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DYNAMIC MODELING AND CONTROL OF A CONVERTER BASED EV CHARGING STATION HYBRID ENERGY SYSTEM

[1] N JAMES DINAKARAN [2]R YEDUKONDALU

[1]PG student in department of electrical and electronics engineering, Dr Samuel George institute of engineering & tech, Markapur.

[2] Associate professor in department of electrical and electronics engineering, Dr Samuel George institute of engineering & tech, Markapur.

Abstract— The prospective spread of electric vehicles (EV) and plug-in hybrid electric vehicles leads to the need for fast charging rates. Higher charging rates lead to high power demands, which cannot be supported by the electrical grid. Thus, the use of on-site sources alongside the electrical grid for EV charging is a rising area of interest. In this dissertation, a photovoltaic (PV) source is used to support high power EV charging. However, the PV output power has an intermittent nature that is dependent on the weather conditions. Thus, battery storage is combined with the PV in a grid-tied system, providing a steady source for on-site EV charging in a renewable energy based fast charging station. Renewable energy based fast charging stations should be cost effective, efficient, and reliable to support the high charging rates demanded when a large number of EVs are connected to the electrical grid. However, fast charging stations, especially super-fast charging stations may stress power grid with potential overload at peaking time, sudden power gap and voltage sag. This project discusses the detailed modeling of a multiport converter based EV charging station integrated with PV power generation and battery energy storage system. In this project, the control scheme and combination of PV power generation, EV charging station and battery energy storage (BES) provides improved stabilization including power gap balancing, peak shaving and valley filling, and voltage sag compensation. As a result, the influence on power grid is reduced due to the matching between daily charging demand and adequate daytime PV generation. MATLAB/Simulink Simulation results are presented to confirm the benefits at different modes of this proposed multiport EV charging circuits with the PV-BES configuration.

I. INTRODUCTION

The current environmental challenges of reducing greenhouse gases and the potential shortage of fossil fuels motivate widespread research on electric vehicle (EV) systems. However, the research on EVs is highly impacted by the consumer disposition for switching to EVs as an alternative for conventional internal combustion engine vehicles. This willingness is the main factor in forecasting future demand for EVs. In Reference, the authors depicted that the charging time is one of the main challenges that the EV industry is facing. Generally, the EV charging levels are classified according to their power charging rates. Electric vehicles (EVs) are considered to be the future mode of transportation. Wind, solar, hydropower, geothermal, biogas or tidal energy is excellent sources of renewable energy to power electric vehicles in the future. Amongst these, the use of solar photovoltaic panels to charge EVs is an attractive option due to several reasons:

1. The cost of solar PV has been continuously falling over the past decades and is less than 1$/Wp.
2. PV power has high accessibility to EV users as PV modules can be installed on the roofs and as solar car parks. The PV potential of rooftops or parking places is largely unutilized today, and this can be exploited in the future.
3. There is both reduced energy and power demand on the grid due to EV charging as the charging power is locally generated in a 'green' manner through solar panels. This reduces/delays the need for grid reinforcement.
4. Conventionally, PV systems use a battery to store the solar energy to manage the seasonal and diurnal variations in solar generation. In the case of charging EVs from PV, the EV battery can serve as energy storage for the PV, and no additional battery will be required.
5. The cost of charging the EV from solar is cheaper than charging it from the grid, and it reduces the impact of low PV feed-in tariffs.
6. PV systems have low noise, have no rotating parts and are practically maintenance free.

With the growing interest in decreasing the fossil fuel utilization and pollution, electric vehicles (EVs) have emerged as an applicable alternative to conventional gas engine vehicles. The development and increasing utilization of EVs requires widely distributed charging stations due to the limited EV battery capacity. However, large scale of directly grid-connected charging stations, especially fast and superfast charging stations, stress power grid stability and reliability with peak demand overload, voltage sag, and power gap issues. Some researchers have been integrating photovoltaic (PV) generation with EV charging infrastructure; however, the PV integration is still considered as a minor portion of power source for EV charging stations in researches. As for the higher demand of fast-speed charging during daytime, the rapid development of PV generation optimizes power consumption at peak hours with its adequate daytime generations. With respect to the intermittency of solar energy, a battery energy storage (BES) can be employed to regulate the DC bus or load voltage, balance power gap, and smooth PV power.

Considering the high power density and high efficiency merits of the multiport power converters, a multiport DC/DC converter is employed in this project for the EV charging station instead of using three separate DC/DC converters. Among the aforementioned research, the charging station architectures can be classified into two topologies: using AC bus or DC bus. As PV output and BES can both be regarded as DC current source, DC bus charging station is chosen here to improve the utilization efficiency of solar energy and decrease the cost and losses of converters. Compared with isolated multiport converters, nonisolated multiport converters that are usually derived from buck or boost converters may feature a more compact design, higher power density, and higher efficiency compared with isolated multiport converters. Accordingly, a DC bus nonisolated structure with SiC switches is leveraged in this project, to improve efficiency and minimize the power losses.

II. DESIGN ASPECTS

Electric vehicles (EV) are considered to be the future mode of transportation, and 500 million EVs are expected to be on the road in 2030. The key drivers for EVs are their high efficiency and zero tail-pipe emissions. However, EVs are only sustainable if the electricity used to charge them comes from renewable sources and not from fossil fuel–based power plants. It is here that the solar charging of EV has gained interest in recent times, as it provides a clean and sustainable method to charge EVs. The goal of this thesis is to “Develop a highly efficient, V2G–enabled smart charging system for electric vehicles at workplaces that is powered by solar energy”. The thesis is composed of three main elements – system design, power converter and smart charging algorithms.

System design

The system design of the solar EV charging station investigates the best design for the photovoltaic (PV) system in order to meet the EV charging demands. The design is focused on the Netherlands and considers the diurnal and seasonal solar variations based on data from the Dutch Meteorological Institute. In spite of the lower solar insolation in the Netherlands, an average of 30kWh/day is generated by a 10kWp PV system. This is sufficient for driving 55,000km/year using a Nissan Leaf EV. There is up to five times difference in energy yield between summer and winter, a phenomenon which cannot be overcome by using a solar tracker. Due to the lower insolation, the PV converter rating can be undersized by 30% with respect to the PV array, resulting in only 3.2% loss of energy. Simple charging schemes such as Gaussian EV charging are proposed that help match the EV charging to the PV generation and reduce the dependency on the grid. The use of a local storage was found to help in managing the diurnal solar variations but had a negligible effect in overcoming seasonal solar variation. Finally, different ways to connect a single EV-PV charger to several EVs at the workplace are proposed. The main benefit is that it enables the sharing of the charging infrastructure, thereby reducing the cost and space occupied by EV charging systems in the parking lot.

Power converter

Currently, solar EV charging stations use the 50Hz alternating current (AC) grid to exchange power from PV to EV. However, this is not efficient and cost-effective for two reasons. First, EV and PV are fundamentally direct current (DC) in nature, so conversion to AC leads to unnecessary conversion steps and losses. Secondly, two separate DC–AC inverters are required, one for EV and PV, increasing the cost and size of the power electronics. A suitable solution is hence to use a single integrated converter that charges the EV from PV on DC and requires only a single, common inverter for both EV and PV. In this thesis, a 10kW three-port converter with an internal DC-link is developed that can charge the EV from both the PV and the AC grid. The charger is bidirectional and can implement vehicle to grid (V2G) where the EV can feed power back to the AC grid. The converter can realize four power flows: PV-EV, EV-Grid, Grid-EV and PV-Grid. A comparison of topologies based on power density, efficiency, controllability and component count has shown that the suitable topology for the PV, EV, and grid port are: interleaved boost converter, interleaved bidirectional flyback converter and

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two-level voltage source inverter, respectively. Interleaving, silicon carbide (SiC) MOSFETs, SiC Schottky diodes and powdered alloy inductors are used in the converter to achieve both high power density and high efficiency. The EV charger is modularly designed and several 10kW power modules can be operated in parallel to scale up to higher powers of up to 100kW easily.

Smart charging algorithms

Smart charging refers to the technique of controlling the magnitude and direction of the EV charging power for different applications. Currently, smart charging algorithms focus on one or few objectives at a time, resulting in small reduction in net costs and numerous charging profiles for the same EV. In this thesis, new charging algorithms are proposed that integrate several applications together for charging the EV. This results in the benefit of each application adding up, thereby reducing the net costs significantly when compared to earlier algorithms. The charging algorithms use mixed integer linear programming to control the EV charging based on: PV forecast, EV user preferences, multiplexing of EVs, V2G demand, energy prices, regulation prices and distribution network constraints. For two specific case studies simulated for Netherlands and Texas, the proposed algorithms reduced the net costs in the range of 32% to 651% when compared to uncontrolled and average rate charging, respectively.

EV–PV charging station

Thus, the EV–PV charging station uses the developed power converter and charging algorithms to directly charge an electric vehicle using solar energy and feed EV power back to the grid. Solar charging of EVs results in net zero CO2 emissions, lower fuel cost, tax benefits and less dependence on PV feed-in tariffs when compared to gasoline cars or grid charged EVs. Charging on DC reduces the conversion steps and the associated loss when compared to charging on AC. The use of proposed smart charging algorithms reduces the net costs of the EV charging from PV and defers the cost of distribution network upgrades. The developed EV-PV converter has a much higher peak (95.2% for PV-EV, 95.4% for Grid-EV, 96.4% for PV-Grid) and partial-load efficiency than existing solutions. In spite of it bidirectional power flow capability, the power density of the converter is 396W/l, which is three times that of existing solutions based on Si IGBT technology and AC power exchange. The charger is compatible with the CHAdeMO and CCS EV standard; and the corresponding standards for EMI and grid integration. Successfully tests have been carried out with a CHAdeMO compatible Nissan Leaf EV by charging it from PV panels and feeding power back to the grid via V2G.

III. PROPOSED SYSTEM

In the conventional architecture of DC bus charging station with PV integration (Fig. 1a), all the three power sources, including PV and EV charger unidirectional sources, and AC grid bi-directional source, are all connected through three separate converters. The proposed DC bus charging station (Fig. 1b), consists of one more bi-directional power source BES sharing the same DC bus. The BES is utilized to maintain the DC link voltage and balance power surplus/insufficiency from the PV. With this configuration, the function and operating modes can be discussed as follows in detail.

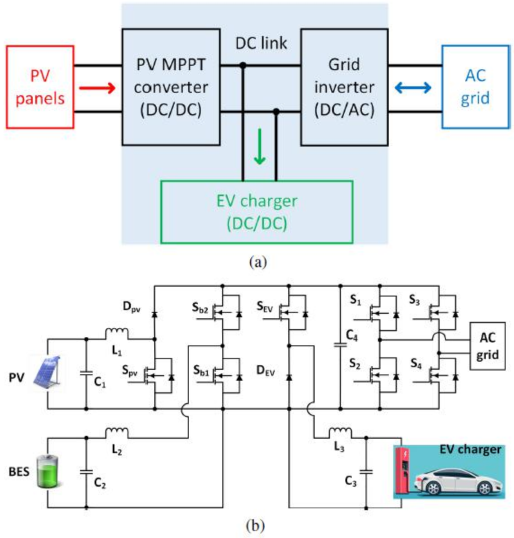

Fig.1: Multiport converter architectures, (a) the conventional architecture of EV charging stations integrated with PV, and (b) the proposed multiport converter based EV charging station architecture integrated with PV and BES.

A. Mode 1: PV to EV

In this mode, the switches Spv, Sb1, and Sb2 are turned off while SEV is turned on (Fig. 2a). Therefore, PV directly delivers power to the load, as shown in Fig. 2a. The differential equations in this stage can be expressed as follows:

$$i_{PV} = C_1 \frac{dv_{C1}}{dt} + i_{EV}$$

$$C_2 \frac{dv_{C2}}{dt} = \frac{v_{Bat} - v_{C2}}{r_b} - i_{L2}$$

$$i_{EV} = C_3 \frac{dv_{C3}}{dt} + \frac{v_{EV}}{R_{EV}}$$

$$v_{C1} - v_{C3} = L_3 \frac{i_{L3}}{dt}$$

$$L_2 \frac{i_{L2}}{dt} = -v_{C2}$$

where C1, C2, C3, L1, L2, L3, and rb represent the capacitance of the PV port capacitor, the capacitance of the BES port capacitor, the capacitance of the EV port capacitor, the inductance of the PV port inductor, the inductance of the BES port inductor, the inductance of the EV load port inductor, and the equivalent resistance between vBat and C2, respectively, as shown in Fig. 1b; iPV , iEV , iL2, and iL3 represent the output current from PV panels, the current of EV load, the current through inductor L2, and the current through inductor L3, respectively; vC1, vC2, vC3, vBat, and vEV represent the voltage across capacitor C1, the voltage across C2, the voltage across C3, output voltage from BES, and the charger voltage, respectively. The duty cycle for the switch Spv can be obtained with:

$$\frac{V_{DC}}{V_{PV}} = \frac{1}{1 - D_{pv}}$$

where VDC, VPV , and Dpv represent the DC link voltage, voltage of PV array, and duty cycle of switch Spv, respectively.

B. Mode 2: BES to EV

When Spv and SEV are turned on while Sb1 and Sb2 are turned off, BES is discharged to the EV load, as shown in Fig. 2b. The differential equations in this mode can be expressed as follows:

$$i_{PV} = C_1 \frac{dv_{C1}}{dt}$$

$$L_2 \frac{i_{L2}}{dt} = v_{DC} - v_{C2}$$

$$v_{DC} - v_{C3} = L_3 \frac{i_{L_3}}{dt}$$

$$C_2 \frac{dv_{C2}}{dt} = \frac{v_{Bat} - v_{C2}}{r_b} - i_{L2}$$

$$i_{EV} = C_3 \frac{dv_{C3}}{dt} + \frac{v_{EV}}{R_{EV}}$$

where vDC refers to DC link voltage, which equals to the voltage across capacitor C4. The duty cycle for switch Sb1 can be obtained with:

$$\frac{V_{DC}}{V_{Bat}} = \frac{1}{1 - D_{b1}}$$

where VDC, VBat, and Db1 represent the DC link voltage, voltage of BES, and duty cycle of switch Sb1, respectively.

C. Mode 3: PV to BES

When Sb2 is turned on while Sb1, Spv and SEV are turned off, BES is charged from the PV surplus energy, as shown in Fig. 2c. The differential equations in this mode can be expressed as follows:

$$i_{PV} = C_1 \frac{dv_{C1}}{dt} - i_{L2}$$

$$L_2 \frac{i_{L2}}{dt} = v_{C1} + v_{DC} - v_{C2}$$

$$L_3 \frac{i_{L3}}{dt} = v_{DC} - v_{C3}$$

$$C_2 \frac{dv_{C2}}{dt} = \frac{v_{Bat} - v_{C2}}{r_b} - i_{L2}$$

$$i_{EV} = C_3 \frac{dv_{C3}}{dt} + \frac{v_{EV}}{R_{EV}}$$

The duty cycle for the switch Sb2 can be obtained with:

$$\frac{V_{Bat}}{V_{DC}} = D_{b2}$$

where Db2 represents the duty cycle of the switch Sb2.

D. Other Modes: PV to BES, Grid to EV, and PV to Grid The operating principle of other modes including PV to BES, grid to EV, and PV to grid. Besides, the differential equations can be similarly expressed with the same analysis method in Modes 1 to 3. The detailed simulation analysis will be provided in the following section.

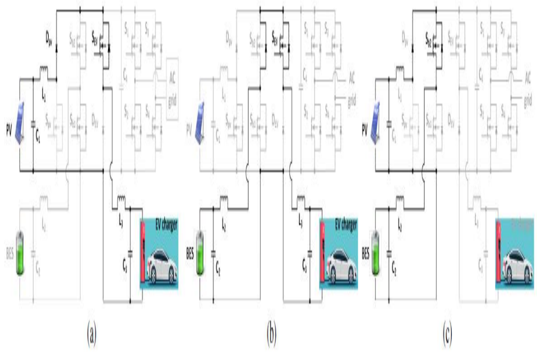

Fig.2: Multiport converter operating modes, (a) PV supplies EV charging when solar energy is sufficient, (b) BES supplies EV charging during

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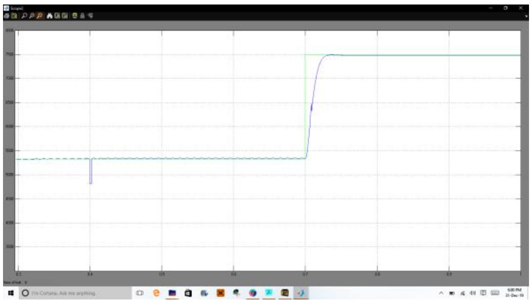
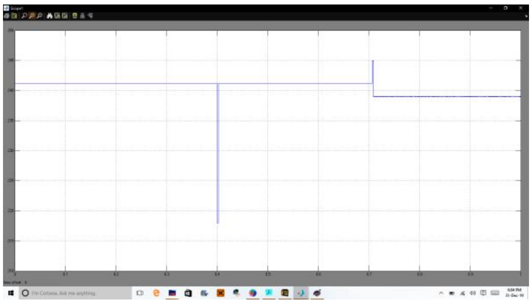
PV intermittent, and (c) PV charges BES when solar generation is surplus.

IV. SIMULATION RESULTS

CASE-1: EV CHARGING:



(a) demand and consumed power of EV charging.

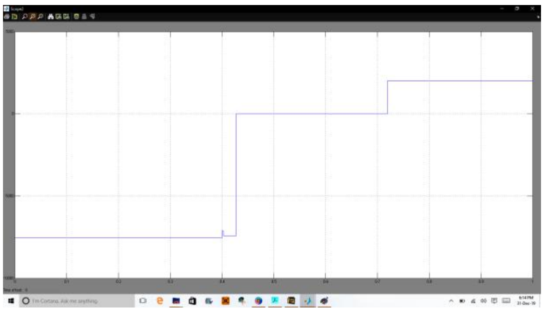


(b) Terminal voltage of the EV charger.

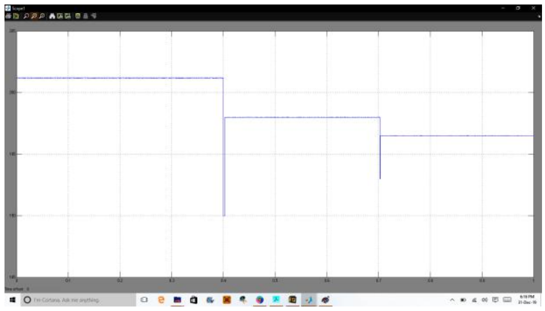
Fig.3: The simulation results of EV charging.

The control scheme is simulated with MATLAB/Simulink. At 0.4ms of the simulation time, the irradiance drops from 700k/W^2 to 600k/W^2, and at 0.7ms of the simulation time, the load should be varied. At 700ms of the simulation time, EV charging demand suddenly goes up from 5.7kW to 7.7kW; it can be seen in Fig. 3.

CASE:2- BATTERY ENERGY STORAGE:



(a) Output power from BES.



(b) Terminal voltage of the BES.

Fig.4: The simulation results of the BES.

In this case, between the simulation time of 0 to 0.4ms, the EV charging demand is low while the PV generation is sufficient. Therefore, both PV-to-EV and PV-to-BES modes are triggered, and the surplus PV generation charges the BES. Between the simulation time of 0.4ms to 0.7ms, the PV panels can provide 5.7kW which meets the EV charging amount. As a result, the system is operated in PV-to-EV mode and no BES charging/discharging is required. After the charging demand increase at 0.7ms, the PV panels are not able to supply all the required 7.7kW charging power under the condition of 400k/W^2 irradiance. Therefore, the BES starts to discharge and supply EV charging with 2kW and provides voltage support, as shown in Fig. 4.

CONCLUSION

In this project, a multiport converter based EV charging station with PV and BES is proposed. A BES controller is developed to regulate the voltage sag, and balance the power gap between PV generation and EV charging demand. With the proposed control design, BES starts to discharge when PV is insufficient for local EV charging, and starts to charge when PV generation is surplus or power grid is at valley demand, such as during nighttime. As a result, the combination of EV charging, PV generation, and BES enhances the stability and reliability of the power grid. Different operating modes and their benefits are investigated and then, simulation and thermal models of the multiport converter based EV charging stations and the proposed SiC counterpart are developed in ANSYS TwinBuilder. Simulation results show that the efficiency can be improved by 5.67%, 4.46%, and 6.00%, respectively, for PV-to-EV mode, PV-to-BES, and BES-to-EV mode at nominal operating condition, compared to Si based EV charging stations under the same operating conditions.

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