Charging of Electric Vehicle with Constant Price Using Photovoltaic Based Grid-connected System

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***Abstract*—The charging of plug-in electric vehicle (PEV) imposes an additional burden on the utility grid, particularly during the (day) peak hours. This burden is normally controlled by shifting PEV charging to the grid off-peak hours. This shifting not only reduces the autonomy of anytime charging but also creates the uncertainty about the charging price every hour. To mitigate this problem, this paper proposes an energy management scheme (EMS) for the charging station that combines the photovoltaic (PV) and energy storage unit (ESU) with the grid. The models for PV power, ESU, PEV demand and grid electricity price are developed as the components of EMS. The scheme is capable of providing interruption-less charging during day-time. Moreover, the EMS has the capability to charge PEV with constant per unit price at and below the level of solar grid parity. The additional feature of EMS is that it can fulfill charging demand of each PEV within one hour at a lower price than standard grid (SG) charging while reducing the extra burden on the grid. The idea to reduce the economic loss of charging station due to cheaper and constant price charging is the involvement of valley-filling operation by both ESU and PEV along with selling the surplus PV energy to the grid. The EMS algorithm comprises of rule-based strategies. To determine the effectiveness of the scheme, numerous charging scenarios are simulated using Matlab. The initial results indicate that the charging through proposed scheme is much cheaper than the charging by conventional SG scheme. Moreover, it has shown to reduce the considerable amount of EV charging burden from the grid. It is envisaged that this is the first effort to propose constant price PEV charging and it will provide an exciting prospect in the field of PEV charging using renewable energy sources.**

Keywords—electric vehicle; energy management scheme; heuristic rule-based; photovoltaic; charging station

I. INTRODUCTION

The growth in technology and increased public interest has brought about a rapid evolution in the realm of e-mobility. While generally viewed as non-polluting and environmentally friendly, the Electrical Vehicles (EVs) could still contribute significantly towards indirect emissions, depending on the source of their energy. The only way they can be made truly emission free is if they are charged from renewable energy sources. Therefore, the EV charging station with PV array as the main component is selected in this study. However, due to the volatility of the solar irradiance, the power available for charging is unpredictable. Besides, there is a need to ensure that the EV is charged continuously without adversely affecting the distribution network. Therefore, it is proposed that an energy storage unit (ESU) be incorporated into the grid. However, with the addition of these two new sources i.e. PV array and ESU, in the presence of grid power with the dynamic electricity price (GE_Pr) the complexity of the charging system increases significantly. This is where an optimized energy management comes into the picture. In order to optimize the real-time power flow between source and load sides during the operation of the charging station, an appropriate charging scheme is required. Broadly, the EV charging schemes available in literature can be divided into three main groups; aggregator based schemes (ABS) [1], distribution system operator based schemes (DBS) [2] and system-based schemes (SBS) [3]. The ABS mainly focuses on the interest of charging station owner as well as EV users, regardless of the electric network constraints [4]. In the case of DBS, the constraints of distribution network are handled at first priority. However, in the SBS the concerns of both distribution system operator as well as charging station owner are considered through compromises among the interests of the stakeholders. The latter two groups of schemes do not give the guaranty about the interests of the EV user to be fulfilled completely. Therefore, to keep the interests of EV users at top priority, the ABS is selected in this study. However, in order to provide the guaranteed low price charging in case of ABS, most of the authors shift the charging to the off-peak hours of the grid [5], which reduces the autonomy of charging the EV any time. The charging of the battery when the grid is at the off-peak condition or in other words when GE_Pr are low is called valley-filling (VF) operation. Moreover, in some cases [6], the EVs are forced to participate in V2G or V2V operations to get cheaper charging which reduces the EV battery life. Additionally, the EV charging process in the presence of VF and V2G or V2V operations creates the uncertainties for EV users about charging rates every hour. To overcome these deficiencies while reducing the EV charging burden on the utility grid, an energy management scheme (EMS) is developed with the help of heuristic rule-based strategies. The EMS will ensure the lossless operation of charging system at par and below grid parity while providing uninterrupted and constant price EV charging during office hours. The EMS works on charging while parking rather than park for charging [7]. The

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EMS is well suited for the charging stations which contains PV array and ESU having a connection from the utility grid.

II. CHARGING STATION ARCHITECTURE

A one-line diagram of the charging system under study is shown in Fig. 1 [1]. The developed smart charging station is located in a workplace, possibly a university campus, which contains 15 parking spaces. It consists of a grid-connected charging park involving a PV system with a total capacity of 140 kW, whose maximum power point is continuously tracked and integrated into the dc-bus. The energy storage unit in the system has a maximum capacity of 97 kWh. Hence, the charging park appears as a dc microgrid with local generation from the PV system and a storage system. The rated capacity of PV array and ESU are taken according to [1]. However, these can be optimized through system sizing using any of optimization algorithm like PSO. The charging station is connected to the main grid through a bi-directional converter. The bi-directional converter is a fully controlled inverter that has the capability of controlling the amount of power flowing between the ac and dc grid in both directions. Hence, the amount of power flowing in either direction is possible, which is decided by the developed EMS. The central controller will implement the EMS depending upon proposed heuristic rule-based strategies.

III. MODELING OF SYSTEM COMPONENTS

The various models related to different parts of charging station such as PV power, ESU, EV demand and GE price have been developed. The developed models will be used for the decision-making process by the EMS.

A. Modeling of PV Power

In proposed charging scheme, the PV array is considered the main source of power. Therefore, to simulate the charging scheme, it is important to know the amount of real-time power output available from the PV array. This quantity is defined as the PV_Pwr. The PV_Pwr modeling is done using the single diode model of PV cells. For this purpose, the diode model uses the PV module parameters at STC as well as operating parameters like solar irradiance (G) and the module temperature (T). The operating parameters are extracted from meteorological data of California taken from official website of the National Renewable Energy Laboratory (NREL) [8]. Using G and T, the output open circuit voltage for PV module can be calculated as.

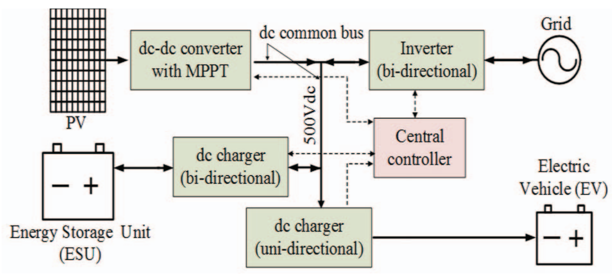

Fig. 1. The structure of PV-EV charging station

$$V_{OC} = V_{OC\_STC} + aT\log\left(\frac{G}{G_{STC}}\right) + k_v\left(T - T_{STC}\right) \tag{1}$$

Where, V_{OC_STC} is reference open circuit voltage at STC given by the manufacturer and k_v is temperature coefficient of voltage normally given by the manufacturer. a is the ideality factor with a typical value between $1 \le a \le 2$. It is to be noting that the output voltage of PV module V_{PV} is equal to that value of V_{OC} at which maximum power is extracted from the module.

The output current of one module using single diode model considering both series and parallel resistors can be found in equation (2). As this is a transcendental equation, so the Newton-Raphson iteration method is used to solve this equation.

$$I_{PV} = I_{Ph} - I_0\left[e^{\left(\frac{V_{PV}+I_{PV}R_S}{V_T}\right)} - 1\right] - \left(\frac{V_{PV}+I_{PV}R_S}{R_P}\right) \tag{2}$$

$V_T = akT/q$ is known as the thermal voltage, R_S and R_P are series and shunt resistances of solar cell respectively.

The value of PV power at any value of G and T is then calculated as.

$$P_{PV} = V_{PV} \times I_{PV} \tag{3}$$

B. Modeling of Energy Storage Unit

The ESU in this work will not only serve as a backup in case of insufficient power from PV array but will make the charging system less reliant on the grid as compared to an SG charging system. The ESU in this work consists of Li-ion battery pack due to high energy as well as power density capabilities which make it more suitable as an energy storage unit for the fast charging systems [9, 10].

To avoid the overcharging and over-discharging of ESU, the upper and lower SOC are set as 90% and 10% respectively and can be shown by equation (4) [11]. The ESU installed on the system will supply the EV charging demand as long as its SOC is above or equal to the lower limit (SOCL) of 10%. On the other hand, the ESU is charged by surplus PV power or grid power till the SOC reaches back to the upper limit (SOCU) of 90%.

$$SOCL \le SOC \le SOCU \tag{4}$$

Where, SOC is state of charge of energy storage unit, SOCL is the lowest limit of battery SOC, SOCU is the upper limit of battery SOC. In this research, the SOC is assigned a random value between SOCL and SOCU using the equation (5) at the start of charging process. However, after that, the SOC is updated according to the scenarios of charging operation.

$$SOC = SOCL + \left(SOCU - SOCL\right) \times rand \tag{5}$$

where rand is random generator function of Matlab.

The SOC of ESU at any time will provide the estimation of energy available with the storage unit (Avl_ESU_Pwr). If SOC is more than SOCL, the ESU can provide the power (ESU_Pwr) to charge the EV. The maximum power that ESU can provide in one hour is equivalent to the difference of current SOC and SOCL given in equation (6).

$$ESU\_Pwr = (SOC - SOCL) \times C_{bat} \tag{6}$$

where, C_{bat} is rated capacity of ESU in kWh.

C. Modeling of EV Power Demand

To check the performance of the proposed EMS for fulfilling the random EV power demand, it is important to develop the EV power demand model which can generate random demand rather than constant.

For the development of the model, it is assumed that at the departure time, the SOC of the EV batteries should be 80% of its full capacity. Moreover, in order to avoid serious damage, the batteries of the EVs should not be over-discharged. Therefore, the EV should stop using electric energy when the SOC of its battery reaches 10% of rated battery capacity. Hence, for the safety of the battery, the electric energy of an EV that can be used before its next charge is 70% of the total battery capacity. In other words, the maximum demand of individual EV is the 70% of its rated battery capacity. The calculation of EV power demand is described in equation (7) which is the governing equation to calculate the random EV power demand [12].

$$P_{EV,\mathrm{i}} = P_{EV,\mathrm{req}} \times S_i \times w_i \times c_i \tag{7}$$

where $P_{EV,\mathrm{i}}$ is power demand by EV in time slot i (kW)

$P_{EV,\mathrm{req}}$ is maximum required power (kW) by EV at the time of plug-in which is equivalent to the difference of maximum required SOC (SOC_{max}=80%) and present SOC_0. The SOC at the time of plug-in (SOC_0) is given in equation (8). S_i is EV connectivity status in time slot i which is 0 if EV is not physically connected to the charging point and 1 if EV is connected and this is used to check non-working days including both weekends and public holidays. w_i is EV charging status in time slot i, which depends on the battery SOC as shown in equation (10) and is set to 0 if EV is not being charged and 1 if EV is being charged. c_i is a control signal for EV in time slot i which is 1 for working hours (09:00 to 18:00) and 0 otherwise.

$$SOC_0 = 1 - E_{dr} / C_{bat} \tag{8}$$

Where SOC_0 is battery SOC when EV is plugged in, E_{dr} is energy used by driving (kWh) given in equation (9), C_{batt} is rated battery capacity (kWh)

$$E_{dr} = d_t \times E_{mil} \tag{9}$$

where, d_t is the distance traveled since the last charge to the current charge; taken a random value between 1 mile to maximum EV electric range to generate random demand, E_{mil} is energy consumption (kWh/mile)

$$w_i = \begin{cases} 0, & SOC_0 \geq SOC_{\max} \\ 1, & SOC_0 < SOC_{\max} \end{cases} \tag{10}$$

where SOC is the instantaneous value of the state of charge of the EV. The required EV power $P_{EV,\mathrm{req}}$ can be found as

$$P_{EV,\mathrm{req}} = (SOC_{\max} - SOC_0) \times C_{bat} \tag{11}$$

where SOCU is the maximum SOC required by each EV

D. Modeling of grid electricity price

The proposed EMS is applicable of charging EV at a constant price for the scenario when the solar grid parity is reached. However, the grid electricity prices at par and below parity are not available through any reliable source. Therefore, hypothetical values of grid electricity price (GE_Pr) are used. For this purpose, the GE_Pr profile similar to US states with the average hot season is selected as a sample. This sample price is then converted to the hypothetical value that meets the criteria of parity. Hence to convert the instantaneous price so that it reflect the parity level, it is multiplied by a constant factor. This constant factor is named as a parity factor multiplier (PFM) which is derived in the equation (12).

$$PFM = \frac{LCOE\ of\ PV}{Average\,GE\ price} \tag{12}$$

where, *Average GE price* is the average of the GE_Pr which is to be converted to parity level (PL). This average is based on the time period (in hours) of the price data under consideration. For example, if the price of 24 hours is to be converted to the level of parity, the sum of hourly prices will be divided by 24 to get *Average GE price*.

When instantaneous values of grid electricity prices are multiplied by PFM as given in equation (13), the average of the new GE_Pr comes out to be equal to the levalized cost of electricity (LCOE) of PV array, hence fulfills the criteria of the parity level (PL).

$$GE\_Pr = elctricity\ price \times PFM \tag{13}$$

Moreover, to manipulate the condition of the below parity, the normal grid electricity price will be multiplied by 1.1PFM, 1.2PFM, 1.3PFM and so on depending upon the desired new level of below parity.

IV. The Proposed Energy Management Scheme

In this work, an energy management scheme has been developed, using rule-based strategies, for the operation of charging station. Rule-based strategies normally consist of IF-THEN statements which are based on human engineering knowledge, heuristic, intuition, even mathematical model and pre-defined driving cycles [13]. Moreover, the rule-based methods tackle the problem by dispatching resources solely based on pre-defined rules, where real-time decisions are directly made without employing optimization techniques. The rule-based strategies save the time and the cost of computation and storage resources [14]. In this work, the rule-based strategies consist of six operating modes, applied under four main scenarios. Here the IF statements are linked to different scenarios of PV_Pwr and EV_Dmd and THEN part is linked to a particular operation of the charging station with the help of operating modes.

A. Operating Modes

The operating modes control the direction of power flow in the charging station according to the pre-defined rules. In this work, the six operating modes are proposed which are summarized as:

Mode 1: PV to EV: If the PV power (PV_Pwr) is sufficient to fulfill the demand of PEV (EV_Dmd), then the charging is entirely done by the PV via the dc/dc fast charger.

Mode 2: ESU to EV: When PV_Pwr is zero and Avl_ESU_Pwr is more than EV_Dmd, the charging of PEV will be done by the ESU.

Mode 3: Gd to EV: When both PV and ESU are unable to supply power to EV the EV will be charged from the grid. This is to make sure the uninterrupted charging of EV. If this mode operates during grid off-peak or low grid electricity price (GE_Pr) conditions, it is called valley-filling (VF). In this research, the grid off-peak conditions are considered when GE_Pr is less than LCOE of ESU which is always less than average GE_Pr for the levels of parity and below.

Mode 4: PV to ESU: If EV is not available and the generated PV_Pwr is less than or equal to required ESU power (Req_ESU_Pwr), then ESU is charged from PV_pwr.

Mode 5: PV to Gd: When the surplus PV_Pwr is available and more than the sum of Req_ESU_Pwr and EV_Dmd, it will be sold to the grid. This mode plays the main role in compensating the economic loss of charging station which is caused due to constant and cheaper price PEV charging.

Mode 6: Gd to ESU: When GE_Pr is less than LCOE of ESU and SOC of ESU is less than SOCU, then ESU will be charged from the grid. This is called VF operation which compensates the economic loss of charging station.

B. Charging Scenarios

The charging scenarios decide the particular operation of charging station through various operating modes depending upon PV power and EV demand. The operation of charging station has been divided into following four scenarios. Under all scenarios, the charging price (Chrg_Pr) is kept constant; one cents less than LCOE of PV.

Scenario 1: Idle load: In this condition, PV_Pwr is not available and the EV_Dmd is also zero. The ESU will be charged from the grid using valley-filling (VF) concept (mode 6). This scenario is dedicated for VF operation by ESU.

Scenario 2: No load: In this condition, PV_Pwr is available but EV_Dmd is zero. The whole PV_Pwr is utilized in two places; first to charge ESU (Mode 4); second, if ESU reached max SOC, energy is fed to the grid (Mode 5).

Scenario 3: Overload: In this case, the EV_Dmd is greater than the PV_Pwr. The priority is to use PV_Pwr to charge EV (Mode 1). However, if PV_Pwr alone cannot satisfy the EV_Dmd, the remaining requirement is fulfilled by ESU (Mode 2). If the latter is not able to fulfill the demand, the power is taken from the grid (Mode 3) to make sure uninterrupted charging.

Scenario 4: Under load: The EV is present but the EV_Dmd is less than PV_Pwr. Surplus PV_Pwr can be fed to ESU (Mode 4) to raise its SOC. If ESU is full, energy is sold to the grid (Mode 5) to compensate the economic loss of the charging station.

V. RESULTS AND DISCUSSIONS

The proposed real-time EMS is tested on a system whose parameters are given in Table I. Moreover, the specifications of EVs used in the case study are given in Table II.

TABLE I. THE PARAMETERS USED IN SIMULATION

Parameter	Value
Grid Electricity price	Hypothetical price at and below grid parity (¢/kWh)
LCOE of PV	16.7 cents/kWh
LCOE of ESU (Li-ion)	15 cents/kWh
PV power	140 kW
Location of solar data	US state California
ESU rating	97 kWh
No. of vehicles	150 per day OR 15 per hour

The EV charging is done through fast dc charger: 500 Vdc/80 A (40kW). The maximum charging time is set equal to one hour [1]. The operation of the charging station is controlled through six operating modes and four scenarios. The power profiles among the various components of the charging station are shown in Figs. 2 and 3. Fig. 2 shows the EV charging results with EMS for the typical office working day (03/01/2013). The results clearly show that the charging price is constant and less than Avg_GE_Pr during the whole daytime. Moreover, the EV_Dmd is being fulfilled without any interruption or any condition of participation in V2G or V2V operations. Because the charging operation is in the winter season and PV_Pwr is normally small in the early morning and cannot meet the EV_Dmd alone, which shows the scenario of the overload condition.

TABLE II. THE EVS USED IN SIMULATION

EV Type	Max. Share (%)	Energy consumption (kWh/mile)	Battery Capacity (kWh)	Range (miles)
Chevy Volt (PHEV)	32.5	0.44	16	38
Nissan Leaf (BEV)	37.5	0.28	24	84
Mitsubishi i-MiEV (BEV)	20	0.16	16	96
BMW i3 (BEV)	10	0.27	22	81

In this situation, the ESU will help the PV to charge the EV. This situation is handled by individual operating mode i.e. mode 2 (ESU2EV) around hour 9. It is clear from the results that energy of ESU is used first instead of grid power because the GE_Pr is higher than ESU_Pr (15 cents). From hour 10 to 17 the PV is generating surplus power. This PV_Pwr is providing not only the EV_Dmd fully but also but also feeding the surplus to the ESU and the grid using mode 1, 2 and 5 respectively.

During the evening time, around hour 18, when PV_Pwr is less than EV_Dmd, again mode 2 (ESU2EV) helps the charging station to fulfill the EV_Dmd completely without charging interruption. During this process, the SOC of ESU becomes less than SOCU. In order to attain the Req_ESU_Pwr, the valley-filling operation using mode 6 (Gd2ESU) is activated during night time around hour 23. This happens when GE_Pr becomes less than LCOE of ESU.

Fig. 3 shows the charging results for the same typical day but 1.2 times below the parity level. In this case, the power flow pattern is a little bit changed from the one observed in Fig. 2. In this case, the VF operation is not executed. This is due to the change of parity level. By decreasing the level of parity (i.e. increasing GE_Pr) the VF operation can be delayed or suspended depending upon the value of the GE_Pr at a below parity level. If the GE_Pr at below parity is not so small and becomes equal or more than ESU_Pr, the VF operation will be suspended. But, if it is small enough and remains less than ESU_Pr even at below the parity level, the VF operation will be carried out but with a small delay. However, the selling of surplus PV_Pwr to grid at the high price compared to the case of parity increases the profit of charging station with a big amount.

Table III shows the numerical results of per day average charging cost using conventional standard grid (SG) as well as proposed EMS through PV-grid system. The results show

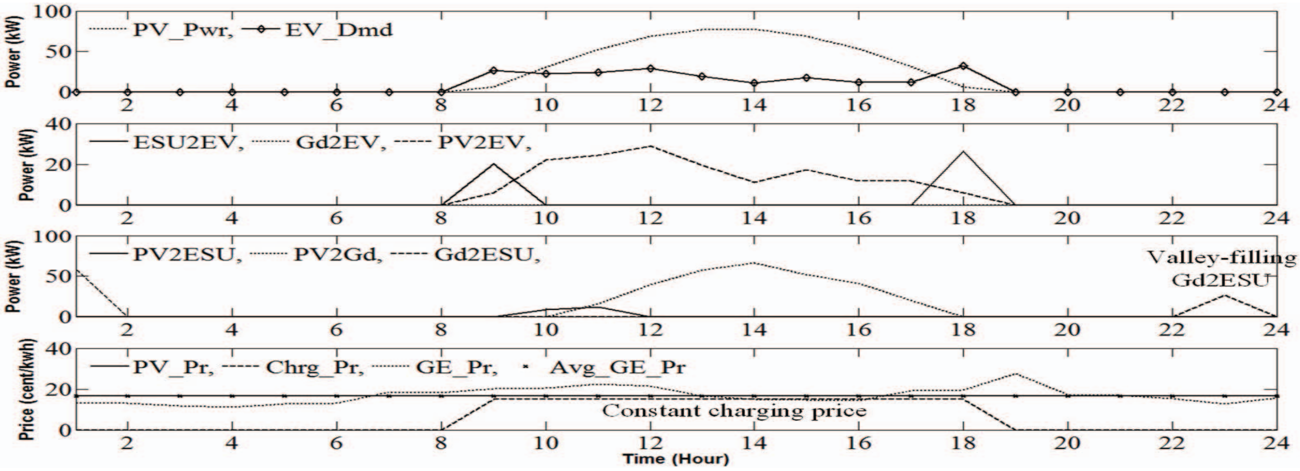

Fig. 2. Results of EMS at parity level for a typical day

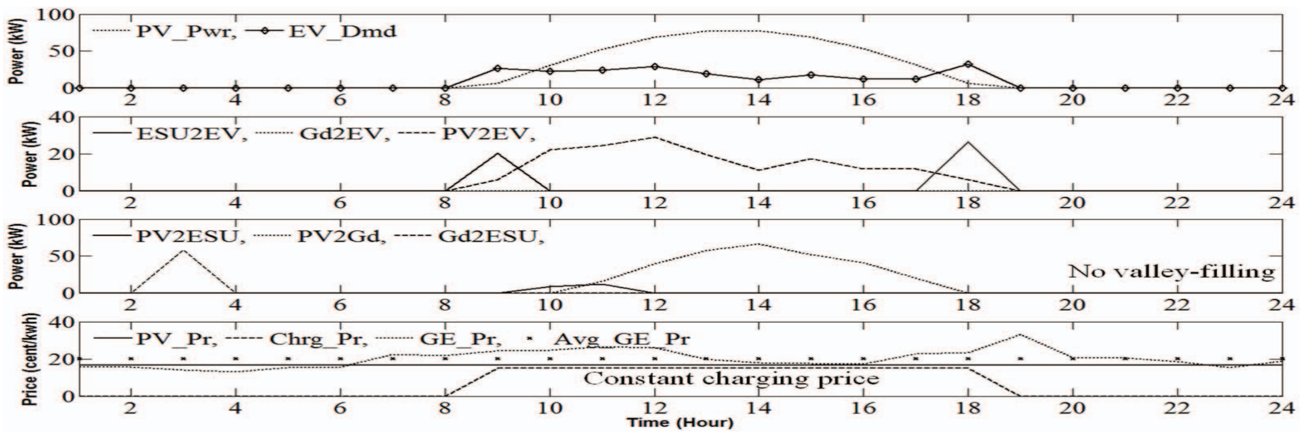

Fig. 3. Results of EMS at below parity (0.8PL) for a typical day

that EMS provides much cheaper charging price compared to SG charging. Moreover, unlike SG charging, the EMS charge EVs at a constant price as shown in previous results.

The results in Table III shows that the charging price by SG charging is high at below parity (0.8PL) as compared to the PL. This is because the grid electricity price (GE_Pr) has increased at below parity. It means the proposed EMS becomes more viable as the parity level decreases compared to SG charging in terms of small EV charging price.

TABLE III. COMPARING CHARGING PRICE BY SG AND EMS

Test scenarios	**Per day average charging price (USD)**		**Decrease in charging price using EMS (%)**
	SG charging	*EMS charging*	
PL	41.86	33.61	19.71
0.8PL	50.23	33.61	33.09

Table IV summarizes the maximum burden on the grid due to EV charging under different cases in the presence of SG and EMS. It is obvious that burden on the grid due to EV charging has been reduced significantly while applying EMS instead of SG scheme. Moreover, the amount of reduction in grid burden due to EMS is similar in the case of PL as well as below (1.2 times) the parity. It could vary by further increasing the GE_Pr. This is due to the reason that at half of PL, the GE_Pr is much higher and the VF by EV would occur less frequently.

TABLE IV. COMPARING EV LOAD ON GRID BY SG AND EMS

Test scenarios	**Maximum EV charging load on grid (kW)**		**Decrease in EV load on grid using EMS (%)**
	SG charging	*EMS charging*	
PL	68.70	46.60	32.16
0.8PL	68.70	46.60	32.16

VI. CONCLUSION

This paper presents a day-time charging scheme for PEVs using the PV-grid based charging station. The charging station provides uninterrupted and constant price charging with the help of EMS which comprises of rule-based strategies. The constant price charging, especially during daytime when electricity prices are quite fluctuating and high, is the special feature of proposed scheme. The scheme has been tested on the typical system at and below parity conditions. The initial results show that the charging of PEV using the PV-grid system in the presence of proposed scheme is more economical as compared to the conventional SG charging. Furthermore, the proposed EMS helps the charging station to reduce PEV charging burden on the utility grid. It is envisaged that this work will provide an exciting prospect to the researchers in the field of PV-EV charging.

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