exchange rate
P_{flow}	active power flow from grid to EV system and loads
P_{grid}	generated power from generation plants
P_{load}	power grid existing loads
P_{target}	target loading
Q_{flow}	reactive power flow from grid to EV system
SOC_n	battery SOC of nth EV
$SOC_{n,max}$	maximum SOC of EV battery
$SOC_{n,min}$	minimum SOC of EV battery
V_{grid}	power grid voltage
$V_{\mathrm{grid,max}}$	maximum limit for power grid voltage
$V_{\mathrm{grid,min}}$	minimum limit for power grid voltage
$V_{\mathrm{regulated}}$	regulated power grid voltage
x	active power coefficient
y	grid voltage coefficient
z	constant coefficient

to grid (V2G) technology. The functional principle of V2G technology is that an EV can act as a mobile energy source other than as a charging load. Hence, V2G technology allows bidirectional energy exchange between EV batteries and power grid for shared advantages, such as ancillary services, active power support and reactive power compensation for power grid whilst revenue benefits for EV owners [9]. There are many V2G studies highlighted in the literature which can be further classified into two categories: (1) the development of smart bidirectional V2G charging station and (2) the implementation of V2G scheduling.

The former research category is well established since it is the initial requirement to realize the V2G technology. Several studies have discussed the development of bidirectional V2G chargers with decoupled real and reactive power control [10]. The proposed control can manage the real power flow for EV battery charging and discharging processes without affecting the reactive power, which is usually set at zero value to achieve unity power factor operation for V2G charger [11]. Meanwhile, reactive power compensation control is adopted in the EV charger proposed in Ref. [12] to regulate the grid voltage utilizing the bidirectional reactive power flow between power grid and EV charger. Similarly, the authors in Ref. [13] have proposed a reduced-capacity V2G charger to provide reactive power support to the power grid. The utilizations of both real and reactive power controls are essential to develop a feasible bidirectional V2G charger.

Optimal V2G management systems are utilized to schedule the charging and discharging operations of a large fleet of EVs to achieve specific objectives. The authors in Ref. [14] have employed the V2G scheduling of electric buses and battery electric transit to reduce electricity generation related carbon emissions. Meanwhile, the authors in Ref. [15] have proposed an optimal V2G dispatch model to achieve the similar objective. Several studies have proposed the optimal V2G scheduling to accomplish profit maximization and cost minimization. A simultaneous scheduling of combined energy exchange modes has been proposed in Ref. [16] to optimize the incentives for both V2G aggregator and EV owners. Optimal V2G scheduling in a renewable micro-grid is presented in Ref. [17] to minimize the operation cost. Furthermore, multi-objective V2G scheduling have also been proposed in the literature. The authors in Ref. [18] have presented a multi-objective resource scheduling for V2G system which focuses on the reduction of power system operation cost and air pollutant emissions. Similar studies have been presented in Refs. [19] and [20], which utilize the V2G technology to achieve maximization of net revenue and emissions savings with the consideration of various uncertainties.

Energy management of large scale EV fleets can be employed to maintain the power grid reliability. In Ref. [21], an optimal-based V2G model has successfully performed the power grid load shifting to flatten the power load curve. Furthermore, a study in Ref. [22] has developed a coordinated control strategy that utilizes a large scale of EVs to achieve power grid frequency regulation and support the renewable energy generation. In addition, a V2G control strategy for power grid spinning reserve service is presented in Ref. [23]. The results reveal that the proposed V2G control strategy significantly decreases the system cost and increases the system capability of integrating with variable renewable sources. Moreover, system loss reduction by V2G technology has attained the attention of many researchers. The authors in Ref. [24] has proposed an optimal EV charging strategy using particle swarm optimization, which can reduce power grid losses. Meanwhile, research in Ref. [25] has achieved power loss reduction and voltage improvement while considering real life practical constraints. The V2G scheduling of active and reactive resources is utilized in Ref. [26] to obtain the best solution from the technical and economical perspectives. On the other hand, the authors in Ref. [27] have presented a multi-objective optimization on the global level to manage the integrated EVs to serve as energy storages for the renewable energy generation.

Despite the increasing literature on the aforementioned V2G research topics, there is rather limited literature which combines both bidirectional V2G charging station and optimal V2G scheduling. In the context of V2G scheduling, all the public, residential and commercial V2G chargers are usually assumed to have enough capability to support the dual power exchange for the large scale V2G application. Inappropriate capacity planning of the V2G charger can limit the performance of the practical V2G system. For instance, improper DC-link capacitor sizing of the V2G charger will not provide sufficient reactive power support to the V2G system for grid voltage regulation. Therefore, proper DC-link capacitor sizing by using optimal V2G scheduling can fulfill the research gap to further enhance the V2G potential with minimal investment.

This paper proposes an optimal V2G planning and scheduling using double layer multi-objective algorithm. The main contributions of this paper are: (1) to highlight comprehensive planning procedures for V2G chargers using optimal V2G scheduling, (2) to present a double layer multi-objective V2G optimization algorithm for grid load variance minimization and grid voltage regulation, (3) to optimize the DC-link capacitor sizing of the bidirectional V2G charger, and (4) to demonstrate real time V2G scheduling for a large EV fleets. The rest of the paper is organized into several sections. Section 2 reveals the planning procedures for the V2G chargers using proposed optimal V2G scheduling. Section 3 describes the design and development of the bidirectional V2G charger in a generic test network, which has the capability of regulating the grid voltage during EV charging and discharging processes. The scenario modelling and problem formulation of the double layer multi-objective V2G optimization algorithm are presented in Section 4, where the objective functions of both layers, constraints and the optimization algorithm are discussed comprehensively. Section 5 shows the optimization results under four different scenarios to investigate the effectiveness of the proposed algorithm. The real time V2G scheduling for a township has been conducted in Section 6. Section 7 concludes the paper.

2. Methods

The provision of V2G chargers plays a crucial role in supporting the development of EV industry. The development of bidirectional V2G charging station requires the consideration of various constraints. Hence, proper planning procedures are important to ensure the implementation of V2G technology can be successful with minimal investment. In this paper, the planning procedures to construct a bidirectional V2G charging station with optimal sizing of DC-link capacitor are presented, as follows:

i. *Design of the bidirectional V2G charger*: The software model of a bidirectional V2G charger is constructed using the PSCAD/EMTDC software. The developed V2G charger has the capability of controlling the bidirectional active power flow between EV and power grid, which is essential to support the power grid demand response. Moreover, the proposed charger can provide reactive power compensation function to the power grid in order to prevent the voltage drop issue due to large EV charging demands.

ii. *Modelling of the power distribution grid*: These planning procedures involve the modelling of a power distribution grid model using the PSCAD/EMTDC software. In this paper, a specific radial-configured power distribution grid is developed to provide the interconnection point for the bidirectional V2G charging station.

iii. Formulation of the relationship between the active power flow (P_{flow}), reactive power flow (Q_{flow}) and regulated power grid voltage ($V_{\text{regulated}}$): A comprehensive analysis and evaluation will be performed to determine the relationship between P_{flow}, Q_{flow} and $V_{\text{regulated}}$. This relationship is formulized by determining the P_{flow} and Q_{flow} relationship while maintaining the power grid voltage at a constant voltage level. Several sets of P_{flow} and Q_{flow} relationship are gathered by repeating this procedure at various regulated voltage levels. All parameters involved in this formulization technique are strictly bound within their own constraint limitations. For instance, $V_{\text{regulated}}$ is limited to $+5\%$ and -3% of voltage difference. Meanwhile, the apparent power capacity is limited by the distribution transformer rating.

iv. *Double layer multi-objective V2G optimization algorithm*: The developed V2G optimization algorithm is separated into two layers. The first layer of this algorithm minimizes the grid load variance. The second layer of the optimization algorithm utilizes the formulized relationship between $V_{\text{regulated}}$, P_{flow} and Q_{flow}, as well as the attained optimal V2G scheduling in the first layer to acquire the optimal Q_{flow} profile required for power grid voltage regulation.

v. *Determine the optimal capacitor sizing*: In the previous optimization procedure, the optimal profile of Q_{flow} is utilized to determine the optimal sizing of the DC-link capacitor of V2G charger. Since the amount of Q_{flow} is directly proportional to the capacitor sizing, the maximum amount of Q_{flow} in the optimal Q_{flow} profile is used to calculate the minimal capacity of the DC-link capacitor at certain voltage level.

vi. *The implementation of real time V2G scheduling*: Real time V2G scheduling is demonstrated in the generic commercial-residential township for three days (two weekdays and one weekend). A total of 1800 EV mobility with EV grid connection probabilities and various initial load profiles are considered.

3. Development of bidirectional V2G charger in a generic test network

An EV charger typically employs two energy conversion stages, which are AC/DC rectification and DC/DC conversion. Fig. 1 depicts the configuration and control strategies of the proposed grid-connected bidirectional V2G charger. The V2G charger is composed of a bidirectional full bridge AC/DC converter and a bidirectional buck-boost DC/DC converter, which is separated by the DC-link capacitor. The AC/DC converter employs a voltage control strategy to regulate the grid voltage and the DC-link voltage simultaneously. The grid voltage regulation is achieved by utilizing the converter switching and the reactive power supply from the DC-link capacitor. Meanwhile, a current control strategy is implemented in the DC/DC converter to determine the magnitude and direction of the battery current for EV charging or discharging operation. Therefore, the overall control strategy of the proposed bidirectional V2G charger has the capability of regulating the grid voltage during both EV charging and discharging processes.

Since the voltage control strategy in AC/DC converter is to regulate the grid voltage and DC-link voltage, these parameters are measured as the essential inputs for the controller. The voltage control strategy has two separated operations. In the first part of the voltage control strategy, the error between the measured DC-link voltage and the prefixed reference is detected. The computed error is led to a Proportional Integral (PI) controller, which responses accordingly by generating an appropriate phase shift angle. The generated output of this PI controller is later added with the grid Phase Locked Loop (PLL) angle to produce the angle for the modulating signal. In the other part of the voltage control strategy, the measured instantaneous grid voltage is transformed into the direct and quadrature voltages. The direct voltage is compared with a reference value and the error is then processed in a PI controller to generate the required magnitude for the modulating signal. The modulating signal is generated based on the outputs from both PI controllers, where the generated angle and magnitude is superimposed onto a carrier waveform to generate the required switching pulses for the converter IGBTs by using the Sinusoidal Pulse Width Modulation (SPWM) technique.

Meanwhile, the bidirectional active power flow between the EV and power grid is managed with the current control strategy implemented in the DC/DC converter. This part of controller has two distinctive functions, which are charging and discharging modes. Initially, the operation mode of the bidirectional buck-boost DC/DC converter will be determined by the operation mode identifier. For charging control, the comparator determines the error between the battery reference current and the measured battery current. The computed error is channeled to a PI controller to produce an informative gain output. This output of the PI controller will be utilized to generate the switching pulse via the Pulse Width Modulation (PWM) technique. The generated switching pulse is used to trigger IGBT1 while IGBT2 is turned OFF during the entire EV charging mode. The current control strategy adopts similar operations for the EV discharging mode, where IGBT2 is controlled

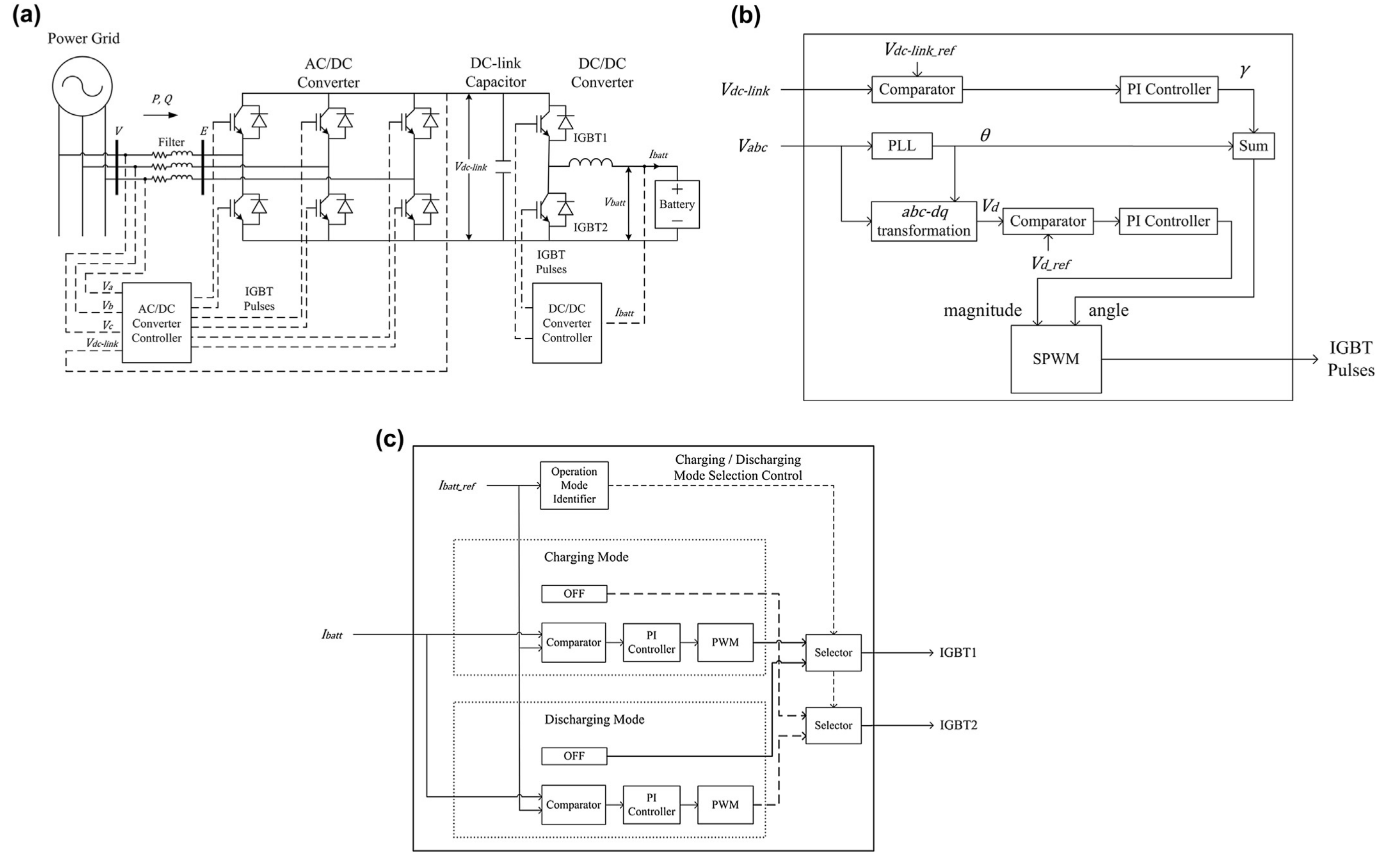

Fig. 1. Proposed grid-connected bidirectional V2G charger: (a) Configuration of the V2G charger, (b) controller of the AC/DC converter and (c) controller of the DC/DC converter.

while IGBT1 is turned OFF. The switching frequency of both converters is set at 10 kHz.

The V2G charger is utilized to control the energy exchange between EV battery and the power grid by meeting the aforementioned objectives. The developed EV battery model is referred to the specification of an available lithium-ion battery in the market, which has a nominal voltage of 330 V and rated capacity of 50 Ah. For practicality purpose, the battery degradation factor will be considered in this study. Fig. 2 shows the single-line diagram of the generic test network. The 11 kV switching substation receives power from the upstream network via the 5 km length of 240 mm^2 three-core armoured copper cables to supply a generic township. The township has 800 units of residential condominiums and 200 units of commercial offices, which are distributed across 22

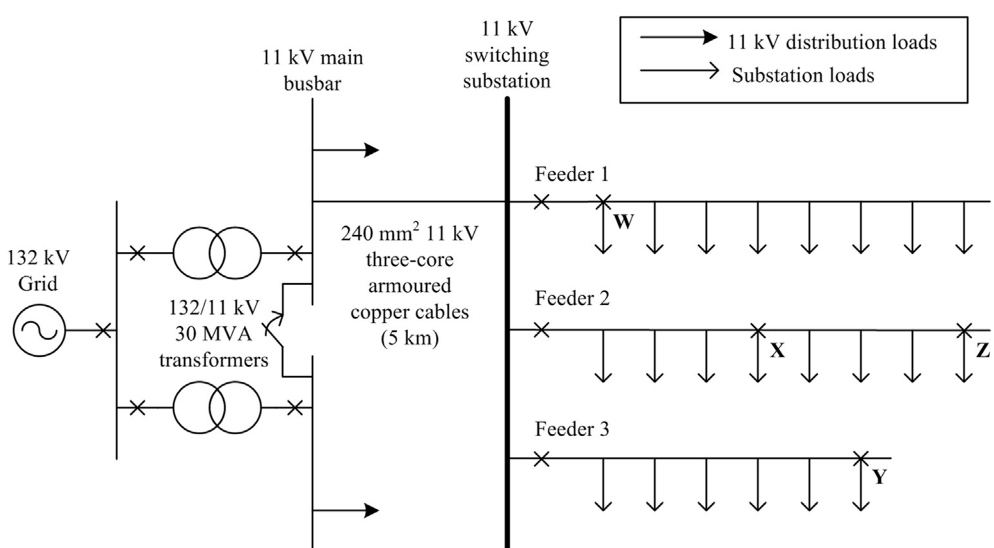

Fig. 2. Single-line diagram of the generic test network.

substations in three feeders. Each residential condominium and commercial office is assumed to have maximum load demand of 10 kW and 15 kW with power factor of 0.95 lagging, respectively. Hence, the combined maximum load demand of the generic township is 11.58 MVA and distributed evenly across the 22 substations. Each substation has an 11/0.4 kV substation step-down transformer with 1 MVA rating to carry the maximum load demand of 0.53 MVA.

As shown in Fig. 2, an EV is connected at the substation marked as "Z" through the proposed V2G charger. The steady state voltage of this substation is 0.945 per unit (p.u.), which is lower than the rated voltage due to the losses across the long cables. Fig. 3 presents the real time simulation results in various operations to demonstrate the functionality of the proposed V2G charger. There are four periods depicted in Fig. 3, which are steady state, improved grid voltage regulation, EV charging and EV discharging.

In the steady state, there is no power exchange between the EV system and the power grid. The steady state voltage of the EV connection point is 0.945 p.u., which is equivalent to 378 V. The grid voltage is improved and regulated to 0.97 p.u. or 388 V by utilizing the reactive power supply from the DC-link capacitor using appropriate converter switching, as shown in the improved grid voltage regulation period. Negative reactive power flow indicates that reactive power is injected into the power grid from the EV system. In the EV charging period, real power is drawn from the power grid to charge the EV battery and opposite operation can be observed in the EV discharging period. The magnitude and direction of real power flow depends on the preset reference current in the control strategy of the DC/DC converter. The voltage control strategy of the AC/DC converter will inject appropriate amount of reactive power to regulate the grid voltage to 0.97 p.u.

The PSCAD/EMTDC simulation results show that the proposed V2G charger with the developed control strategies can effectively determine the required amount of reactive power flow to cater for certain amount of real power flow during EV charging and discharging operations in order to regulate the grid voltage to specific levels. Therefore, the relationship between real power flow (P_{flow}), reactive power flow (Q_{flow}) and grid voltage ($V_{regulated}$) can be utilized to obtain the approximated equation for V2G optimization. Fig. 4 illustrates the relationship between active power flow and reactive power flow under various regulated voltage levels.

4. Scenario modelling and problem formulation of double layer multi-objective V2G optimization algorithm

V2G is an advanced technology that requires explicit planning. The modelling and design of a V2G implementation scenario is an essential task in order to ensure its feasibility. In this paper, a commercial-residential township is chosen for the implementation of V2G technology due to its sustainable EV mobility throughout the day. This township consists of 200 units of commercial offices and 800 units of residential condominiums. Each of the commercial unit has a maximum demand of 15 kW, whilst each residential unit has 10 kW of maximum demand. Fig. 5 shows the power load curve of this township, where the total power load curve is the combination of the commercial and residential load curves. Since the residential units have a larger share of the total township power demand, the total power load curve inherits similar pattern as the residential load curve. The first peak (around 8 a.m.) occurs as the residents actively prepare themselves before work while the second peak (around 8 p.m.) takes place when the residents return home from workplace. Several assumptions have been made for the V2G technology implementation in the generic township, which are listed as follows:

- The bidirectional communication network is assumed to be installed to monitor the power grid information, such as load profile of each substation and EV battery State of Charge (SOC).
- The aggregator can fully control the energy exchange between power grid and EVs for V2G application.
- Each commercial office has five V2G charger units installed at the parking spaces for customers' conveniences.
- Each residential condominium only requires one unit of V2G charger installed at home car park.

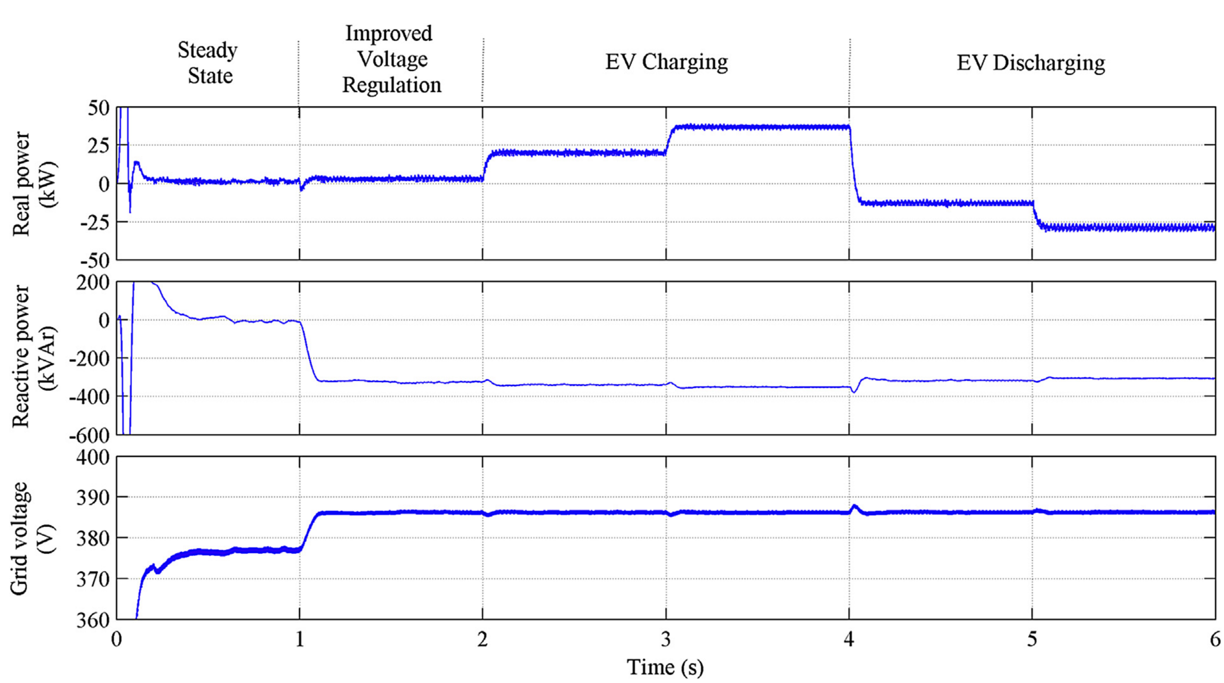

Fig. 3. Simulation results of real power flow, reactive power flow and grid voltage.

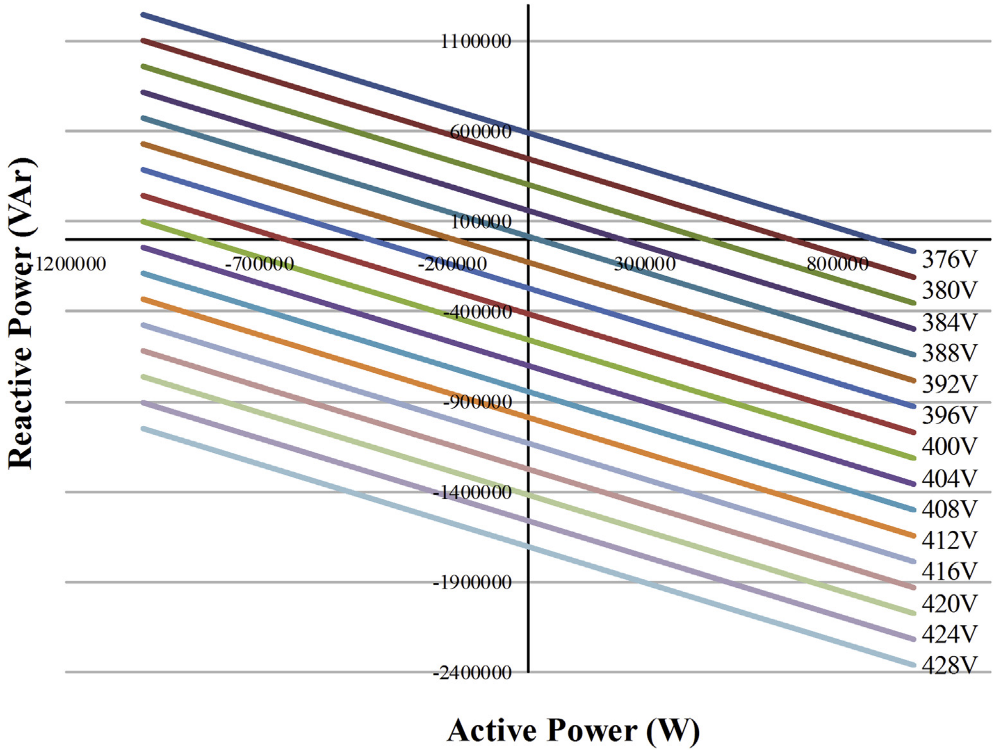

Fig. 4. Relationship between active power flow and reactive power flow under various regulated voltage levels.

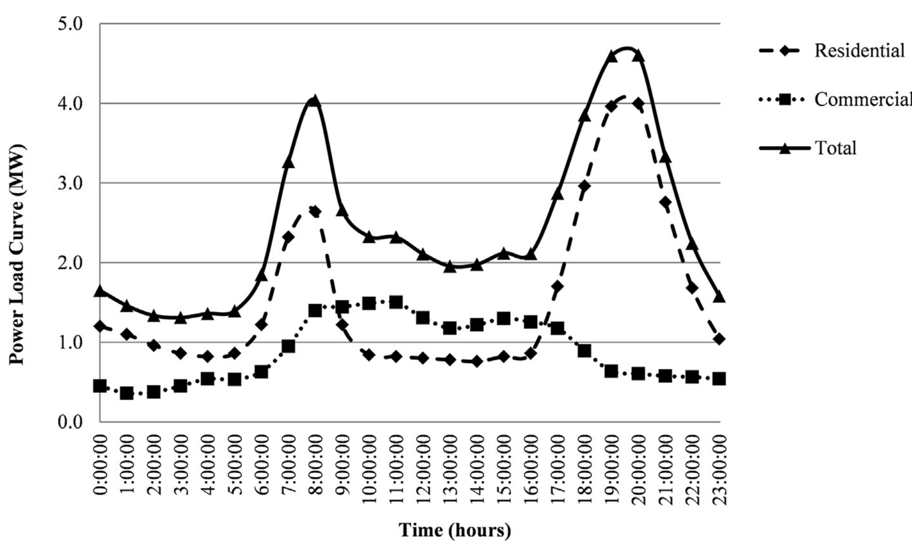

Fig. 5. Power load curves of the commercial-residential township.

- The township has a total of 1800 EV mobility daily, which includes EVs from the proposed and nearby townships.
- All of the commercial, residential, EV load demands and EV mobility are evenly distributed to each substation.
- All EVs have random initial SOC level from 20% to 80%.

V2G technology is a mathematical problem which involves manifold contradictory objectives. Hence, the employment of optimization technique is crucial to assist the implementation of V2G technology in the power grid. In this paper, the formulized double layer multi-objective optimization algorithm utilizes Genetic Algorithm (GA) optimization technique, which is inspired by the natural evolution process and capable of generating optimized solution for the V2G technology problem within an execution time limit. Both the optimization layers shall be utilized as part of the planning stage to determine appropriate value of the V2G charger's DC-link capacitor for the practical implementation of V2G technology.

4.1. Objective functions

In this paper, the proposed double layer multi-objective V2G optimization algorithm performs distinctive objective optimization in each algorithm layer. In the first layer of the proposed V2G algorithm, the objective function is to minimize power grid load variance by determining the optimal charging and discharging power for each grid-connected EV, which is described by Eq. (1). EVs will discharge the batteries energy to support the power grid when the grid loading is greater than the desired target loading and this operation is denoted as peak load shaving. In contrast, load levelling is executed to charge the grid-connected EVs when the grid loading is less than the target loading. EV charging and discharging events are disabled when the grid loading equals to the target loading. These operations can be expressed as in Eq. (2). All variables have been defined in the Nomenclature section.

$$\begin{aligned} \min \Delta \mathrm{P} &= P_{\text{target}}(t) - P_{\text{flow}}(t) \\ &= P_{\text{target}}(t) - [P_{\text{load}}(t) + P_{\text{EV}}(t)] \\ &= P_{\text{target}}(t) - P_{\text{load}}(t) - P_{\text{EV}}(t) \end{aligned} \tag{1}$$

$$P_{\text{EV}}(t) = \begin{cases} \left(\sum_{n=1}^{N} A_n D_n K_n\right) \times P_{\text{EV,charging}} & \text{, if : } P_{\text{load}} < P_{\text{target}} \\ \left(\sum_{n=1}^{N} A_n D_n K_n\right) \times P_{\text{EV,discharging}} & \text{, if : } P_{\text{load}} > P_{\text{target}} \\ 0 & \text{, if : } P_{\text{load}} = P_{\text{target}} \end{cases} \tag{2}$$

In the second layer of the proposed V2G optimization algorithm, optimization is conducted with the aim to minimize Q_{flow} based on the optimal V2G scheduling in the first layer of the V2G optimization algorithm. Based on the formulation from Fig. 4, the objective function of the second layer is shown in Eq. (3) where all variables and coefficient have been defined in the Nomenclature section. Since the amount of Q_{flow} is directly proportional to the capacitor sizing, the minimized Q_{flow} will be utilized to determine the optimal sizing of the DC-link capacitor of V2G charger.

$$\min Q_{\text{flow}} = xP_{\text{flow}} + yV_{\text{regulated}} + z \tag{3}$$

4.2. Constraints

In this paper, the proposed V2G optimization algorithm will comply with some crucial constraints while achieving the aforementioned objective functions. The definitions of all variables are listed in the Nomenclature section.

4.2.1. Power balance

The requirement to balance the power supply with the power demand is important to achieve system stability. Therefore, the generated power from the power generation plants and the EVs discharging supply must match the grid load demand and EVs charging demand.

$$\begin{aligned} & P_{\text{grid}}(t) + \sum_{n=1}^{N} A_n D_n K_n P_{\text{EV,discharging}}(t) \\ & = P_{\text{load}}(t) + \sum_{n=1}^{N} A_n D_n K_n P_{\text{EV,charging}}(t) \end{aligned} \tag{4}$$

4.2.2. Grid voltage

According to the Malaysian Distribution Code [28], the low voltage network which is 400 V has voltage tolerances of +10% and −6%. The proposed V2G charger is designed to supply adequate amount of reactive power to the power grid in order to regulate the power grid voltage within these voltage tolerances. The voltage tolerances used in the V2G optimization algorithm is further narrowed to provide stringent margins for grid voltage, which is set at +5% and −3%.

$$V_{\text{grid,min}} \le V_{\text{regulated}} \le V_{\text{grid,max}} \tag{5}$$

4.2.3. EV battery SOC

During the V2G operation, EV battery SOC must be kept within certain range to protect the battery health and for propulsion purpose. In this paper, EV charging process is permitted if the EV battery SOC is below *SOCn,max* which is set at 90% to prevent battery overcharging issue. Meanwhile, EV discharging process is prevented if the battery SOC is lower than the *SOCn,min* which is set at 55% to reserve enough battery energy for EV propulsion. Both EV charging and discharging processes are allowed if the battery SOC is within the range of *SOCn,min* and *SOCn,max*.

$$SOC_n \le SOC_{n,\min} \quad \text{, allow for charging only} \tag{6}$$

$$SOC_{n,\min} \le SOC_n \le SOC_{n,\max} \quad \text{, allow for charging and discharging} \tag{7}$$

$$SOC_n \ge SOC_{n,\max} \quad \text{, allow for discharging only} \tag{8}$$

4.2.4. EV grid connection probability

The dynamic EV mobility characteristics indicate that EVs can be connected to and disconnected from the power grid at any period. In this paper, the EV grid connection probability is approximated depending on the EV mobility or traffic, as well as the working schedule of the township residents and commercial workers. Fig. 6 depicts the EV grid connection probability of residential and commercial car parks. The combination of the EV grid connection probability of residential and commercial car parks presents the total EV availability in the proposed generic township. This total EV availability has captured the peaks of both residential and commercial EV grid connection probability profiles. Nonetheless, the consideration of different necessity of V2G charging infrastructure between each commercial office (five units of V2G chargers) and residential condominium (one unit of V2G charger) has caused the peak of commercial EV grid connection probability to be higher than the peak of residential EV grid connection probability. Hence, the total grid-connected EV probability has the tendency to follow the pattern of the commercial EV grid connection probability profile, where the peaks occur during day time periods.

$$A_n = 1 \quad \text{, if } n^{\text{th}} \text{ EV is connected to the power grid} \tag{9}$$

$$A_n = 0 \quad \text{, if } n^{\text{th}} \text{ EV is not connected to the power grid} \tag{10}$$

4.2.5. EV power exchange rates

In order to protect the battery health, the power exchange rate between EV battery and power grid should be limited within a safe range. In this paper, the current rate and power rate of EV battery is limited to 10 A and 3.3 kW, respectively.

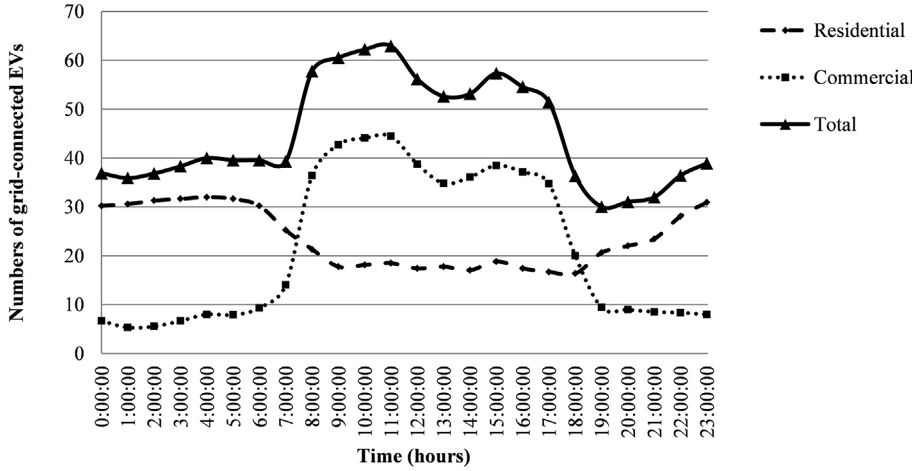

Fig. 6. EV grid connection probability of the generic township.

$$P_{\mathrm{EV,charging}} \leq P_{\mathrm{EV,max}} \tag{11}$$

$$P_{\mathrm{EV,discharging}} \leq -P_{\mathrm{EV,max}} \tag{12}$$

4.2.6. EV battery degradation

The actual capacity of EV battery is highly depends on several degradation factors, such as battery calendar and cycle aging. For a practical V2G application, battery degradation factor should be taken into consideration. Many automobile manufacturers have deliberated on the EV battery reliability issue and stated that EV battery depreciates to approximately 70% after five operating years [29]. Hence, this information is utilized as EV battery degradation coefficient for the optimization algorithm in this paper.

$$D_n = 0.94,\ 0.95, \ldots, \text{or } 0.99 \quad , \quad \text{if n}^{\text{th}}\text{EV is in the first operating year} \tag{13}$$

$$D_n = 0.88,\ 0.89, \ldots, \text{or } 0.93 \quad , \quad \text{if n}^{\text{th}}\text{EV is in the second operating year} \tag{14}$$

$$D_n = 0.82,\ 0.83, \ldots,\ \text{or } 0.87 \quad , \quad \text{if n}^{\text{th}}\text{EV is in the third operating year} \tag{15}$$

$$D_n = 0.76,\ 0.77, \ldots,\ \text{or } 0.81 \quad , \quad \text{if n}^{\text{th}}\text{EV is in the fourth operating year} \tag{16}$$

$$D_n = 0.70,\ 0.71, \ldots,\ \text{or } 0.75 \quad , \quad \text{if n}^{\text{th}}\text{EV is in the fifth operating year} \tag{17}$$

4.3. Flow chart of the V2G optimization algorithm

The flow chart of the proposed V2G optimization algorithm is formulated in MATLAB software, as shown in Fig. 7. The optimization algorithm consists of a time iteration loop, which is utilized to execute the algorithm for every hour. The available EV quantity and energy capacity are determined before implementing the grid load variance minimization in the first layer of GA optimization. In the second layer of the V2G optimization algorithm, the reactive power supply is optimized to regulate the grid voltage within the preset voltage limits according to the attained optimal V2G scheduling in the first layer. The optimized reactive power supply is utilized to obtain the optimized sizing of the DC-link capacitor of the V2G charger.

5. Results and discussion

The proposed V2G optimization algorithm achieves two unique objective functions, which are to minimize grid load variance by peak load shaving and load levelling services (denoted as coordinated EV charging) and DC-link capacitor sizing optimization by minimizing the reactive power supply (denoted as voltage regulation). The functionality of the proposed double layer multi-objective V2G optimization algorithm is examined under various scenarios, as follows:

- Scenario 1: Uncoordinated EV charging without voltage regulation
- Scenario 2: Coordinated EV charging without voltage regulation
- Scenario 3: Uncoordinated EV charging with voltage regulation
- Scenario 4: Coordinated EV charging with voltage regulation

The four scenarios are tested at the furthest substation of the second feeder of the generic township marked as "Z". In order to investigate the feasibility of the proposed V2G optimization algorithm, the initial load and voltage profiles of substation "Z" will be used as base reference to be compared with the optimized profiles in all four scenarios.

5.1. Uncoordinated EV charging without voltage regulation

Scenario 1 shows the worst case scenario, which the grid-connected EVs receive charging from the power grid without the utilization of the proposed V2G optimization algorithm. For uncoordinated EV charging, the EV owners can charge their EVs at any time without contributing the EV battery energy to the power grid for peak load shaving. In addition, the absence of reactive power optimization in this scenario means that the grid voltage is not regulated. Fig. 8 illustrates the real power load curve and voltage profile at substation "Z" before and after the uncoordinated EV charging without voltage regulation scenario. The results indicate that the uncoordinated EV charging has introduced extra power

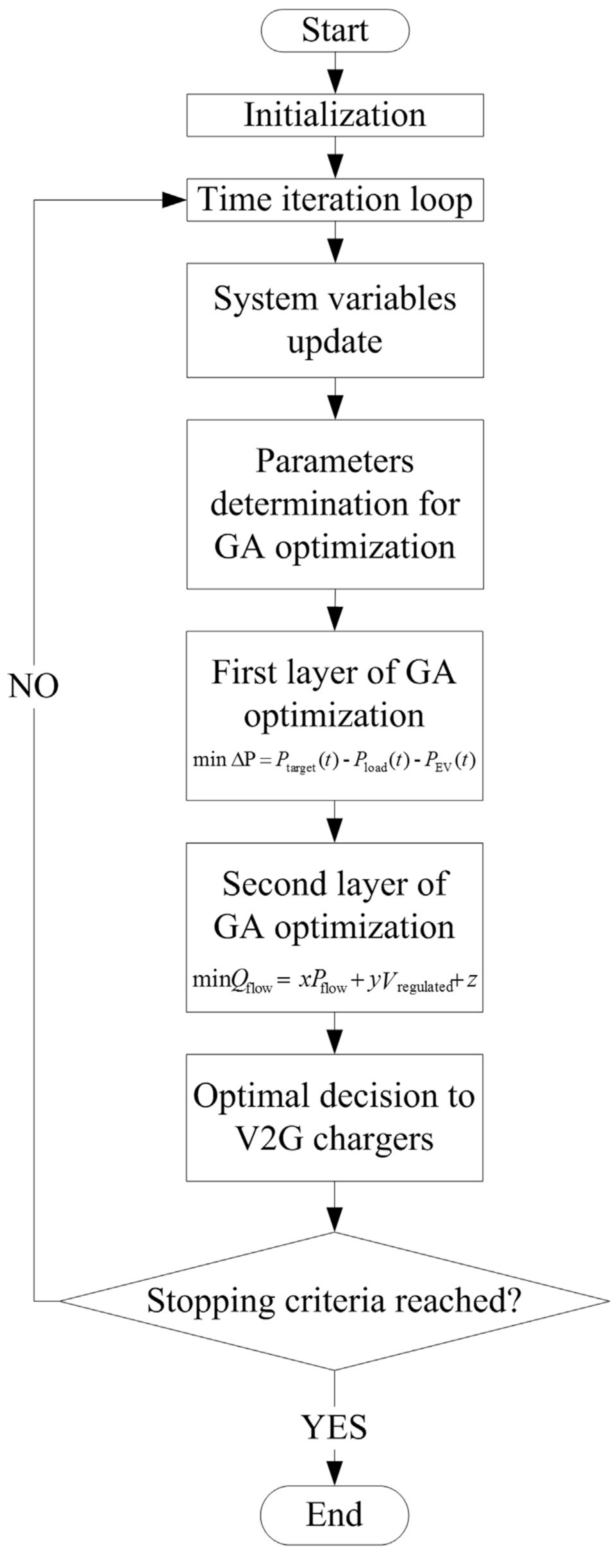

Fig. 7. Flow chart of V2G optimization algorithm.

loading to the substation by introducing a new peak load of 250 kW. The extra EV loading results in additional voltage drop and even violates the grid voltage limit of −6% during the peak load periods. Hence, uncoordinated EV charging without V2G management system is not favorable and could introduce negative effects to the power grid.

5.2. Coordinated EV charging without voltage regulation

In this scenario, the first layer of the proposed V2G optimization algorithm is implemented but the second layer is excluded. In other words, the proposed V2G optimization algorithm is solely utilized to minimize grid load variance by coordinated EV charging. However, the optimization on reactive power supply and DC-link capacitor sizing for voltage regulation is not carried out. Fig. 9 depicts the results of coordinated EV charging without voltage regulation scenario. The coordinated EV charging consists of two operation modes, which are peak load shaving and load levelling. These operations are performed to minimize the grid load variance between target loading and existing loading, so that the actual power loading reaches as close as possible to the target loading which is set at 130 kW. Fig. 9 demonstrates that the optimized power load curve with coordinated EV charging follows closely to the preset target loading. Due to the optimal V2G scheduling, the grid voltage profile in this scenario is also improved. Nonetheless, the grid voltage profile is heavily dependent on the optimized V2G scheduling and operated near to the safe voltage limit. Therefore, voltage regulation function is strongly recommended to have full control and flexibility on the grid voltage.

5.3. Uncoordinated EV charging with voltage regulation

In scenario 3, the proposed V2G optimization algorithm minimizes the reactive power flow from EV system to power grid for voltage regulation and subsequently, optimizes the sizing of the DC-link capacitor of bidirectional V2G charger. However, the minimization of grid load variance function is not included. This scenario is an opposite case compared to Scenario 2, where the first layer objective function is excluded while the second layer objective function is performed. The results of this scenario are shown in Fig. 10. The uncoordinated EV charging has introduced additional loading to the initial power load curve and caused voltage drop at the EV interconnection point. Nonetheless, the second layer of the proposed V2G optimization algorithm effectively supplies the minimal amount of reactive power supply to regulate the grid voltage to 0.97 p.u., which is predetermined to provide stringent voltage limit of −3%. Since the amount of reactive power supply is directly proportional to the capacitor sizing, the optimal sizing of the DC-link capacitor is calculated as approximately 9600 μF based on the optimized reactive power supply.

5.4. Coordinated EV charging with voltage regulation

Fig. 11 illustrates the optimization results of Scenario 4. With the implementation of the proposed double layer multi-objective V2G optimization algorithm, both grid load variance and reactive power compensation are minimized. The optimized power load curve is levelled at approximately 130 kW. A constant power load curve can maximize the utilization of equipment capacity and enhance the efficiency of power generation. Furthermore, the grid voltage is successfully regulated to 0.97 p.u. with minimal amount of reactive power compensation using the proposed V2G optimization algorithm. In this scenario, the optimal sizing of the DC-link capacitor is computed as approximately 8000 μF, which is significantly less than the previous Scenario 3. The reason is due to the optimal V2G scheduling in the first layer of the V2G optimization algorithm

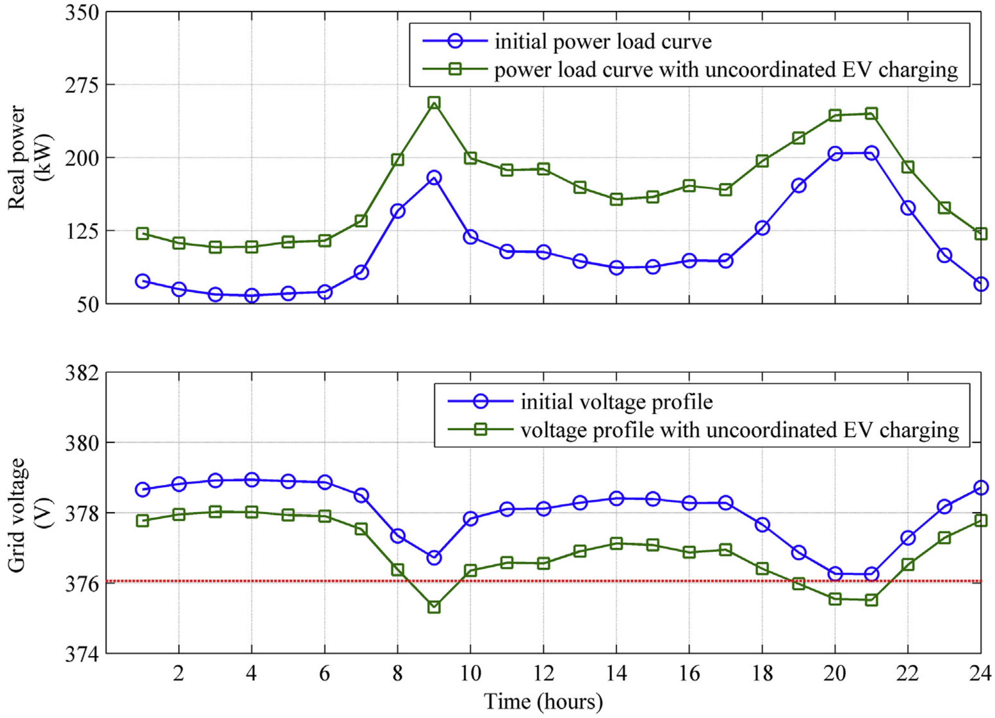

Fig. 8. Results of uncoordinated EV charging without voltage regulation.

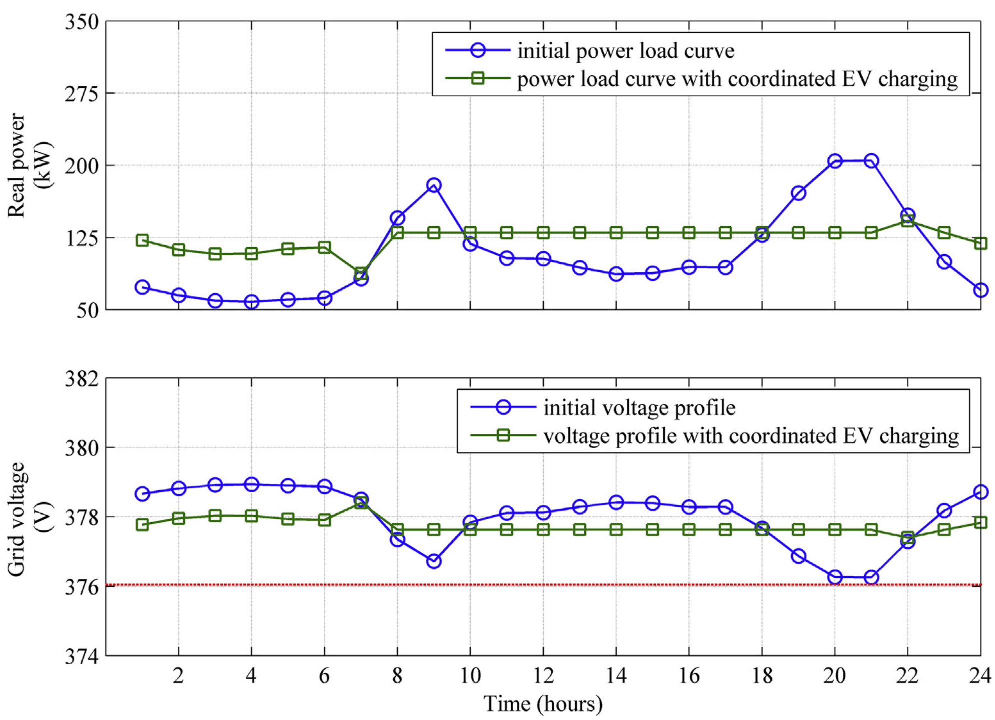

Fig. 9. Results of coordinated EV charging without voltage regulation.

provides slight improvement on the grid voltage regulation. Both overloading and voltage drop problems are solved in this scenario. Hence, the proposed V2G optimization algorithm is able to improve the grid load profile by applying peak load shaving and load levelling service, as well as provide appropriate grid voltage regulation with minimal sizing of DC-link capacitor.

6. Real time implementation of a large scale V2G system

In the planning procedures, the optimal sizing of the EV

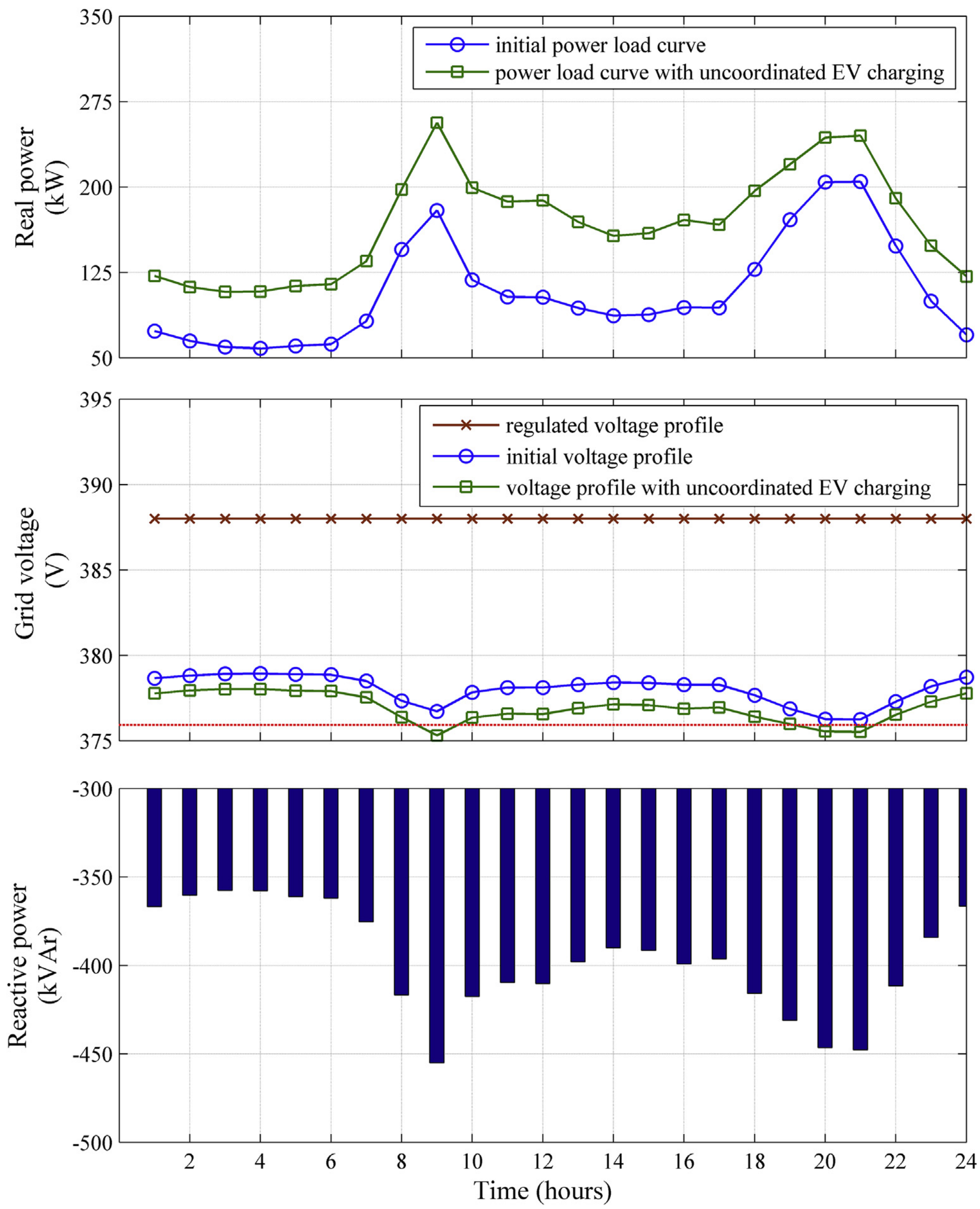

Fig. 10. Results of uncoordinated EV charging with voltage regulation.

charging stations at each substation has been determined. In this commercial-residential township, a case study utilizing large scale V2G management can be used to examine the real time implementation of the proposed V2G algorithm. Fig. 12 illustrates the information and energy interaction among the aggregator, power grid and V2G chargers to achieve the real time V2G application. In this V2G system, all the grid-connected EVs will contribute to the V2G operation in achieving the peak shaving and load levelling services for the 11 kV switching substation. Meanwhile, the installed V2G chargers at each 400 V substation will regulate the power grid voltage as instructed by the aggregator.

A continuous three days (two weekdays and one weekend) of real time power grid loadings and EV mobility patterns are fed into the V2G system to examine the performance of the proposed V2G algorithm. This data has been presented in Table A.1, Table A.2 and Table A.3 in Appendix. The V2G scheduling decision is made hourly and each decision is achieved quickly in the real time implementation. Fig. 13 presents the comparison of the initial and optimal power load curves at the 11 kV switching substation. These results have verified the capability of the proposed V2G algorithm in minimizing the power grid load variance utilizing large EV fleets. Meanwhile, the voltage at each 400 V substation has been successfully regulated as instructed by the aggregator. Fig. 14 shows the voltage profiles and the supplied reactive power by the V2G chargers at substations W, X and Y. These results have verified that the optimal-sized DC-link capacitor of V2G chargers at each 400 V substation is capable of regulating the power grid voltage to 388 V.

7. Conclusion

This paper has presented a novel double layer multi-objective V2G optimization algorithm, which can minimize the grid load

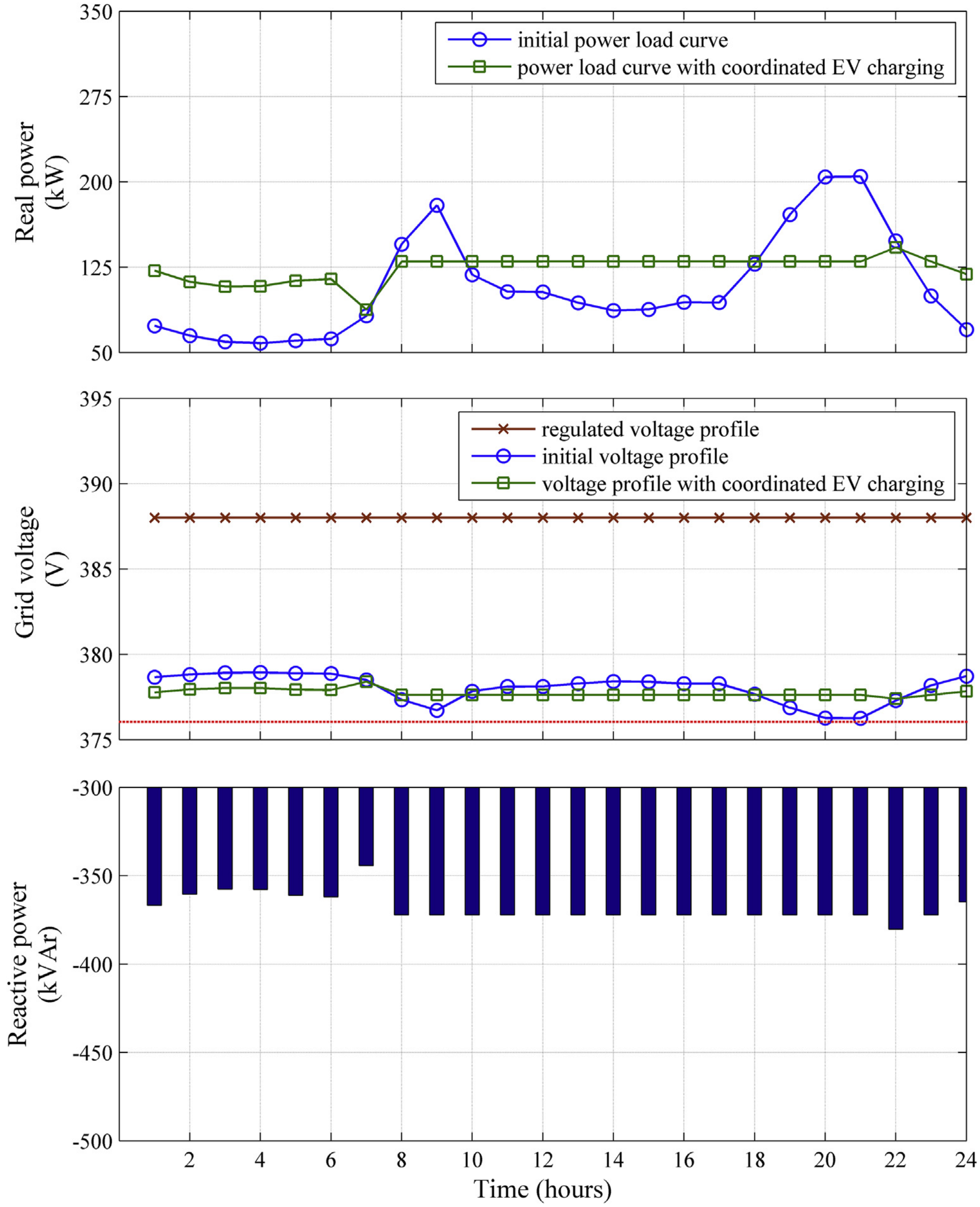

Fig. 11. Results of coordinated EV charging with voltage regulation.

variance in the first layer and regulate the grid voltage in the second layer. The grid load variance minimization is achieved by utilizing the EV battery energy for peak load shaving and load levelling services. Meanwhile, the grid voltage regulation is accomplished by reactive power compensation using the minimal sizing of DC-link capacitor of the V2G charger. Moreover, the development of the bidirectional V2G charger with appropriate control strategies was demonstrated. The V2G charger has the capabilities of regulating the grid voltage during EV charging and discharging processes, where these relationships were formulized and used in the V2G optimization algorithm. The proposed V2G optimization algorithm has been tested under four different scenarios and the results have shown the importance of each layer's objective function. As presented in Scenario 4, the implementation of both objective functions using the proposed V2G optimization algorithm has expressed the best performance for optimal power load curve and regulated voltage profile. The practicality of real time V2G application was also demonstrated in the commercial-residential township using the proposed V2G algorithm. In summary, the following key findings and contributions are highlighted:

- The proposed double layer multi-objective V2G optimization algorithm can effectively minimize grid load variance and regulate grid voltage with the consideration of various EV and power grid constraints.
- The proposed V2G algorithm can be used in the planning stage to determine the optimal DC-link capacitor sizing of the V2G charger. The planning and sizing of V2G chargers can enhance the V2G potential with minimal investment.
- The proposed V2G algorithm can perform real time V2G scheduling for large EV fleets for voltage regulation and grid load variance minimization.

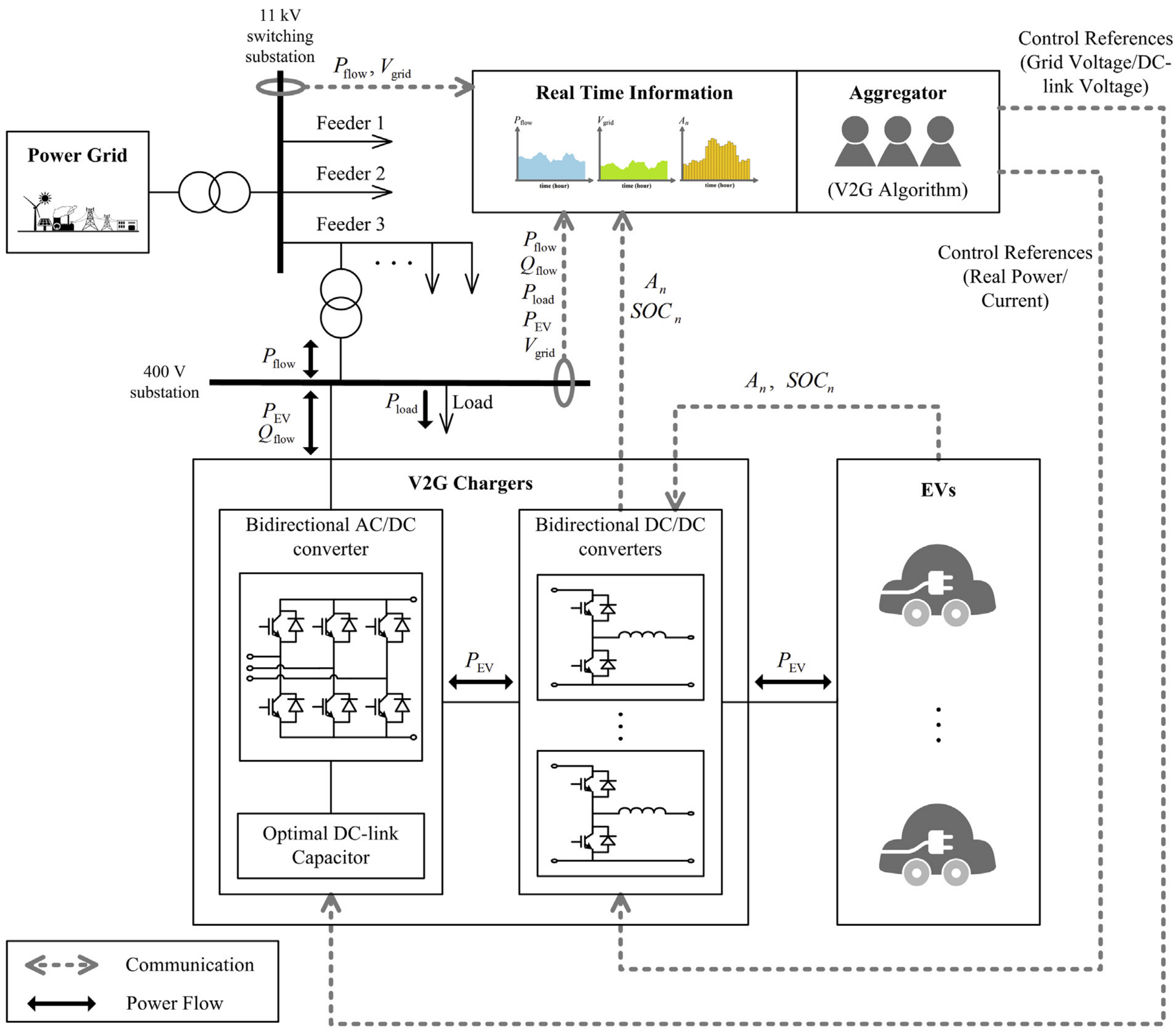

Fig. 12. Framework of the real time V2G application.

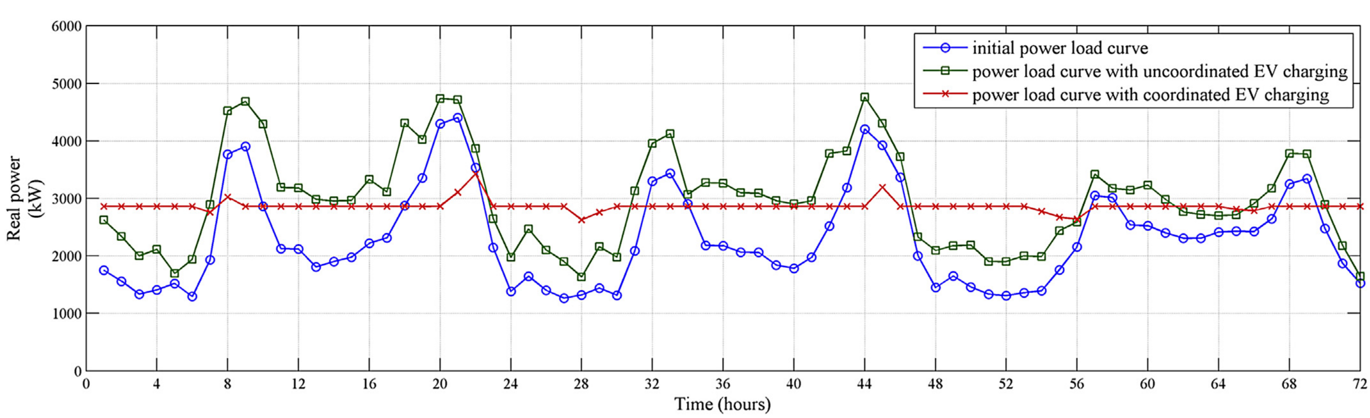

Fig. 13. Comparison of the initial and optimal power load curves at the 11 kV switching substation.

This study has assumed the active participation from EV owners, where this ideal situation is difficult to be realized in large scale V2G application. In addition, the effectiveness of the proposed V2G algorithm is also dependent on the location of implementation. The dynamic interaction of various factors such as EV availability, EV battery storage capacity, EV owner preference and power grid strength in the V2G system directly affect the V2G algorithm performance. In the future, renewable energy integration can be included to achieve a sustainable smart grid system.

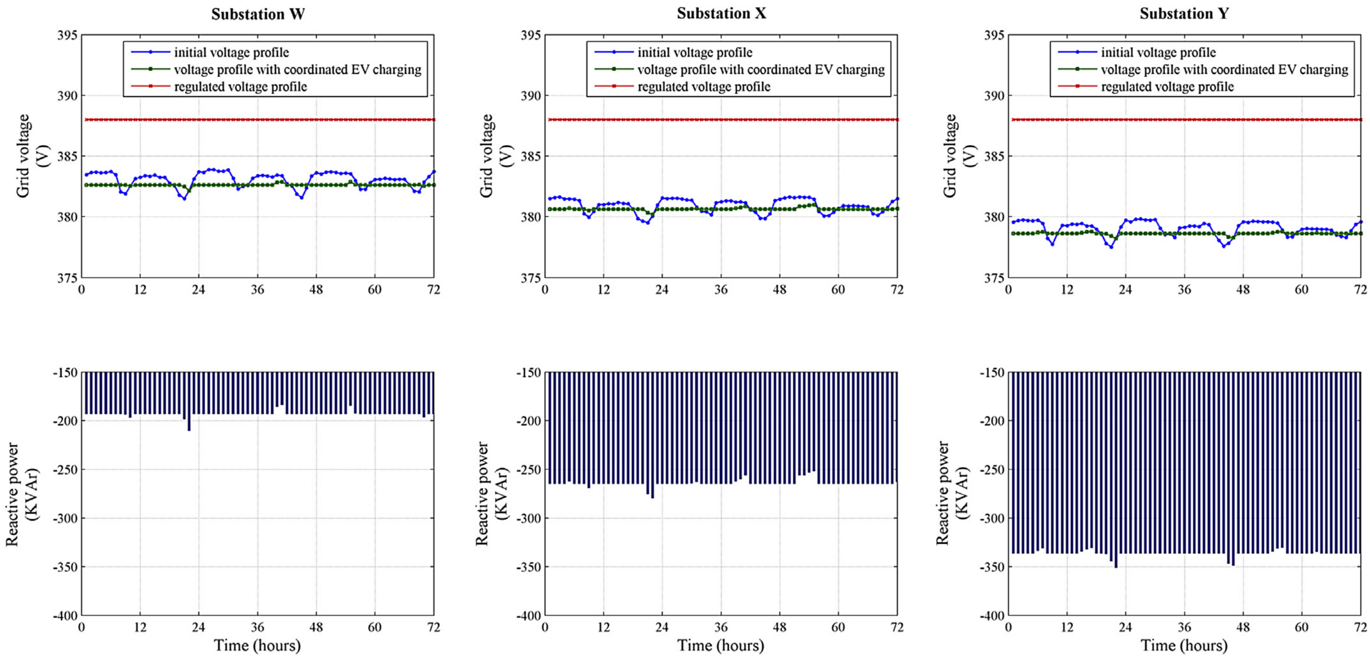

Fig. 14. Voltage profiles and the supplied reactive power by the V2G chargers at substations W, X and Y.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.energy.2016.07.008.

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