Electric Vehicle Charging Method for Smart Homes/Buildings with a Photovoltaic System

Young-Min Wi, Jong-Uk Lee, and Sung-Kwan Joo, *Member*, IEEE

Abstract —*Due to the increased penetration of electric vehicles (EVs) and photovoltaic (PV) systems, additional application for home/building energy management system (EMS) is needed to determine when and how much to charge an electric vehicle in an individual home/building. This paper presents a smart EV charging method for smart homes/buildings with a PV system. The paper consists of two parts: EV charging scheduling algorithm for smart homes/buildings and implementation of prototype application for home/building EMS. The proposed EV charging algorithm is designed to determine the optimal schedules of EV charging based on predicted PV output and electricity consumption. The implemented prototype application for home/building EMS can provide EV charging schedules according to user preferences. Numerical results are provided to demonstrate the effectiveness of the proposed smart EV charging method*[1].

Index Terms —Home Energy Management System, Building Energy Management System. Smart Electric Vehicle Charging, Photovoltaic System

I. Introduction

Increases in fuel prices and environmental concerns have led to alterations in the configuration of power systems. One of the significant changes is the increasing use of new energy resources such as renewable energy resources, electric vehicles (EVs), and high-capacity, high-power batteries in a power grid. Many experts have noted that these new energy resources can overcome fuel price and environment problems. If EVs can be deployed at low cost, they can be used to improve the energy efficiency and renewable energy penetration.

This perspective is from the power system operation and control. However, there is a lack of research on the operation of individual electric vehicle such as efficient determination of when and how much to charge an electric vehicle in an individual home/building. There are only a handful of papers on individual EV charging [1], [2]. Most of these studies focus on the EV charging scheduling problem without considering other electricity consumption and generation resources such as photovoltaic (PV) systems.

In a smart home/building environment, however, EV charging is likely to not to be independently controlled, but to be controlled by the central energy management systems [3]-[6] of individual homes/buildings for enhancing energy efficiency. In this case, EV charging is determined in accordance with any other electricity consumption requirements, generation resources, and real-time prices from a smart meter. Thus, smart EV charging requires an integrated operating management system considering all energy resources in individual homes/buildings.

This paper presents a cost-effective method for improving EVs charging efficiency in a smart home/building environment. Smart EV charging is one of critical technologies used for home energy management systems (HEMS) as well as in building energy management systems (BEMS). In this paper, a smart electric vehicle charging algorithm has been developed and implemented for smart homes/buildings with a PV system. The proposed algorithm can be divided into two stages: prediction and scheduling. In the prediction stage, the PV output and electricity consumption are forecasted using a time series model with weather sensitivity. In the scheduling stage, the EV charging schedule is determined based on the result of the first stage as well as EV and electricity price information. The EV charging scheduling is optimized subject to various constraints such as vehicle charge level and battery capacity, charging rate, and user preference.

On the basis of the proposed algorithm, a prototype EMS application for scheduling EV charging in smart homes/buildings with a PV system has been implemented in this research. The implemented application is composed of five modules: input data module, data gathering module, prediction module, optimization module, and reporting module. The proposed method for scheduling EV charging can be applied as part of HEMS or BEMS application.

This paper is extended from preliminary work [7]. The remainder of this paper is organized as follows. In Section II, the background and related work of the EMSs and EV are presented. In Section III, an integrated operating algorithm for smart EV charging in smart homes/buildings with a PV system is proposed, and in Section IV, implementation of the integrated scheduling program is addressed. Finally, in Section V, the numerical results are presented and analyzed to demonstrate the effectiveness of the proposed method.

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II. BACKGROUND

In this section, EMSs for smart homes/buildings and EVs are briefly described.

A. Energy Management Systems for Smart Home/Building

Globally, the interest in smart grids has been growing. One of the key features of smart grids is enhanced energy efficiency and manageability of available resources. In particular, EMSs can play an important role in monitoring and controlling home/building energy consumption [8].

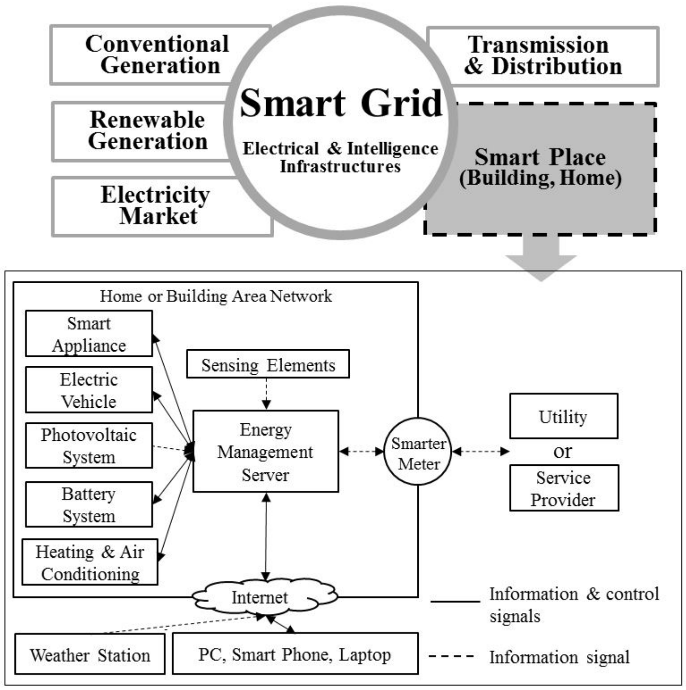

Fig. 1. Overview of energy management systems for smart homes/buildings.

Fig. 1 illustrates the schematic overview of EMSs for smart homes/buildings in a smart grid environment. The energy management server, as shown in Fig. 1, is designed to collect and analyze data from various appliances and devices. In addition, it transmits control signals to the appliances and devices for reducing energy costs.

The markets for smart HEMSs and BEMSs are expected to grow substantially over the rest of this decade. According to a recent report [9] from Pike Research, the number of HEMS users will grow to more than 40 million in 2020, and global spending on BEMSs is forecasted to reach $319 million by 2020.

B. Electric Vehicles

In recent years, EVs have received more attention because of the progressive exhaustion of fossil fuels and the enhanced awareness of environmental protection. In developing countries, particularly in China [10], a grand development plan with the objective of increasing EV ownership numbers (including hybrid EVs (HEVs), pure EVs, and fuel-cell EVs, etc.) to 5 million by 2020 has been brought forward.

According to the U.S. Energy Information Administration (U.S. EIA), an EV is defined as a motor vehicle fully or partially powered by an electric motor that draws current from rechargeable storage batteries, fuel cells, PV arrays, or other sources of electric current. There are three main types of EVs: Battery Electric Vehicles (BEVs), Plug-In Hybrid Electric Vehicles (PHEVs), and Hybrid electric Vehicles (HEVs).

A BEV is a type of EV that must be plugged into an electrical source to obtain energy for driving the vehicle. It uses electric motors only instead of an internal combustion engines. BEVs typically exhibit the following characteristics: operate solely on electric power and most likely to demand faster charging owing to potential use on longer trips. Therefore, BEVs have relatively larger battery capacity compared with the other two types of EVs.

A PHEV is hybrid vehicle that use rechargeable batteries, or some other energy storage device, that can be restored to full charge using an external electric power source. According to the Argonne National Laboratory, a PHEV operates on battery power derived from the vehicle‘s gasoline engine or by plugging into an electrical outlet or charging station. PHEVs require shorter recharge times owing to small battery size.

A HEV combines an internal combustion engine propulsion system with an electric propulsion system. HEVs cannot be recharged from the electric grid.

BEVs and PHEVs can be used by applying the algorithm proposed in this paper because their batteries can be charged using an external power source. According to a recent report [11] from Pike Research, annual worldwide EV sales will reach nearly 3.8 million by 2020, showing annual growth in each year of the study period.

III. SMART ELECTRIC VEHICLE CHARGING ALGORITHM FOR SMART HOMES/BUILDINGS WITH PV SYSTEM

In this section, the proposed smart EV charging algorithm is discussed. The block diagram of the two-stage smart EV charging algorithm is shown in Fig. 2, and a more detailed explanation is provided in the following subsections.

A. Prediction Model with Weather Adjustment for PV Output and Electricity Consumption

Predictions of PV output and electricity consumption are required for reducing electricity costs of smart homes/buildings with a PV system. The proposed algorithm is designed to use a time series model with weather adjustment for the predicting PV output and electricity consumption. The prediction procedure is as follows:

Step1. Data Selection: Historical data collected from the most recent qualifying days are selected. Unlike PV output, the electricity consumption typically varies by the day-type (i.e., weekend or weekday). For increasing the accuracy of the electricity demand forecast, historical electricity consumption data should be selected from relevant past data based on the day type of a predicted day [12].

Step2. Prediction: Using the data selected in Step 1, the PV output and electricity consumption are estimated using the following exponential smoothing model:

$$\hat{E}_d^{pre}(t) = \alpha \cdot E_{d-1}(t) + \alpha(1-\alpha) \cdot E_{d-2}(t) + \alpha(1-\alpha)^2 \cdot E_{d-3}(t) + (1-\alpha)^3 \cdot \hat{E}_{d-3}^{pre}(t) \quad (1)$$

where $\hat{E}_d^{pre}(t)$ is the pre-forecast value of the PV output or electricity consumption at time t on the $d-th$ day; $E_{n-1}(t)$ is the historical value of the PV output or electricity consumption at time t on the $(d-1)-th$ day; and α is an exponential smoothing coefficient.

Step3. Weather Adjustment: The pre-forecast value is adjusted using the weather sensitivity coefficient, which is calculated as the ratio of the forecast and actual value for the pre-scheduled period before the start of the scheduled period. The following weather adjustment with weather sensitivity is proposed for adjusting the pre-forecast value of the PV output or electricity consumption:

$$\hat{E}_d(t) = \hat{E}_d^{pre}(t) \cdot \{1 + w\}$$
$$w = \frac{(E_d(t-1) + E_d(t-2))}{\left(\hat{E}_d^{pre}(t-1) + \hat{E}_d^{pre}(t-2)\right)} \quad (2)$$

where $\hat{E}_d(t)$ is the adjusted forecast value for the PV output or electricity consumption at time t on $d-th$ day and w is the weather sensitivity coefficient.

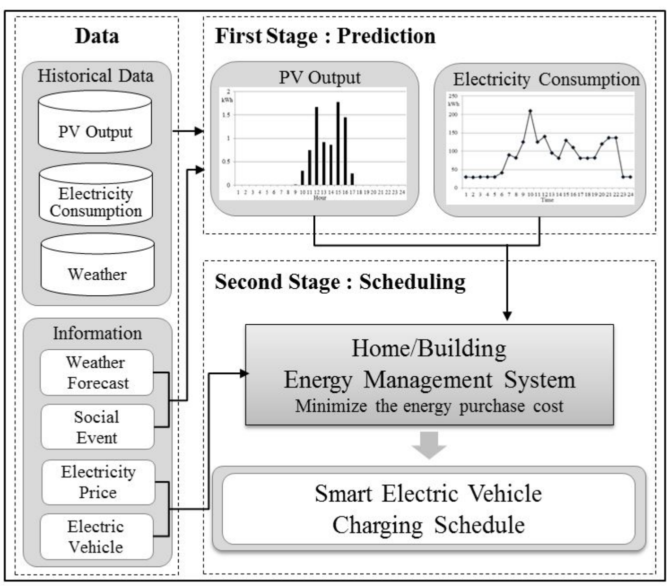

Fig. 2. Overview of proposed smart electric vehicle charging algorithm.

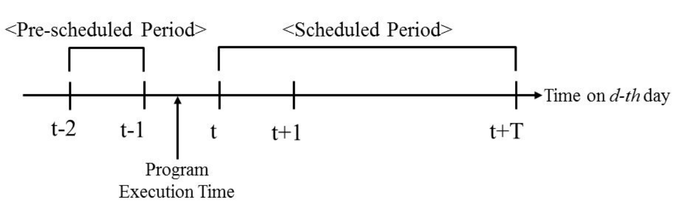

Fig. 3. Time line of proposed prediction algorithm.

The time line of the proposed prediction algorithm is illustrated in Fig. 3, where the total period is divided into two sub-periods: pre-scheduled period and scheduled period.

B. Optimization Model for Smart Electric Vehicle Charging

The objective of solving the electric vehicle charging scheduling problem is to determine the best charging time and amount of charge for each time step in order to minimize the electricity costs, while satisfying the constraints of the charging level and rate, battery capacity, and user convenience.

The objective function for smart EV charging problem is expressed as follows:

$$minimize\ C = \sum_{t=1}^{T} \{E_{grid}(t) \cdot P(t)\} \quad (3)$$

where C is electricity costs over the scheduled period; $E_{grid}(t)$ is the amount of electricity bought from the power grid at time t; $P(t)$ is the electricity price at time t; and T is the length of the charge scheduled period.

This optimization problem should be solved subject to the following constraints:

- Electric energy balance of smart home/building constraint

$$E_{grid}(t) + PV(t) = E_{load}(t) + EV(t) \quad (4)$$

where $PV(t)$ is the PV generation at time t; $E_{laod}(t)$ and $EV(t)$ are the electricity consumption and charging capacity of the EVs at time t, respectively.

-Battery capacity limits of each EV

$$SOC_i^{min} \le SOC_i(t) \le SOC_i^{max} \quad (5)$$

where $SOC_i(t)$ is the state of charge (SOC) of the $i-th$ EV at time t; SOC_i^{min} and SOC_i^{max} are the minimum and maximum SOC limits, respectively, of $i-th$ EV.

- Charging rate limits of the charger

$$CR_i^{min} \le CR_i(t) \le CR_i^{max} \quad (6)$$

where $CR_i(t)$ is the charging rate of the charger connected to the $i-th$ electric vehicle at time t; CR_i^{min} and CR_i^{max} are the minimum and maximum charging rates, respectively, of the charger connected to the $i-th$ EV.

- User preference: it represents that the constraints set by the user such as the set of target states-of-charge (SOC) and expected departure times of electric vehicles. The following equation is the target SOC constraint:

$$SOC_i(T) = SOC_i^{target} \quad (7)$$

where $SOC_i(T)$ is the SOC value after scheduling; SOC_i^{target} is the target SOC value of $i-th$ electric vehicle.

The formulated optimization problem is a mixed integer linear problem (MILP).

IV. IMPLEMENTATION OF SMART ELECTRIC VEHICLE CHARGING METHOD FOR SMART HOMES/BUILDINGS WITH PV SYSTEM

This section describes an implemented prototype EMS application for smart EV charging in smart homes/buildings with a PV system. The flowchart of the proposed smart electric vehicle charging algorithm is shown in Fig. 4.

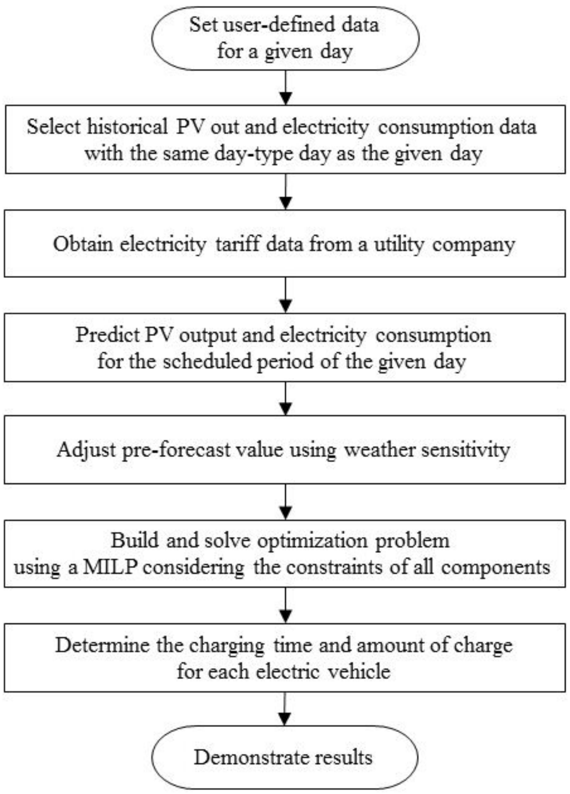

Fig. 4. Flowchart of proposed smart electric vehicle charging algorithm.

The proposed HEMS or BEMS application in this research is composed of five components: input data module, data gathering module, prediction module, optimization module, and reporting module.

- Input data module: This module is designed to obtain user-defined data such as electric vehicle information (initial SOC, target SOC and departure time), scheduled time duration, and day-type of scheduling day. All input data can be imported from files in a spreadsheet file.
- Data gathering module: This module involves selecting the electricity tariff, historical electricity consumption and PV output data that satisfy user-defined criteria.
- Prediction module: This module is designed to forecast the hourly electricity consumption and PV output over the scheduled duration using the exponential smoothing model with the weather adjustment.
- Optimization module: This module involves formulating an optimization problem for smart EV charging using MILP and determining smart EV charging schedule.
- Reporting module: In this module, all output data can be exported to a spreadsheet file.

Fig. 5 shows the module configuration of the implemented prototype EMS application for smart EV charging in smart homes/buildings with a PV system. Each module and its function are described in Fig. 5

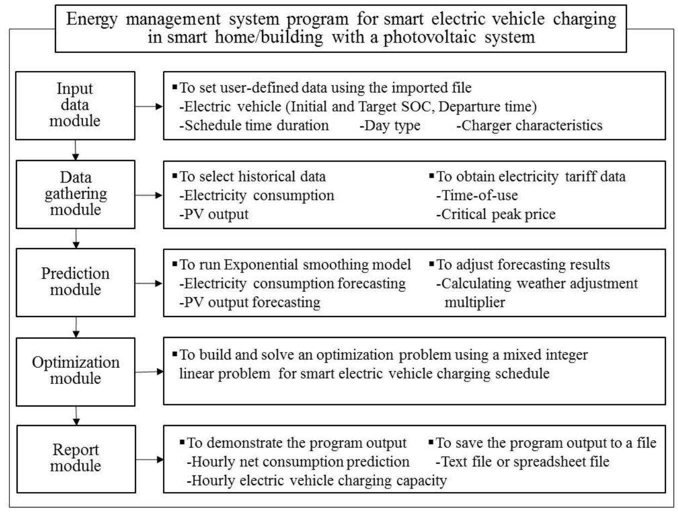

Fig. 5. Overview of proposed prototype EMS application for smart homes/buildings with PV system.

(a)

(b)

Fig. 6. User interface screenshots of the implemented prototype EMS application for smart homes/buildings with PV system.

The prototype EMS application based on the proposed method for scheduling EV charging in smart homes/buildings with a PV system was implemented. Fig. 6 shows user interface screenshots of the implemented prototype EMS application. Fig. 6 (a) shows the initial screen of the implemented application. User-defined data in spreadsheet format can be read. The imported data can be also identified and modified directly on the GUI. After data acquisition and setting EV charging conditions, the simulation can be performed by clicking the 'Solve' button.

Fig. 6 (b) shows the simulation results of the proposed method using a bar chart and a table. Simulation results can be saved as a spreadsheet file by selecting the ‘Save results’ button.

V. Numerical Results

In this section, the numerical results are presented. For smart EV charging scheduling, a commercial building with a 50-kW PV panel system was considered in this study.

For generating 50-kW PV data, data from the 3-kW PV panels installed in a school were used and converted. Fig. 7 shows the PV systems installed on the roof of the school building. In addition, for determining the electricity consumption of a commercial building, commercial building data were obtained from a utility company in Korea.

In this case study, 12 electric cars were used. The EVs were divided into three groups depending on their initial SOC. Table 1 summarizes the details of the electric cars used in this case study. The EVs used here were identical except for the initial SOC. The maximum and minimum charging rates of the EV charger used in the case study are 1 kW and 7.7 kW, respectively.

In this case study, electricity rates were assumed to be based on the time-of-use (TOU) tariff from a utility company. There are two periods under the TOU tariff: on-peak and off- peak. The former period is 11 am to 4:00 pm. The latter period is 9:00 am to 11:00 am and 5:00 pm and 7:00 pm. Electricity price rates for on-peak and off- peak periods are 7.77 ¢/kWh and 21.71 ¢/kWh. Selling electricity to the grid is not considered in this case studies.

Fig. 7. PV systems installed on the roof of the school building.

TABLE I
Electric Vehicle Information

Group No.	#	Arrival Time	Departure Time	Initial SOC	Target SOC	Battery Capacity
1	4	08:00	19:00	20%	80%	24kWh
2	4	08:00	19:00	30%	80%	24kWh
3	4	08:00	19:00	40%	80%	24kWh

is the number of EVs in a group.

The test day is set as a summer weekday. Summer weather is hot and humid in Korea. During this period, the electricity consumption for cooling purposes increases. Therefore, electricity consumption of commercial buildings is high during the daytime period.

The hourly PV output and electricity consumption on the test day can be predicted using the proposed prediction algorithm. Fig. 8 shows the net hourly consumption over the scheduled period on the test day. The net consumption is defined as the sum of hourly prediction results of PV output and electricity consumption on the test day. One hour data represents the average value for one hour in this study.

Fig. 9 shows the change in SOC of an electric vehicle during the scheduled period using the proposed method. The EVs are charged during the off-peak period, and each of the EV meets its target (user-defined) SOC at the end of the period. The EVs are not charged during the peak period owing to the relatively higher electricity price rate. Table II presents a comparison of electricity costs between the baseline and proposed methods. The baseline is composed of two cases. Baseline #1 is to charge electric vehicles as soon as EVs are parked in the parking lot of the commercial building and baseline #2 is to charge EVs after lunchtime. The proposed method achieves cost savings of 6% and 15.2% over Baseline case #1 and #2, respectively.

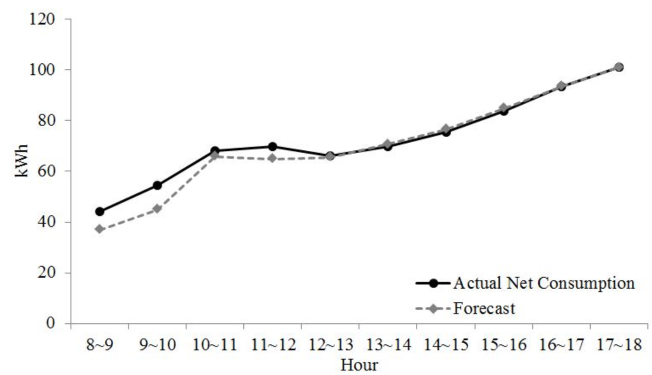

Fig. 8. Results of net consumption forecast.

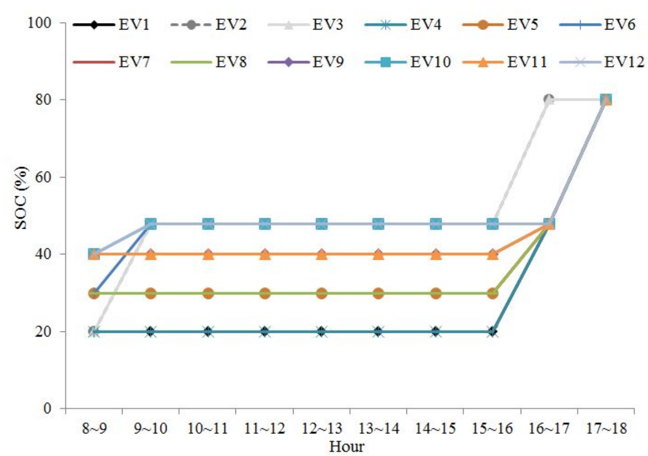

Fig. 9. Change in SOC of electric vehicle during scheduled period.

TABLE III
Comparison of Electricity Costs Between Baseline and the Proposed Method

Method	Electricity Purchase Costs
Baseline #1	$119.49
Baseline #2	$132.37
The proposed method	$112.30

From these results, it can be seen that the proposed method is effective in order to minimize the overall charging costs while attaining the target SOC.

VI. Conclusion and Future Work

The EMS application is required to determine optimal EV charging scheduling for smart homes/buildings with a PV system. In this paper, a cost-effective EV charging method is proposed and implemented for smart homes/buildings with a PV system. The proposed smart EV charging algorithm for smart homes/buildings consists of two stages: prediction of PV output and electricity consumption, and EV charging scheduling. Numerical results are presented to demonstrate the effectiveness of the proposed method.

Further work is required for considering the effects of PV output and electricity consumption forecast errors, and vehicle-to-grid on the performance of the proposed method.

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