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Multi-Objective Optimal Predictive Energy Management Control of Grid-Connected Residential Wind-PV-FC-Battery Powered Charging Station for Plug-in Electric Vehicle

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Abstract – Electric vehicles (EV) are emerging as the future transportation vehicle reflecting their potential safe environmental advantages. Vehicle to Grid (V2G) system describes the hybrid system in which the EV can communicate with the utility grid and the energy flows with insignificant effect between the utility grid and the EV. The paper presents an optimal power control and energy management strategy for Plug-In Electric Vehicle (PEV) charging stations using Wind-PV-FC-Battery renewable energy sources. The energy management optimization is structured and solved using Multi-Objective Particle Swarm Optimization (MOPSO) to determine and distribute at each time step the charging power among all accessible vehicles. The Model-Based Predictive (MPC) control strategy is used to plan PEV charging energy to increase the utilization of the wind, the FC and solar energy, decrease power taken from the power grid, and fulfil the charging power requirement of all vehicles. Desired features for EV battery chargers such as the near unity power factor with negligible harmonics for the ac source, well-regulated charging current for the battery, maximum output power, high efficiency, and high reliability are fully confirmed by the proposed solution.

Keywords: Plug-in Electric Vehicles (PEVs), Predicative control, Wind-PV-FC battery charging station, Smart grid, Grid to Vehicle (G2V), Energy management, Multi-objective particle swarm optimization

1. Introduction

A wide range of Electric Vehicles (EV) are turning into the main option to the conventional transportation sector due to their potential for diminishing the greenhouse gases and fuel utilization and capacity to build the utilization of different types of green renewable energy sources into the sector of transportation [1]. The implementation of the renewable energy sources in the transportation business sees expanded encouragement in the form of investments, financing and tax payback [2]. With the continuous technological progression in the battery innovation and power electronic converters, EV is expected to make genuine advances in the transportation business and start the combination of electrical power and transportation frameworks [3]. The charging of the batteries by utility grid forces an additional load especially amid the high demand period [4]. One feasible alternative for diminish the negative effect is to advance charging utilizing renewable energy sources. With the consistent descending pattern on the cost of the PV modules and wind turbines, they are perceived as the competitive source for the charging stations [5]. Moreover, the PV-Wind hybrid renewable framework is practically maintenance free, fuel and labour free [6]. The utilization of the PV-Wind hybrid renewable framework is further upgraded by the advancement in power electronic converters and the artificial intelligent energy management for the battery [7]. The battery charging while parking from the PV-Wind renewable energy system at work environments and parking areas especially during the day time or peak demand period is a cost-effective and convenient solution [8, 9]. Therefore the electricity savings from the electricity tariff especially during the peak demand period is significant [10, 11]. Economic matters of PV-Wind based charging station work environment has been considered in [12, 13]. The examination demonstrates the suitability of a PV-Wind based work environment parking structure with advantages to the vehicle owner when contrasted with the vehicle charging at home charging, to such an extent that the owner of the charging station will get the compensation of establishments, maintenance cost and benefit inside the lifetime of the PV-Wind Renewable energy system. As indicated by [13] coordinating a sun collector into a parking area would bring about an a great deal quicker payback-period, empowering broad establishment of sunlight based limit. Reference [14] depicts how intelligent control algorithms can help to coordinate with the present power frameworks. Co-advantages of expansive scale

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integration have been examined in [15]. The review presumes that PV gives a potential supply of peak demand period, while PEVs give a dispatchable load to low power or generally unusable PV generated power amid times of low load requirement [16-18]. The energy stored in the batteries could be utilized to supply house hold appliances, compensate renewable production intermittency and/or support the power grid [19]. Therefore, the electric utility companies begin to redesign the distribution network and introducing smart meters to monitor and control different modes of operation of PEV [20]. The PEV battery charging procedure introduces additional burdens to the utility grid and can exacerbate some power quality issues such as high total harmonic distortion [21]. Consequently, it is to a great degree essential preserve the power quality by providing the PEVs with new designs of the battery chargers to make the battery current very close to sinusoidal waveform and to enhance the battery power factor [22]. The majority of PEVs will introduce a new significant load when charged during the daytime and that could adversely affect the stability of the power grid [23]. The charging of the PEV at home during the evening period is regularly acknowledged in light of the fact that the power grid has unused power. However, a smart and a new design battery charger will be required to be installed at home with a power plug access for the purpose of the night charging process. Hence, it exceptionally vital for an option arrangement, for example, the renewable energy sources; PV and the wind to charge PEVs without intensely influence the utility grid. PEV charging stations based PV and wind renewable energy system has attracted EV companies around the world. An optimized planning methodology for wind energy based EV charging station was proposed in [24]. According to [25-27], the PV based workplace parking garage would bring about a significantly more quick payback-period and support cost and benefit inside the lifetime of the renewable energy devices. A smart grid-connected configuration for a residential charging facility that can be utilized to charge PEVs as well as to supply the existing household loads has been proposed [28-30]. The energy flow direction between the PEVs and the utility gird mainly depends on the charging demand and the amount of energy generated by the hybrid renewable energy (FC/PV/Wind) [31-33]. In some cases, a DC/DC converter has been inserted at the dc link to intelligently control the energy flow to the PEVs based on specified limits of the dc bus voltage [34-35]. This paper proposes Wind-FC-PV-Battery grid connection based parking garage charging concept which is controlled and monitored by MPC-MOPSO control strategy. The power grid is installed and connected to the charging facility to fulfil any load demand more than the output of the hybrid Wind-FC-PV-Battery renewable energy sources by purchasing the electricity from grid. Any extra energy from the hybrid renewable energy system is sold back to the power grid. The paper is structured as follows; Section 2 introduced the Proposed Configuration for Wind-FC-PV Based PEV Charging Station. Section 73 provides explanations of the proposed Model-Based Predictive Control MPC. Section 4 outlines Proposed MPC-MOPSO Controller. Section 5 presents the simulation results of the Proposed Configuration for Wind-FC-PV Based PEV Charging Station. Finally, the conclusions of this paper are presented in Section 5.

2. The Proposed Configuration for Wind-PV-FC-Battery Powered PEVs Charging Scheme

Fig. 1 shows the distributed architecture of the distributed Wind-PV-FC-Battery powered charging scheme to supply constant power to satisfy the high requirement of PEVs. The accessible power from all renewable energy sources to charge numerous PEVs is restricted and uncertain in nature; its energy characteristic is nonlinear. Contingent upon the climate conditions, PEVs can be charged either from the wind turbine, the PV, FC, the battery or the utility grid. The charging station ought to disseminate the accessible energy from the renewable sources to the PEVs viably and securely. The battery bank or the Energy Storage Unit (ESU) and the fuel cell were utilized to improve the reliability of the charging station and facilitate the charging requirement of PEVs using minimum energy from the utility grid. The power generated by the wind turbine and the PV system is stored in the ESU and used by the Electrolyzer to produce and store Hydrogen for future use by the FC for proficient utilization of renewable energy sources, expansion of renewable energy sources commitment. The ESU will bolster the charging of PEVs when there is no power accessible either from the utility grid or the Wind-FC-PV hybrid renewable energy sources. Each renewable energy source and the ESU are connected through a particular DC-DC converter to a common DC

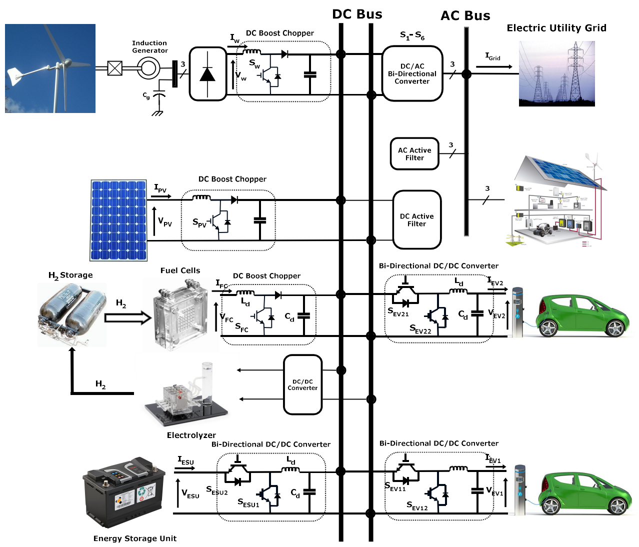
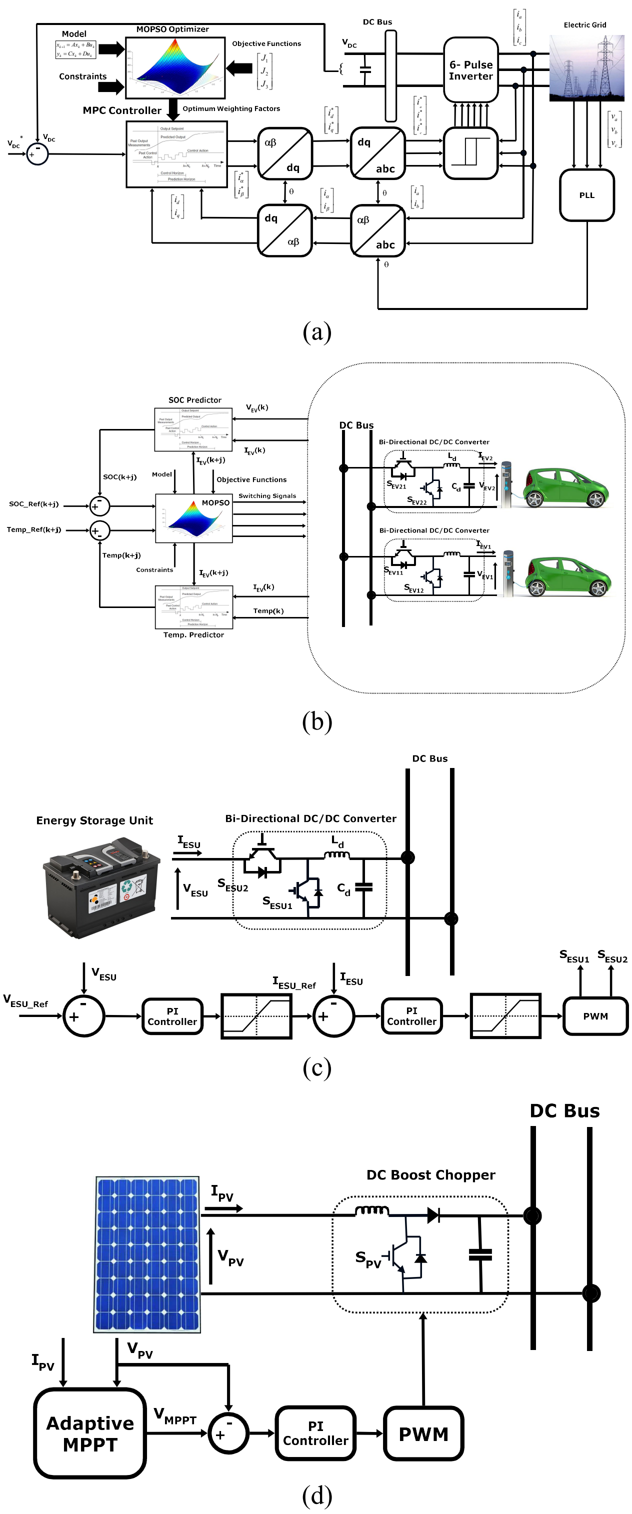


Fig. 1. The proposed PEVs Battery charging station



(a) (b) (c) (d)

Fig. 2. Control scheme of different converters: (a) Control scheme of the bidirectional DC/AC Converter, (b) Control scheme of the DC/DC Converter, (c) Control scheme of the bidirectional DC/DC Converter, (d) Block diagram of DC-DC converter with MPPT

bus. A DC-AC converter is connected between the power grid and the battery charger to facilitate the direction of the energy between the PEVs and the utility grid. Hence, the charging procedure requires intelligent control of the DC-DC and DC-AC converters to deal with the energy management of the Wind-FC-PV-Battery integrated charging scheme. The control strategy creates the control signals to control the different converters in the charging station taking into account the measured voltage and current quantities as shown in Fig. 2.

3. Model-Based Predictive Control MPC

MPC is a sort of control that predicts the future execution of a procedure u utilizing the precise model. The control activity is gotten by handling an obliged optimization issue to limit the distinction between the assessed future output and the reference through the utilizing of least control vitality and fulfilling the constraints of the plant [36-37]. The working guideline of MPC is to apply the plant models to anticipate the reactions to conceivable future control successions and to locate the best future control action by enhancing the particular targets. Given a grouping of future inputs, the length of which is defined as the prediction horizon P, the future plant states can be anticipated taking into account the dynamic plant model. The future plant response under the succession of inputs can then be assessed taking into account a behaviour indicator. Two points of interest of MPC clarify the rationale. Firstly, it can anticipate future battery states under a conceivable future charging grouping and henceforth assess charging performance over a relatively long stretch. Also, it computes the best charging succession utilizing an optimization strategy, which can take care of multi-target issues. The main components of the MPC are the process model, the cost function, the optimizer and the process constraints. 1. For every moment k, the framework model is shaped as a state-space model and used to assess the future response of the charging station over a proposed horizon. 2. For every cycle k, an arrangement of future control activities over a proposed control horizon is calculated to optimize the selected objective function considering the pre-characterized imperatives. 3.

The future system conduct is upgraded by figuring at every cycle, k, the ideal esteem of the control variables which is executed to the framework. Based upon the available data and measurement, the proposed energy management system generates the reference power values for the power converters to manage the split power between the PV, FC, wind turbine, grid and the energy battery system according to the weather conditions to satisfy the varying and unpredictable load demand and the power required for charging the battery of the electric vehicle while considering all objective functions, SOC of the ESU battery and the EV battery and all system constraints. The proposed energy management system maintains SOC within a specified range between SOC_{max}

and SOC_{min} (20% - 90%). The different modes of operation of the energy management system are as follows; the generated power by the PV and the wind turbine has the first priority to fulfil the load and the EV charging requirements. If the generated power by the PV and the wind exceeds the load and the EV charging requirements i.e., $P_{PV} + P_{Wind} > P_{EV\_Charging} + P_{Load}$, the surplus power will be utilized to charge the battery of the ESU. The battery of the ESU continues in the charging process until the SOC of the battery reach to the maximum level i.e., SOC_{max} = 90%. Then the remaining power will be utilized by the Electrolyzer to generate hydrogen for SOFC until the pressure reach to its maximum level. Then the surplus of the generated power will be exported to the grid. If the load and the EV charging requirement surpasses the generated power by the PV and the Wind i.e., $P_{PV} + P_{Wind} < P_{EV\_Charging} + P_{Load}$, depending on the ESU battery SOC, if adequate charge is accessible the distinction power will be delivered to the load and the EV charging requirements by the battery. The generated power by the FC is utilized in case of the load demand is not fulfilled by the ESU battery. The EMS checks the SOC while the battery continues to supply the load until the SOC reaches to its minimum level (SOC_{min} = 20%). Then the battery will be switched off and the load power will be imported from the utility grid. The power requirement from all vehicles is ascertained as the total of the charging powers for every vehicle, given by

$$P_{charge}(k) = \sum_{n=1}^{N} P_{ch}(n,k);\ k = 1:24 \tag{1}$$

The grid power is considered as positive when supplied to the parking garage. Solar power is always positive and charging power is positive when supplied to the vehicles. This charging power is supplied through the hybrid Wind-FC-PV renewable energy system and the power grid. Therefore,

$$P_{\text{charge}}(k) = P_{\text{Renewable}}(k) + P_{grid}(k) \tag{2}$$

The accessible energy from the utility grid can be calculated by the following equation:

$$E_{grid}(k) = \left(P_{charge}(k) - P_{\text{Renewable}}(k)\right)\Delta t \tag{3}$$

where E_{grid} is in kWh, P_{charge} and $P_{Renewable}$ is in kW and Δt is one hour. The charging power on the source side is managed by a simple rule such that the hybrid Wind-FC-PV renewable energy system gets first priority and supply maximum possible power. The remaining demand is supplied through the grid. The objective of the energy management controller is to control the charging power of the vehicles such that the grid power utilization is minimized. Therefore the state equation for the problem can be written as:

$$x(k+1) = x(k) + E_{demand}(k) - \left(P_{\text{Renewable}}(k) + P_{grid}(k)\right)\Delta t \tag{4}$$

$E_{demand}(n)$ is the energy demand of the n^{th} vehicle, N is the total number of vehicles in the parking garage.

4. Proposed MPC-MOPSO Controller

The MPC-MOPSO controller determines the optimal charging power at t for each vehicle by estimating the charging demand of the vehicles and the hybrid Wind-FC-PV renewable energy sources such that the vehicle is fully charged when it leaves the parking garage while satisfying some objective function of the grid power is minimized.

1. The first objective function is to reduce charging time by following a particular SOC track. The achievement index J_1 is calculated by:

$$J_1 = \left|SOC^*\left(k+p\right) - SOC\left(k+p\right)\right| \tag{5}$$

where SOC^* is the reference SOC trajectory, SOC is the actual SOC during the charging process.

2. The second objective function is to minimize the battery temperature during the charging process which gives an indication about the charging performance and the energy efficiency. J_2 is calculated by defining a particular temperature track and followed by the proposed controller.

$$J_2 = \left\{T^*\left(k+p\right) - T\left(k+p\right)\right\} \tag{6}$$

3. The third objective is to minimize the influence on the utility grid by minimizing the Energy from the grid and capturing the potential of the renewable energy sources based charging station to offset the grid power by the power of the hybrid Wind-FC-PV renewable energy sources. This objective function can be converted to electricity cost or emissions by multiplying with the appropriate conversion factor. If Pgrid > 0, when energy flows from the grid to the parking garage, we have

$$J_3 = \int_{day} \max\left(0, P_{grid}(t)\right) dt \tag{7}$$

with power and energy balance equations

$$\begin{aligned} &P_{grid}(t) = \sum_{n=1}^{N} P_{ch}(n,t) - P_{\text{Renewable}}(t) \\ &\int_{day} \left(P_{\text{Renewable}}(t) + P_{grid}(t)\right) dt - \int_{day} \sum_{n=1}^{N} P_{charge}(n,t)\, dt = 0 \end{aligned} \tag{8}$$

$P_{Renewable}(t)$ is the renewable power, $P_{grid}(t)$ is the grid power, $P_{ch}(n, t)$ is the charging power of the nth vehicle at time t.

Subject to:

$$P_{\min} \le P_{charge}\left(k+p\right) \le P_{\max} \tag{9}$$

Where P_{charge} is the power flowing in or out of the battery during charging or discharging. P_{min} = 2 KW; P_{max} = 9 KW.

$$SOC_{\min} \le SOC\left(k+p\right) \le SOC_{\max} \tag{10}$$

Where SOC_{min} = 20%; SOC_{max} = 90%.

$$T\left(k+p\right) \le T\left(k+p\right)_{\max} \tag{11}$$

Where T_{max} = 50°C. To acquire the optimal solution for this complicated optimality problem, the following single weighted target function will be utilized:

$$J_o = \alpha_1 J_1 + \alpha_2 J_2 + \alpha_3 J_3 \tag{12}$$

Where α_1, α_2, and α_3 are the coefficients of the single weighted objective function which are determined using the SOPSO algorithm where the maximum and minimum limits (α_{dmin} = 0.01, α_{dmax} = 0.99) of these coefficients are assigned as follows:

$$\alpha_{d\min} \le \alpha_d \le \alpha_{d\max} \quad \text{where: d =1,2,3} \tag{13}$$

The velocity and the position of each particle are updated as follows:

$$\begin{aligned} v_{id}(t+1) &= \omega \times v_{id}(t) + c_1 \times r_1(\ ) \times \left(p_{pd}(t) - k_{id}(t)\right) \\ &+ c_2 \times r_2(\ ) \times \left(p_{rd}(t) - k_{id}(t)\right) \ where:\ i = 1,2,...,n = 20 \end{aligned} \tag{14}$$

Where are randomly chosen from the Pareto archive,

$$\alpha_{id}(t+1) = \alpha_{id}(t) + \alpha_{id}(t+1) \tag{15}$$

Considering the following limits for velocity and position:

$$\begin{aligned} &if\ v_{id}\left(t+1\right) \ge v_d^{\max}\ then \quad v_{id}\left(t+1\right) = v_d^{\max} \\ &if\ v_{id}\left(t+1\right) \le v_d^{\min}\ then \quad v_{id}\left(t+1\right) = v_d^{\min} \end{aligned} \tag{16}$$

$$\alpha_d^{\min} \le \alpha_{di}\left(t+1\right) \le \alpha_d^{\max} \tag{17}$$

In the proposed MOPSO algorithm, two mechanisms were implemented to reduce the non-dominated solutions. The first mechanism is called “adaptive grid” which is formed by hyper-cubes and includes N of particles. The “adaptive grid” redistributes non-dominated particles when the maximum capacity of the Pareto Archive is reached. The second mechanism is called “relaxed form of Pareto dominance” which keeps up a subset of created arrangements. It ensures meeting and assorted variety as per the criteria of the resolution of the grid which is defined by the ε value. The space of the objective function is divided into cubes of size ε that has one possible solution. The strategy acknowledges a new solution into the “ε-Pareto” set if it is the only arrangement in the cube and it dominates other arrangements. Furthermore, a “hyper-plane distribution” mechanism was implemented in the paper to perform a good distribution of the non-dominated arrangements. The hyper-plane space is characterized by the optima from the targets and utilizes the re-distribution to choose a delegate subset from the entire arrangement of non- dominated arrangements. The algorithm requires as information, an arrangement of non- dominated arrangements and the amount n of alluring final arrangements. At that point, the algorithm chooses those arrangements which have the ideal solution on every target. A hyper-plane among all ideal arrangement is calculated. Then, the algorithm partitions the space into n cubes. Subsequently, on the space of each cube, a normal line to the hyper-plane is determined. Finally, the algorithm just acknowledges those arrangements which are nearest to each line.

5. Simulation and Experimental Results

Simulation and laboratory prototype studies of the following modes of operation of the bidirectional battery charger were carried out utilizing Matlab Simulink with parameters given in Table 1 to validate the effectiveness of the proposed MPC-MOPSO. *Mode I; w*hen the hybrid Wind-FC-PV renewable power generate very small power and the PEV battery is charged by the utility grid or the battery power is transferred to the grid during the discharge mode. Mode II; when the required battery charging power surpasses the accessible power from the hybrid Wind-FC-PV renewable system, all the hybrid Wind-FC-PV generation power is utilized to charge the battery and the remaining power is transferred from the utility grid. *Mode III; when* the hybrid Wind-FC-PV renewable energy system generates sufficient power for charging the PEVs battery and the local loads. Mode IV; when available power from the hybrid Wind-FC-PV renewable energy system

Table 1. Parameters

Power Rating	1.5 KW	Sampling	10 µSec
Grid Voltage	220 V	Capacitor	150 µF
Utility Grid Frequency	60 Hz	PEV Battery Capacity	12 V, 10 A, 250 Ah
DC bus Voltage	250 V	ESU Battery Capacity	24 V, 10 A, 500 Ah
Input Filter Inductance	2 mH	PV array Size	150 V, 12 A, 2 KW
Input Filter Resistance	0.05 Ω	Switching Frequency	100 KHz

is substantial than the required charging power by the PEVs battery. The hardware setup of the proposed battery charger station which was developed in the power systems laboratory at the University of Trinidad and Tobago (UTT) consists of the following items; DC/AC bidirectional converter for the utility grid integration, three (3) DC/DC bidirectional converters; one for the energy storage battery and two (2) for the EV charging schemes, three (3) DC boost choppers for the wind turbine, the PV and the FC, the drive circuit for the IGBTs, the control command circuit, the measurement sensors and the microcontroller DSP. Figs. 3-4 shows the simulation and the experimental results for the operation of the charging station during the off peak period or mode I; where the PV system and the FC unit do not generate any power, the wind turbine contribute with a power of 200 W, the PEV battery consumes 500 W for charging, the Electrolyser consumes 150 W for hydrogen production, the ESU consumes 200 for charging and local load demand is 1000 W while the utility grid continues to delivers 1650 W to supply the deficit power for full battery charging and supply the required power for other load attached with the charging station. It is clear that the voltage and current signals drawn by the charging station are in phase. Operation of Mode-2 was tested using the simulation and the experimental and the results of the mode are shown in figures 5 and 6. In this mode the power generated by the PV-Wind-FC system is less than the required charging power by the PEV and the power demand by the local loads. Therefore all the power generated by the PV-Wind-FC-Battery is utilized to charge the battery of the PEV and the remaining required power is provided by the grid. The power generated by the PV is 200W, by the Wind is 150W, the FC does not generate any power, the electrolyzer consumes 100 W to continue producing Hydrogen, the PEV consumes 400 W in the charging process, the ESU receives 200 W for the charging process as well, the local power demand is 650 W and the utility grid supplies 1000 W. The simulation and the experimental results for the operation of Mode III are shown in figures 7-8 where the PV-Wind-FC-Battery

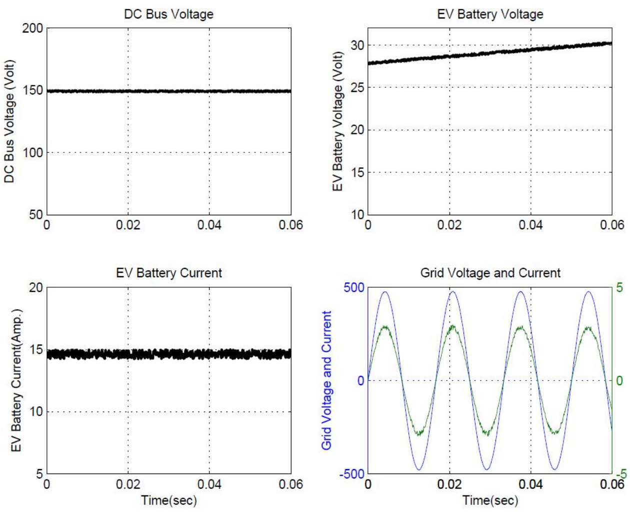


Fig. 3. Matlab Simulation results for mode-I

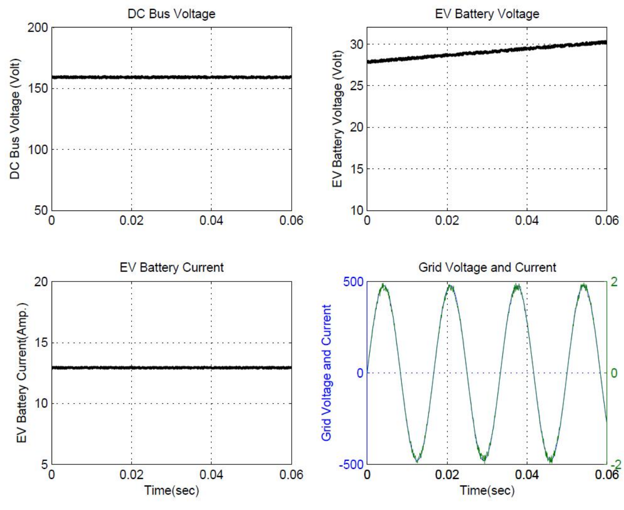


Fig. 5. Matlab Simulation results for mode-II

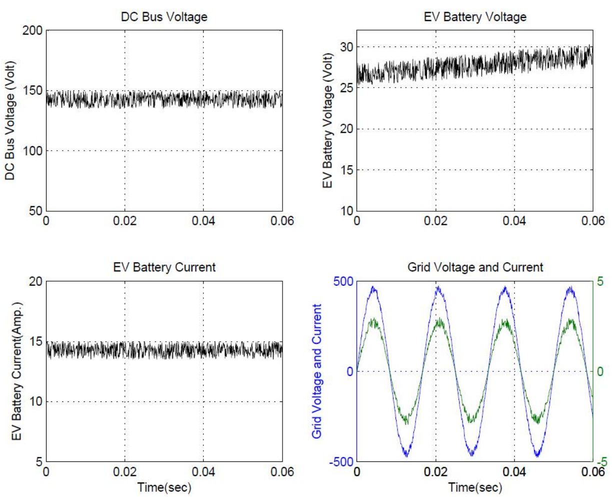


Fig. 4. Experimental results for mode-I

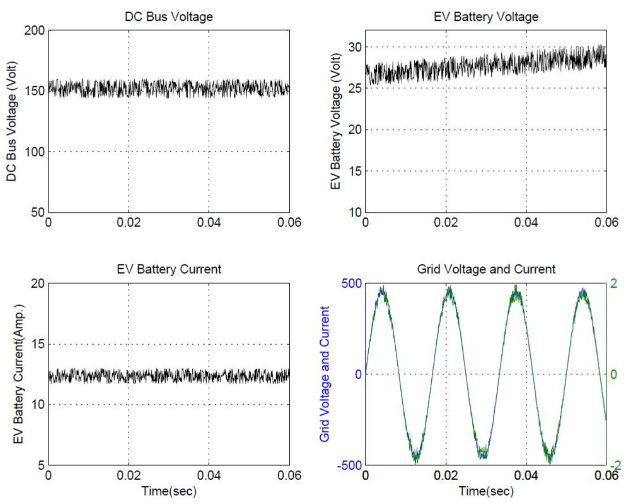


Fig. 6. Experimental results for mode-II

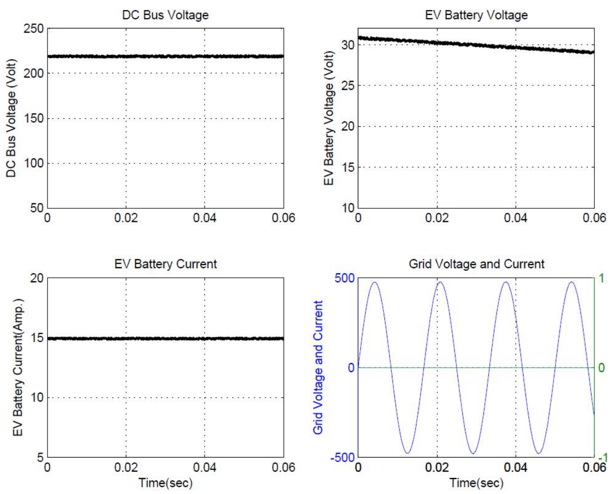


Fig. 7. Matlab Simulation results for mode-III

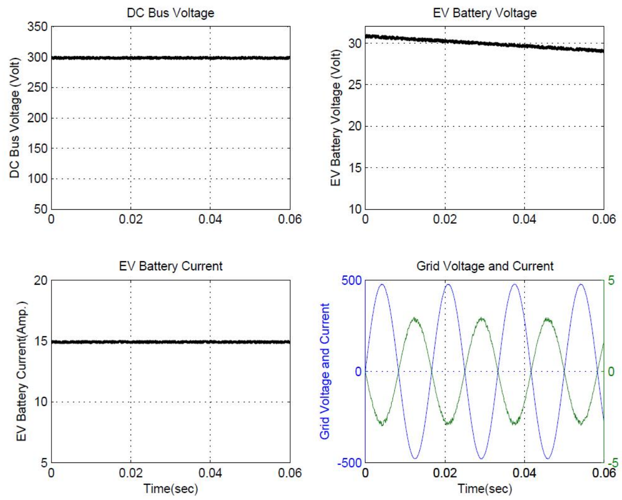


Fig. 9. Matlab Simulation results for mode-IV

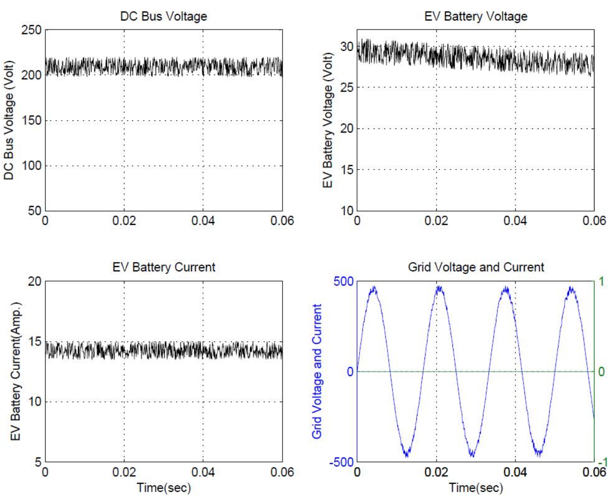


Fig. 8. Experimental results for mode-III

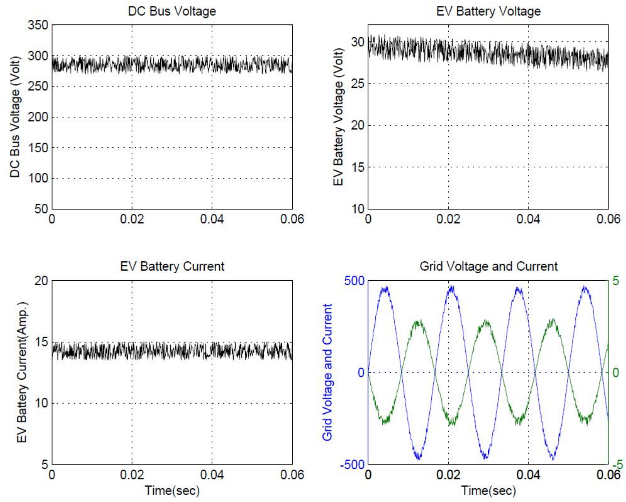


Fig. 10. Experimental results for mode-IV

system generates all the power required to charge the PEV and the power demand by the local loads and the utility grid does not supply any power. The power generated by the PV increases to 500 W, by the Wind is 100 W, by the FC is 400 W, the electrolyzer consumes zero power, the power supplied by the ESU is 400 W, the power demand by the local loads is 900 W, the battery of the PEV is working in the discharging mode supplying power of 400 W. Figs. 9-10 shows the simulation and the experimental results for the operation Mode-4 where the PV-Wind-FC-Battery renewable energy system generates excess power and sends it back to the utility grid. Once the PEVs are completely charged, all the excess power is sent to the grid. The generated power by the PV reached to its maximum level of 700 W, the wind power is 400 W, the FC power is 400 W, the local loads demand is 500 W, the ESU power is 300 W working in discharging mode, the battery of the PEV is working in the discharging mode and supplying power 400 W, finally the power sent to the utility grid is 900 W. With the suggested MPC-MOPSO energy

Table 2. System performance comparison

Control Technique	Conventional PID Controller	SOPSO-MPC	MOPSO-MPC
Charging Time Reduction %	-	3.85	1.67
Battery Temperature Reduction %	-	6.79	4.58
Energy From The Grid Reduction %	-	8.36	4.18
THDv (Inverter Voltage) %	8.16	5.02	2.16
THDI (Inverter Current) %	7.46	6.46	3.58
THD DC Bus Voltage %	7.12	5.08	3.14
THD DC Bus Current %	8.46	6.92	4.37
DC Bus Voltage Error %	6.7637	4.45	2.39

management technique, the dynamic performance of the charging station and stabilization at its reference input voltage when sudden load change of battery charging is highly improved. Therefore, the suggested charging station together with the proposed energy management scheme shows its superiority in the charging performance. The results obtained show that the proposed MPC-MOPSO energy management scheme ensures a better and accurate performance than the one achieved with the SOPSO energy management scheme and the conventional PID controller and that it guarantees a stable operation under transient conditions. To compare the performance of the PV-Wind-FC based charging station with the proposed MOPSO-MPC controller, the SOPSO-MPC controller and the conventional PI controller were tested and full comparison with the proposed controller is given in Table 2. From the outcomes, it is clear that the proposed MOPSO-MPC can enhance the THD and the performance of the charging station and diminish the impacts of the charging unsettling influences.

6. Conclusion

The paper presented a novel energy management strategy for a Wind-FC-PV based residential PEV smart charging station based on MPSO and MPC which determine the direction of energy to minimize the loading on distribution transformers and enhance the effectiveness of the battery charger. The proposed design is reasonable for establishment at parking spots, for example, gated communities, colleges, shopping centres where the charging requirement of PEVs and their parking period in the parking garages are profoundly changing in nature. The energy expected to charge the PEV originates from the hybrid Wind-FC-PV-Battery renewable energy system or the utility grid or both. Since the system is subjected to random variations in renewable power and the SOC of each vehicle in the parking garage, it is important that the system operation is robust against these disturbances. A MPC based on MOPSO control algorithm is designed to make the decisions about when to start the charging of a battery, at what power and what combination of sources to utilize so that the maximum amount of solar energy is utilized for charging purposes and the energy exchanged with the power grid is minimized. The effectiveness of the proposed charging station is validated through simulation results.

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Nomenclature

EV	Electric vehicle
EMS	Energy management system
V2G	Vehicle to grid
G2V	Grid to vehicle
PEV	Plug-in electric vehicle
MOPSO	Multi-objective particle swarm optimization
SOPSO	Single-objective particle swarm optimization
MPC	Model-based predictive
FC	Fuel cell
PV	Photo-voltaic
ESU	Energy storage unit
MPPT	Maximum power point tracking
SOC	State of charge
P_{PV}	Generated power by the PV
P_{Wind}	Generated power by the wind
P_{FC}	Generated power by the FC
$P_{EV\_Charging}$	EV charging power requirements
P_{Load}	Load power requirements
P_{charge}	Charging power
P_{grid}	Utility grid power
E_{grid}	Accessible energy from the utility grid
$P_{renewable}$	Power from renewable energy system
$E_{\mathbf{demand}}$	Energy demand of the EV

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