Performance Analysis of Photovoltaic-Grid Connected System for Electric Vehicle Charging

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1   Introduction

The transportation sector has seen substantial growth in recent years owing to ever increasing population and improving economic conditions. This has led to increased use of internal combustion engines (ICE) vehicles. The ICE vehicles depend on fossil fuels for their operation that adds up to global air pollution substantially. The increasing air pollution and greenhouse effect, caused by the release of CO_2 from the ICE vehicles as well as limited availability of fossil fuels in the future, has necessitated shifting to an alternate clean approach. Electric Vehicles (EVs) being a clean source of transportation are an effective alternative. With features like immediate torque, silent ride and premium performance along with lower fuel and maintenance costs, the acceptance of EVs is on the rise. According to a report, the market share of electric vehicles will increase from 1% in 2015 to 9% in 2025 [1]. As per another forecast, EV market share will rise from 1.1 million worldwide in 2017 to 11 million worldwide by 2025 surging to 20 million by 2030 [2]. Although EVs provide us with a lot of benefits over the ICE vehicles, there are still some economical and technical issues like the stability of the power grid with regard to the usage of high-power chargers, battery management, such as thermal ratings, safety and cell balancing, which need to be addressed. Operating the power plants at their maximum generation range raises many issues regarding their capabilities especially the aging factor and increase in pollution levels by operating coal-fired plants for longer hours. Another issue of charging time for the battery of EVs is a primary concern, as the vehicle needs to absorb power from the grid [3]. The various types of charging
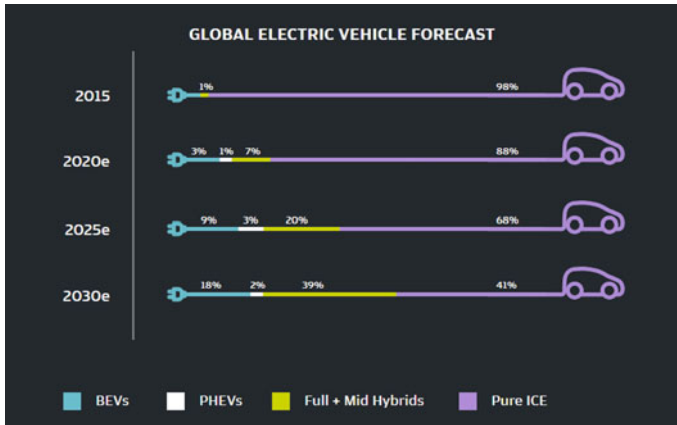
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Fig. 1 Percentage penetration forecast of electric vehicles

methods have been compared in [4] to select the most efficient charging method. Ali et al. have modelled hybrid energy storage system using EV batteries and super capacitors for enhancing lifetime of the EV batteries and compared the performance for different optimization strategies [5]. A conceptual architecture and an assessment framework were proposed to explore integration scenarios of EVs and renewable energy generation in distribution networks [6]. The combination of PV energy and EVs in uncontrolled charging and smart charging strategies has been studied [7], as was a two-stage framework for the economic operation of an EV parking deck with renewable energy generation [8]. Most of the researches on charging of EVs and renewable energy generation have focused on design, operation and optimal charging strategies [9–13] (Fig. 1).

The issue of electric vehicle charging and power supply from grid and renewable energy sources is a topic of research worldwide. The integration of PV with the EV charging system has been on the rise due to rapid growth of EVs and concern over the effects of greenhouse gasses. An overview of different charging approaches of EVs is discussed and a PV-grid charging method incorporating a battery management system is elaborated by Bhatti et al. [14, 15]. Khan et al. [16] have presented the charging technologies of EVs, their sustainable development and characteristics. They also forecast the current status, economic assessment, power market operation and control and safety aspects of charging EV system. An electric vehicle charging system incorporating energy storage system (ESS) for power quality improvement and providing fast charging is discussed [17, 18]. A Battery Energy Storage Station (BESS)-based hybrid power station to tackle the disadvantageous unstable power output from PV and wind power generations is elaborated and SOC-based control strategy has been adopted for smoothing the output fluctuation [19]. Mortaz and Valenzuela have modeled a micro grid consisting of renewable energy resources connected within a grid and using EV batteries in the parking facility for energy storage [20]. A rule-based energy management system to provide uninterrupted

constant price charging is proposed. The model incorporates a PV-grid system along with an energy storage unit. A daytime charging system using a PV, an ESU unit and a micro grid with the help of heuristic rule-based strategies is proposed [21, 22]. The model has helped to reduce burden on the micro grid as well as provided efficient cost saving.

A PV-grid system for EV charging using particle swarm optimization PSO algorithm to find optimum size of PV modules and ESU's need has been modeled [23]. The proposed system allows charging EVs at a fixed energy rate without facing economic losses. However, not much has been discussed about the power quality issues related to electric vehicle charging on a PV-Grid system.

In an electric power system, a harmonic is a voltage or current at a multiple of the fundamental frequency of the system, produced by the action of non-linear loads such as rectifiers, discharge lighting or saturated magnetic devices. The Total Harmonic Distortions (THD) occurring in a system can be calculated using Eq. (1).

$$\text{Total Harmonic Distortion, THD} = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \cdots + V_n^2}}{V_1} \tag{1}$$

Harmonic frequencies in the power grid are a frequent cause of power quality problems. Harmonics in power systems result in increased heating in the equipment and conductors, misfiring in variable speed drives, and torque pulsations in motors. Thus it becomes of utmost importance to tackle this problem. The effect of harmonic distortions on the distribution transformers has been analyzed in [24]. To tackle these power quality issues coordinated charging has been proposed in [25] to minimize the power losses and to maximize the main grid load factor. As charging of electric vehicles has led to main power quality issues, thus, in this work an analysis of performance of PV-Grid system for EV charging is done.

In the present paper, a PV-grid system for electric vehicle charging has been designed for four charging stations having eight vehicles each. The battery specifications of EVs considered are same as that of being used in real-life batteries of EVs. The analysis is done for effect of different internal resistances and different SoCs of EVs, total harmonic distortion (THD) and scheduling of PV-grid system. Section 2 of the paper describes the proposed PV-grid model for EV Charging. The description of specified model and its working is given in Sect. 3. The simulations, performance analysis and results are discussed in Sect. 4. Sections 5 and 6 of the paper describe the economic aspect and conclusion, respectively.

2 Proposed PV-Grid Connected Model for EV Charging

One of the most viable and abundant renewable energy sources is solar energy. This solar energy can be harnessed and used for day-to-day power needs. This harnessed energy can be used for the purpose of electric vehicle charging as well. So rather than

depending on the AC grid solely for charging of electric vehicles, the PV module can be scheduled in a way so that maximum energy can be accessed from it for charging during its operation and the rest of the charging needs can be fulfilled from the AC grid. This decreases the overall stress on the grid due to electric vehicle charging.

For this purpose, the model has been designed with four charging stations, each serving eight electric vehicles at a time. The power generated from the PV module will be continuously measured and the shift between PV and grid will take place on the basis of comparison between these measured values and a predefined threshold value of 10 kW.

2.1 Design Parameters

The proposed PV-Grid model is designed in MATLAB/Simulink. The various components along with their ratings, used for designing of the proposed PV-Grid system are given in Table 1:

Table 1 Components and their ratings used in the PV-Grid system

S. no	Component	Ratings	
1	AC grid	3-phase ac source	20 MVA, 13.8 kV, 50 Hz
		3-phase transformer	20 MVA, 13.8/230 kV, 50 Hz
		3-phase active load	5 MW
		3-phase reactive load	500 kVA
2	PV module	PV module rating	236 kW, 480 V
		Temperature	450 °C
		Irradiance	1000 W/m^2
3	Electric vehicles	Battery rating;	48 V, 24 Ah
		Discharge current	10.4348 A
		Capacity Nominal Voltage	21.7 Ah
		Range of initial SOC%	[30%–80%]
4	AC-DC converters	Diodes	6
5	Filters	Resistor	1 Ω
		Capacitor	10 μF

3 Modelling and Description of the Proposed Model

The schematic diagram for the proposed PV-Grid system is shown in Fig. 2. In the proposed model a PV-Grid system has been used in which power is being supplied from the PV module and AC grid to charge the electric vehicles connected to the charging stations. The photovoltaic modules use light energy (photons) from the Sun to generate electricity through the photovoltaic effect. Nominally rated maximum power out (kWp) of a solar array of n modules, each with a maximum power of Wp at STC is given by Eq. (2).

$$kWp = n \times Wp/1000 \tag{2}$$

The available solar radiation (Ema) varies depending on the time of the year and weather conditions. However, based on the average annual radiation for a location and taking into account the efficiency (η) of the cell, the estimation of an average PV system energy yield is obtained as per Eq. (3).

$$Ep = Ema \times kWp \times \eta \tag{3}$$

In the present model, four charging stations are being used to observe the results where each charging station consists of eight charging points for connecting the electric vehicles. Out of these eight charging points, six charging points can be
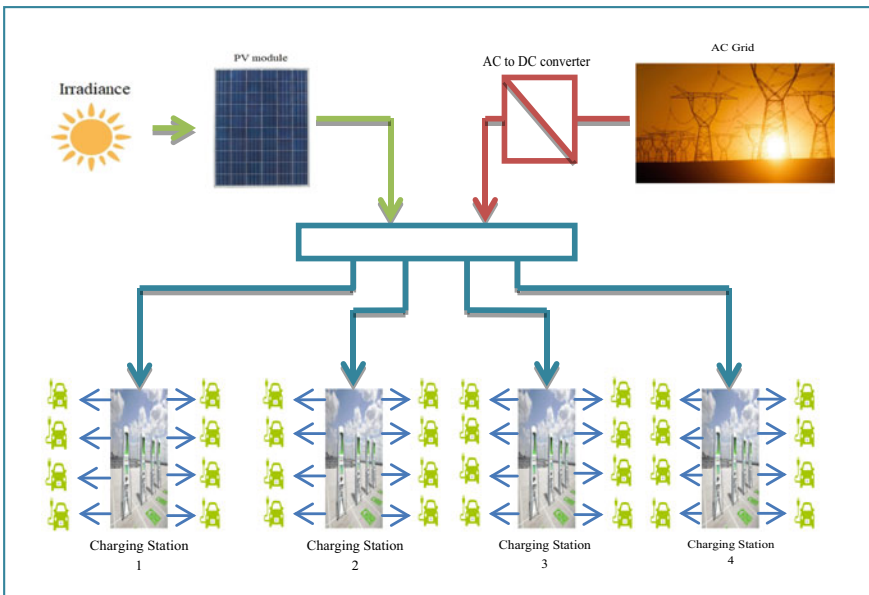

Fig. 2 Schematic diagram for the proposed PV-Grid system for EV charging stations

connected to the grid or PV module. The reason for this is to give provision for backup storage. The two charging points can be Energy Storage Units to prevent any wastage of solar energy in case all the charging points are not being used to supply energy. These Energy Storage Units can then be used to provide supply for charging even when there is no solar energy generation for instance at night.

3.1 Flowchart

The flowchart depicting the entire process of working of the proposed PV-Grid hybrid system is shown in Fig. 3. The process is described as follows:
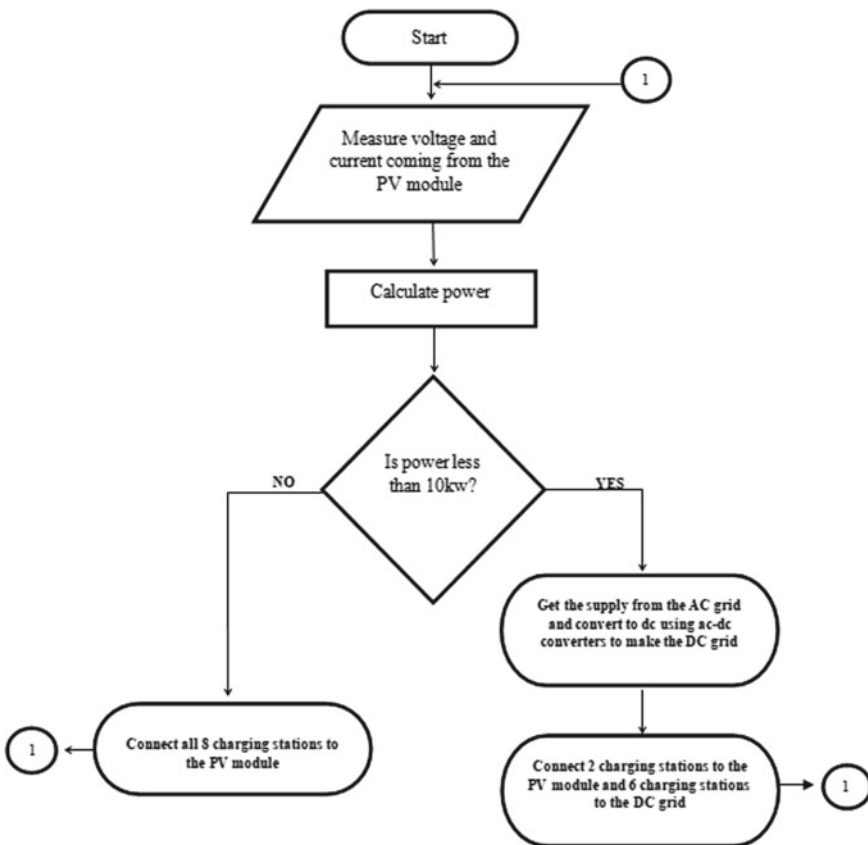

Fig. 3 Flowchart depicting the scheduling process of the PV-grid system

- Initially, when the operation starts, the PV module is being used to charge the EVs. The PV module makes use of irradiance and temperature as inputs to generate the output power.
- As the irradiance is high and power generated is enough to charge the electric vehicle batteries but as time passes the irradiance starts decreasing and so does the power and as a result PV alone is not sufficient to charge the electric vehicle batteries. As a result, all the eight charging points in a charging station are connected to the PV module supply.
- After some time when the power drops below the threshold limit of 10 kW, the electric vehicle charging points are shifted from the PV module supply to the AC grid. The AC supply from the AC grid is converted to DC current using AC-DC converters to form a DC grid.
- Six out of eight charging points are connected to the DC grid whereas two remaining charging points are connected to the PV module exclusively.
- The basis of this operating model is the switching between PV and AC grid. For this purpose, a threshold has to be assigned to the system after which the shift between PV and grid happens.

4 Simulations and Results

4.1 Real-Life Applications

The electric vehicle industry is on the rise and its increasing popularity has drawn many major manufacturing companies to compete in the e-automobile market worldwide. A number of major automobile companies have started implementing EV technology and new electric vehicle products have started emerging. The vehicle manufacturing companies like Hero Electric, Tunwal E-Vehicle, etc. are investing in the EV domain and have come up with various EV products like EV cars, EV bikes, EV scooters, etc. For example, Nyx E5 by Hero Electric is an electric vehicle scooter and Mini Lithino 48 V by Tunwal E-Vehicle with 48 V/28 Ah and 12 V/28 Ah batteries, respectively. The battery specifications used in the present model are same as used in real-life vehicle batteries. Hence, such vehicles can easily be incorporated with the proposed model to provide electric vehicle charging.

4.2 Effect of Different Internal Resistances on Battery Performance

In the real world, all the electric vehicles do not have the same rating. The batteries manufactured by the different manufacturers have varied specifications. To take this into account, batteries with different internal resistances in the range from 0.002 Ω to

Table 2 Internal resistance in terms of percentage of base value

S. no	Battery no	State of charge (%)	Value of internal resistance (ohms)	Percentage of base value (%)
1	Battery 1 & 2	80	0.012 (base value)	100
2	Battery 3	50	0.002	16.67
3	Battery 4	50	0.006	50
4	Battery 5	40	0.010	83.34
5	Battery 6	40	0.014	116
6	Battery 7	30	0.018	150
7	Battery 8	30	0.022	183.34

0.022 Ω have been selected and have been used for simulations. Also, different values of state of charges for batteries have been considered. The base value considered for the batteries is the value of the internal resistance as per default specifications in the Simulink. The range of values taken for internal resistance of batteries and its percentage with respect to the base value of the battery is shown in Table 2. The batteries 1 and 2 with the internal resistance of 0.012 Ω are supplied by the PV alone.

Case 1: Batteries with the same State of Charge

Initially, the same state of charge (SOC) for all the electric vehicles i.e., 80% with different internal resistance is considered. The range of values taken for internal resistance of batteries and its effect on the battery state of charge, battery current and battery voltage is shown in Table 3.

From Table 3 it can be seen that as the internal resistance of the battery increases:-

- The rate of charge of the battery decreases.
- The battery current decreases.
- The battery voltage remains almost constant.

Table 3 Battery performance with different internal resistances and same State of Charge
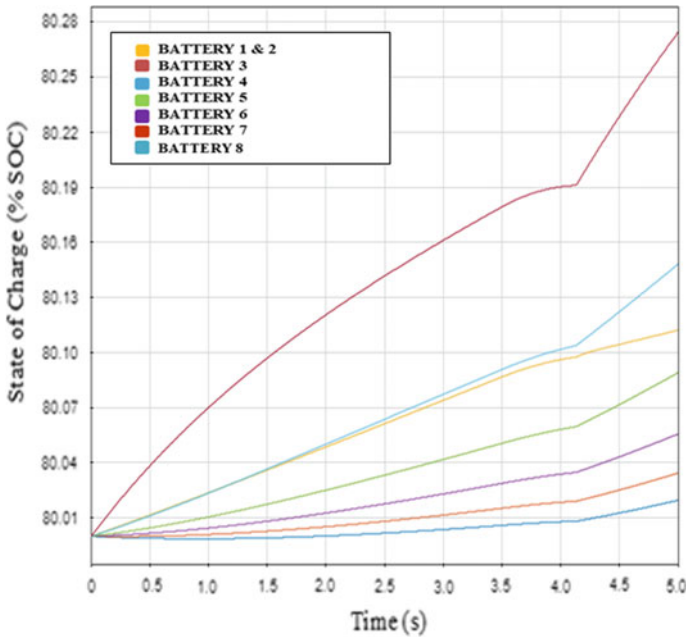
	Internal resistance (Ω)	Battery SOC (%)	Battery current (A)	Battery voltage (V)
Battery 1 & 2	(0.012)	80.06	−22	50.21
Battery 3	(0.002)	80.14	−35	50.02
Battery 4	(0.006)	80.065	−24	50.02
Battery 5	(0.010)	80.025	−14.5	50.02
Battery 6	(0.014)	80.0175	−42.85	50.02
Battery 7	(0.018)	80.075	−8.5	50.02
Battery 8	(0.022)	80.0012	−6	50.02

Figure 4 shows the relation between internal resistances and the rate of charge of batteries. It can be concluded that as the value of internal resistance increases, the rate of charge of batteries decreases.

Case 2: Batteries with different State of Charge

In this case, electric vehicle batteries with different internal resistances and different state of charge are considered. The range of values taken for internal resistances and its effect on battery state of charge, battery current and battery voltage is shown in Table 4.

Fig. 4 Rate of charge of batteries with different internal resistances at same SOC

Table 4 Battery performance with different internal resistances and different SOC

	Internal resistance (Ω)	Battery SOC (%)	Battery Current (A)	Battery Voltage (V)
Battery 1 & 2	(0.012)	80.037	−13	50.065
Battery 3	(0.002)	50.155	−44	49.85
Battery 4	(0.006)	50.053	−20.55	49.85
Battery 5	(0.010)	40.041	−16	49.85
Battery 6	(0.014)	40.022	−11	49.85
Battery 7	(0.018)	30.028	−9.5	49.85
Battery 8	(0.022)	30.018	−7.4	49.85

4.3 Scheduling of Power for Charging Electric Vehicles in the Proposed PV-Grid System

The proposed model has been run for 5 s (simulation time in Simulink) in Simulink and the various outputs obtained are as follows.

Battery State of Charge (SOC)

Figure 5 shows the variation of State of Charge (SOC) with time for different values of internal resistance of batteries of Electric Vehicles.

From the graph, it can be seen that as the internal resistance of the battery increases, the rate of charge of the battery decreases. Also, it can be seen that the shift from the PV module to the AC grid occurs at time 4.2 s (approximately) when power from the PV module drops below the threshold value of 10 kW.

Battery Voltages

The rate of change of battery voltage w.r.t. time for different 8 values of internal resistance of electrical vehicles is shown in Fig.6.

From Fig. 6 it can be seen that the Battery Voltage remains fairly constant. Batteries 1 & 2 show the graph for the charging point being supplied from the PV alone. It can be seen also that the shift from the PV module to the AC grid occurs at time 4.2 s (approximately) when power from the PV module drops below a threshold value of 10 kW.

Battery Currents

The following are the Time vs Current graphs, which show the rate of change of current of EVs with time. The graphs here are plotted for 8 different values of internal resistance.
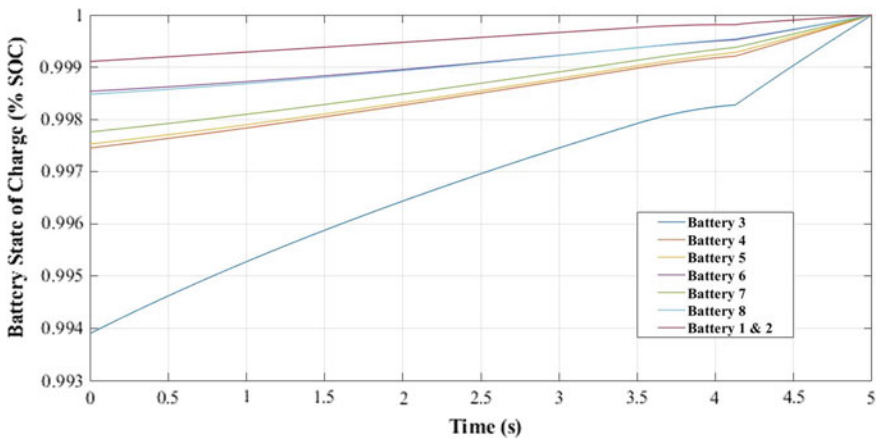

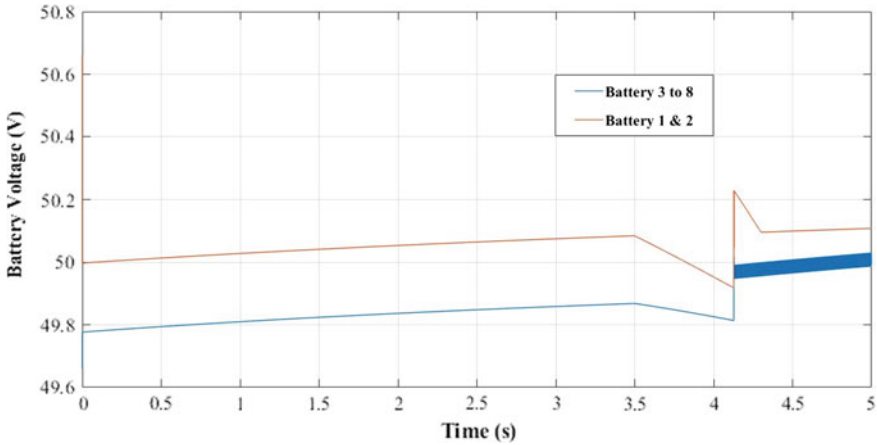**Fig. 5** Battery SOC with Internal Resistance ranging from 0.002 to 0.012 Ω

Fig. 6 Rate of change of voltage of batteries 1–8 with different internal resistances

From Fig. 7 it can be seen that the Battery Current decreases as the internal resistance of the battery increases. Batteries 1 & 2 show the graph for the charging point being supplied from the PV alone. Here it can be seen that from Fig. 8, the shift from the PV module to the AC grid occurs near 4.2 s (approximately) when power from the PV module drops below 10 kW.
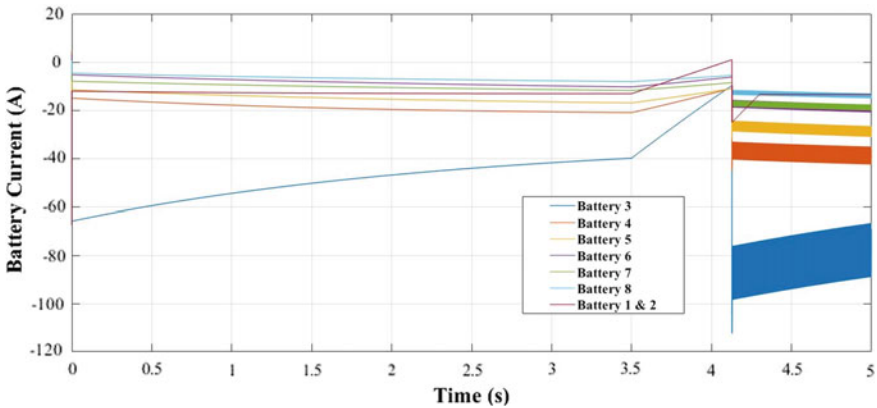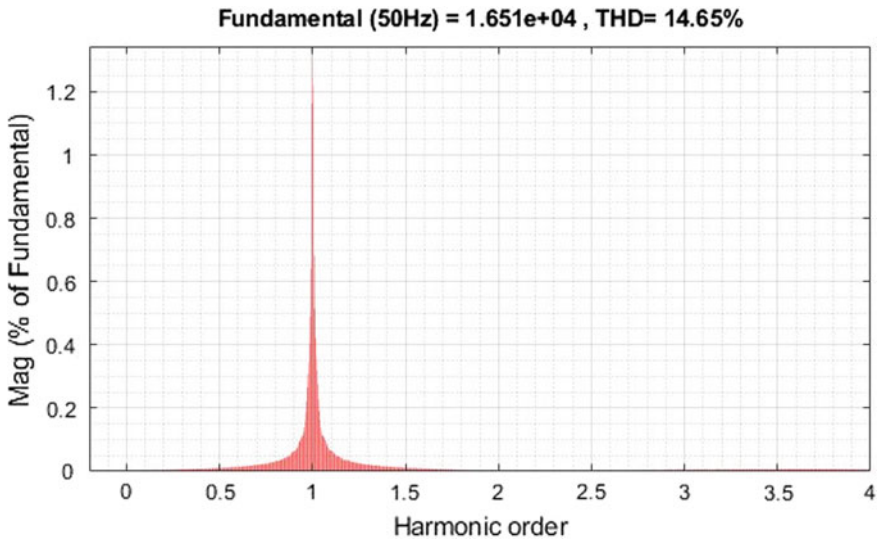

Fig. 7 Rate of change of current of batteries with different internal resistances

Fig. 8 THD (voltage distortions) injected in the grid caused due to the charging of electrical vehicles

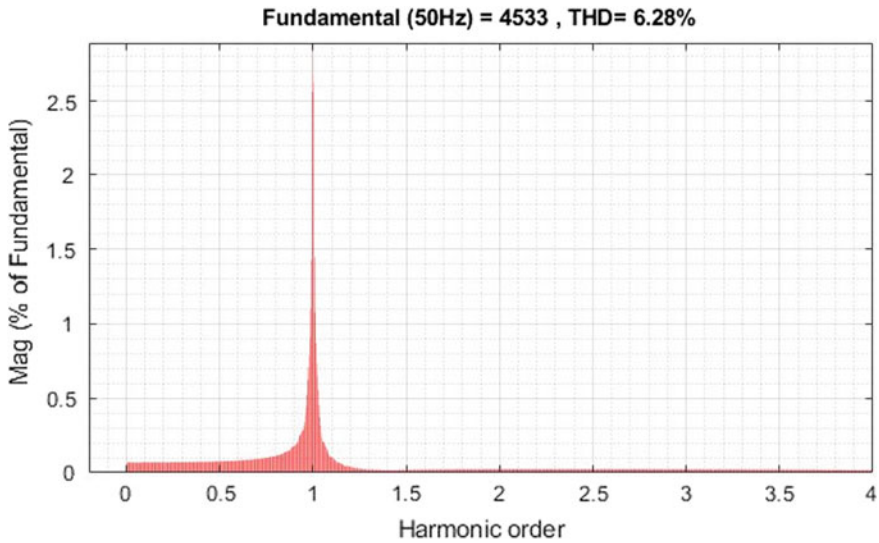## 4.4 Electric Vehicle Charging on AC Grid Alone

Electric vehicles are comprised of non-linear loads such as batteries which are known to cause harmonic distortions in the electrical grid. By using an AC grid designed in Simulink the Total Harmonic Distortions occurring in the system have been calculated due to the charging of electric vehicles.

The acceptable THD limit as per standard IEEE 519 is 5%. The results show that the Harmonic Distortion caused by charging electric vehicles through the AC grid is 14.65% for voltage distortions and 6.28% for current distortions as shown in Fig. 8 and Fig. 9, respectively. Hence it is important to reduce these distortions to a minimal value as possible.

4.5 Reduction of THD in the Proposed PV-Grid System

Lower THD in power systems means higher power factor, lower peak currents and higher efficiency. The low THD is an important feature in power systems. The International Standards such as IEC 61,000-3-2 set limits on the harmonic currents of various classes of power equipment. One of the objectives of this model is to control the Total Harmonic Distortions occurring in the system.

To analyze the total harmonic distortions (THD) occurring due to the charging of electric vehicles a PV-Grid system has been designed using MATLAB/Simulink

Fig. 9 THD (current distortions) injected in the grid caused due to the charging of electrical vehicles

software and the impact on the proposed system due to electric vehicle charging has been studied.

It is observed that employing low pass filters and scheduling the charging period of electric vehicles in the PV-Grid system helps in tackling THD. During the day when there is an abundant amount of solar energy, the PV module is used to harness this energy and further utilize it to charge the electric vehicles. As the day passes the irradiance decreases and the power generated by the PV module also decreases. When the power generated by the PV module drops below the threshold value of 10 kW the circuit breakers connecting the ac grid to the charging points in the electric vehicle stations close. After the threshold value of 10 kW, both the PV and ac grid are connected to the charging points on the electric vehicle charging stations to provide the power required to charge the electric vehicles.

It is also observed that connecting the electric vehicles solely to the ac grid results in large harmonics entering the system. On the other hand, by incorporating the PV module into the system these harmonics are reduced to a large extent. In this system, the electric vehicles are connected to PV module during the day when there is an abundant amount of solar energy rather than connecting to the ac grid. As a result, when PV supply is available the ac grid is not used for the electric vehicle charging purpose and the load stress imposed on the system is decreased. Hence harmonics entering into the system are reduced to a significant amount. The values of THD are drastically dropped to 0.36% and 1.27% for voltage and current distortions as shown in Fig. 10 and Fig. 11, respectively, when vehicles are charged on the proposed PV-grid system as compared to the 14.65% and 6.28%, respectively, when charged on ac grid alone.
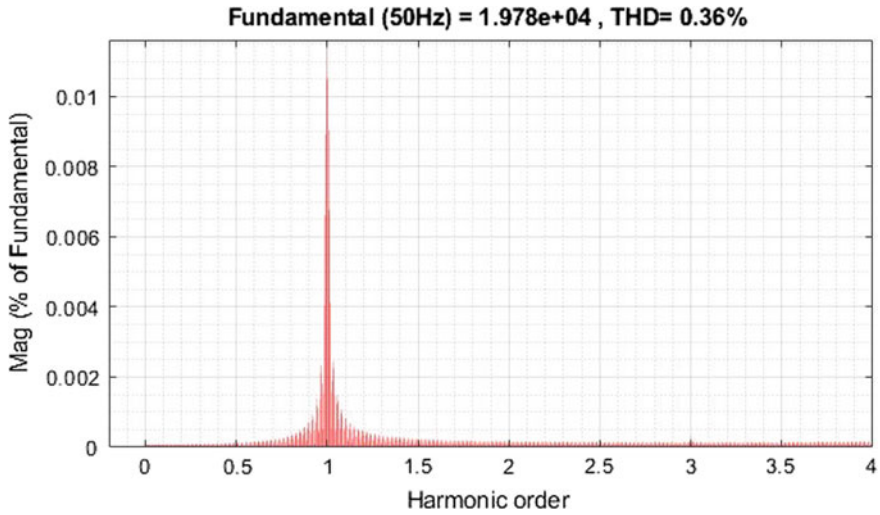
Fundamental (50Hz) = 1.978e+04 , THD= 0.36%

Fig. 10 THD (voltage distortions) injected in the grid due to the charging of electric vehicles by the proposed system
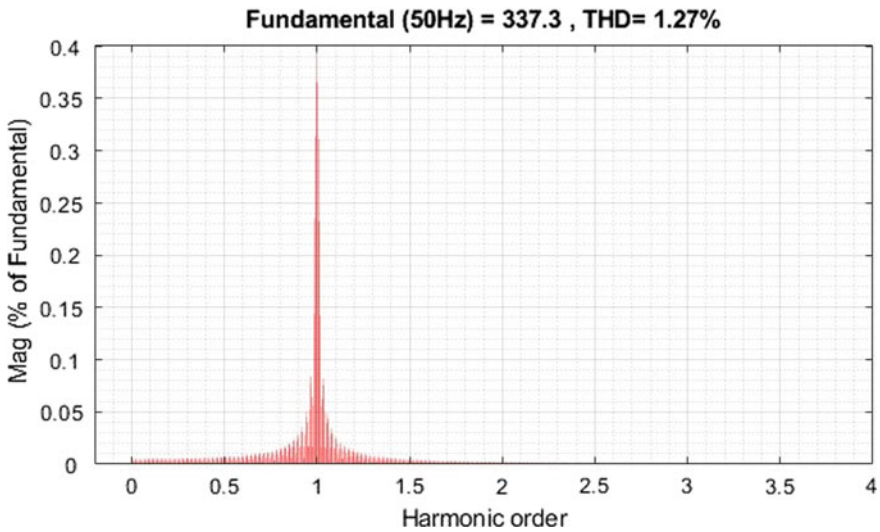
Fundamental (50Hz) = 337.3 , THD= 1.27%

Fig. 11 THD (current distortions) injected in the grid due to the charging of electric vehicles by the proposed system

5 Economic Benefits

The proposed PV-Grid system for charging of the electric vehicles can provide more benefits as compared to charging the vehicles on the grid alone system. During the

peak times of the day when there is an abundant amount of solar energy available, the vehicles are charged on the proposed PV-Grid system in which energy is supplied by the solar modules. The solar energy has the least negative impact on the environment as compared to any other type of energy source. PV modules do not create any noise pollution, which is a major benefit. It does not produce greenhouse gasses and does not pollute the environment and also has the least maintenance cost.

6 Conclusion

Ever-increasing pollution owing to emissions from ICE vehicles and limited fuel sources has shown the importance of shifting to an alternate clean and renewable energy resource. In the proposed work, a PV-Grid system has been developed for the purpose of charging electric vehicles in MATLAB/Simulink. As the electric vehicles manufactured by different industries may have different internal resistances so the effect of different internal resistances on battery performance has been observed for same SOC and different SOC conditions. The passive filters have been designed in the proposed PV-GRID system to further enhance harmonic mitigation. The system performance for various load conditions has been analyzed by employing different charging stations. The system has been designed in such a way that the load on the grid is scheduled for on-peak and off-peak hours i.e., during day and night. This scheduling decreases the stress on the grid that could have been imposed if the grid had been used for the purpose of electric vehicle charging for the entire 24 h period. It is observed that the proposed system has been successfully able to suppress the total harmonic distortions (THD) to a great extent i.e. 14.65% to 0.36% for voltage distortion and from 6.28% to 1.27% for current distortions, respectively. The widespread use of hybrid renewable energy will not only solve the energy issues but also ensure a green planet.

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