Integrated solution for future transportation and power systems through wind-solar hybrid power plant with energy storage

Thananjeyan S., Arunan S., Thiruvaran T., Atputharajah A., V.K. Ramachandaramurthy

Abstract: This paper addresses integrated solutions with the energy storage, which plays multiple roles in applications in transportation and power systems. The proposed integrated and automated control concept for a battery charging station, which can be also used for electric vehicle applications, improves the performance of solar power plant while effectively using the power systems network. This has number of benefits such as: (i) eliminates power fluctuations in the grid, which generated due to intermittent nature of solar intensity or wind speed, and allows to increase renewable energy penetration (ii) charge the batteries by absorbing all fluctuating active power components, which eliminates voltage flicker at the grid, (iii) allow facility for load shifting, (iv) allow grid voltage or reactive power control if it is required by the system operator and (v) finally fast charging of battery is also possible when ever need arises. This coordinated control technique helps to utilize the power electronic devices together with energy storage to achieve number of operations together or separately. Therefore it is called as all-in-one-device concept in this paper. This is an excellent value addition for any of the existing power electronic converters already used especially in solar power generation. Further this is going to be the trend with (i) boosting electric vehicle technology for transportation and (ii) viable solar power plant technology, where energy storages are commonly applied.

Keywords: Solar power plant, battery charging control, eliminating power fluctuation, electric vehicle application, energy storage

1. Introduction

The development of power electronic technology is bringing the "grid connected solar power plant" as an economically viable project [1-3]. It became more attractive with advancement of electric vehicles applications in future transportation. Here energy storage plays major role. However, in today's concept the energy storage is not fully utilized.

Several controls for battery charging, grid integration, eliminating power fluctuation, reactive power and all those controllers' operations [4-7] are being proven by researchers. Today's concept on technology is towards utilizing the available components in the system. As a result the best and implementable technology always uses existing components to achieve number of operations. This paper also with the same idea and therefore all-in-one concept is considered. Individual controls [8] of power electronic circuits, energy storage devices, power system network operations, electric vehicle applications are merged in this paper. This has been simulated using the PSCAD/EMTDC

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software and the results shown excellent result. It has been proven the performance of individual controllers and their combine operations.

This study can be extended further to implement an excellent man-machine interaction. This will allow the dynamic operation to achieve the best performance of the battery charging station according to the requirement from both power systems as well as electric vehicles.

2. Configuration of the studied system

There are two configurations of solar systems used in normal operations. As shown in Figure 1, wind-solar system connected to the main grid. A dc-dc converter is used for maximum power extraction and then dc-ac converter is used to couple the solar plant to grid. In this case the proposed controllers can be implemented in the dc-ac converter already used in the solar plant and used as Battery Charging Station (BCS) to Electric Vehicle (EV) applications. If required the power electronic devices may need to be upgraded with extra rating at the designing stage of the plant.

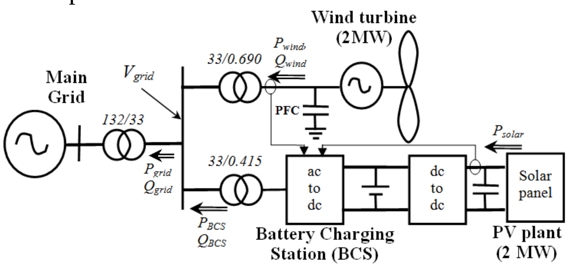

Figure 1: Battery charging station embedded with ac-dc converter control of the solar power plant

The wind-solar plants set up shown in Figure 2, uses only dc-ac converter to couple the solar plant to the grid while achieving maximum power tracking in the solar plant. In this case the existing converter cannot be used to implement battery charging station to the EV with proposed control technique. Here additional converter station, as shown in Figure 2, has to be placed at the grid connecting bus and almost similar control technique can be used for battery charging station while eliminating the power fluctuation going to the grid side.

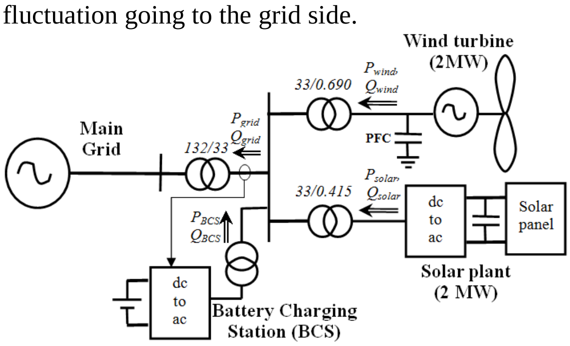

Figure 2: Separate battery charging station for solar power plant without the dc-dc converter

3. Proposed control concept

The proposed control concept is explained with some theoretical analysis as shown in Figure 3. All vertical axes are active and reactive powers in MW and MVAr while horizontal axes are time in seconds.

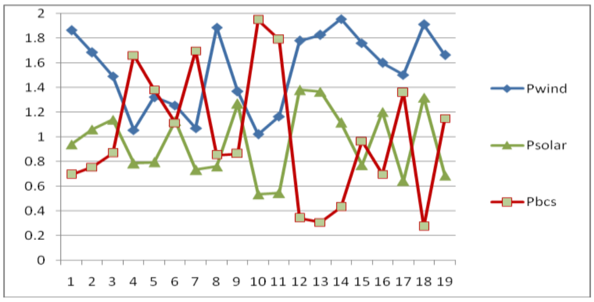

Figure 3a: wind, solar power fluctuation and BCS power

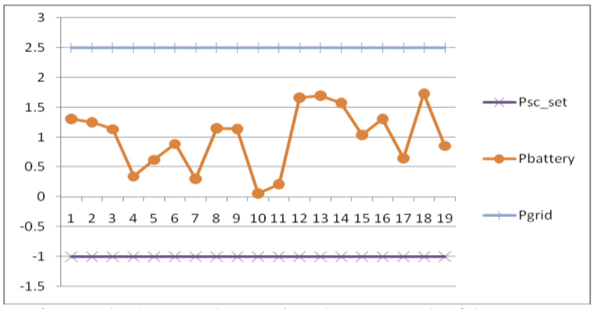

Figure 3b: C control set value, battery and grid power

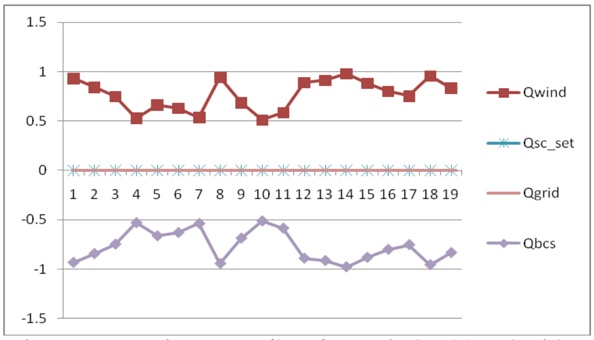

Figure 3c: Reactive power flow from wind, BCS and grid

Figure 3a shows that the fluctuating wind, solar power and accordingly with the theoretical controller action the BCS power also fluctuating. Figure 3b shows the 2.5MW constant active power flow in grid, system control set power was adjusted to 1MW and thus makes all the time, battery is charged without going to negative power. This shows the targeted active power controller's operation. Finally Figure 3c shows the reactive power where all the reactive power absorbed by the wind farm is injected from the BCS. Here the reactive power system control set point was set to zero to make this operation at grid connection point to be unity.

4. Proposed control technique

a) Phase angle detection of the voltage at the grid connection

This paper discusses further on the coordinated control technique proposed for the configuration shown in Figure 1. The measured three phase instantaneous grid voltages in per unit (v_{grid_abc}) was sent through PLL **[9],** as shown in Figure 4, to detect phase angle.

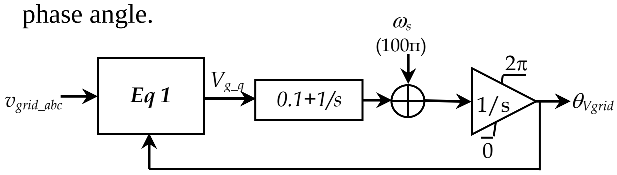

Fig. 4: Control block diagram of the three-phase PLL

$$v_{gq} = v_{ga}\sin\theta + v_{gb}\sin\left(\theta - 2\pi/3\right) + v_{gc}\sin\left(\theta + 2\pi/3\right) --- Eq\ 1$$

b) Calculating the constant active power (P_{grid}) to be injected to the grid

Solar power plant instantaneous output power (P_{solar}), as shown in Figure 1, is calculated from by multiplying the solar plant output dc-voltage and current. The instantaneous active power (P_{wind}) from wind power plant is calculated using instantaneous power theory **[10]**. The total power (P_{total}), as shown in Figure 5, was sent through Low Pass Filter (LPF) with the cutoff frequency of 0.5Hz. This filters the power fluctuations up to 0.5 Hz. Active power control set value (P_{SC_set}), based on system control requirement can be used to shift load if the station is equipped with enough batteries or battery charging speed can also be controlled through it.

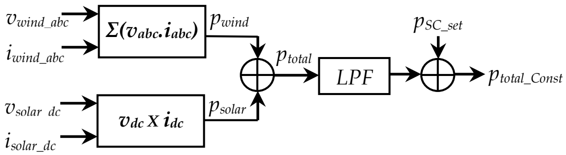

Fig. 5: Block diagram of constant active power calculation

c) Calculating the three phase instantaneous currents of the Battery Charging Station

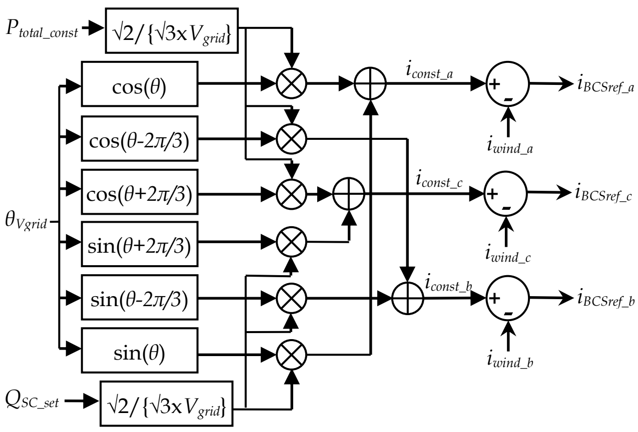

Fig. 6: Calculation of reference three phase output currents for the BCS controller

Fig. 6 shows the block diagram of the BCS output current calculation. To inject additional reactive power, if required by the system control, a system control set value (Q_{SC_set}) is added. This signal can be used to control voltage at grid connection point or power factor control by varying the reactive power. From the calculated active power (P_{total_const}), set reactive power (Q_{SC_set}), rated terminal voltage (V_{grid}) and the phase angle of the terminal voltage (θ_{Vgrid}); the three-phase instantaneous currents (i_{const_abc}) related to the constant power are calculated. These are the currents supposed to be the total injected to the grid at the connection point. Finally the BCS injected currents (i_{BCSref_abc}) are calculate by measured currents at the wind farm (i_{wind_abc}) from the calculated currents (i_{const_abc}). The calculated currents (i_{BCSref_abc}) contains all the reactive power absorbed by the wind farm, fluctuating active power from wind farm as well as solar plant and set active and reactive power by the system control (if any). These calculated currents are the reference currents to the BCS dc-ac converter control, where these currents have to be injected as output ac currents from the BCS.

d) Converter control of the BCS – hysteresis current control

A hysteresis base current control is used as converter control of the Voltage Source Converter (VSC) of the BCS. The technique of the hysteresis current controller, used in this simulation, is shown in Figure 7.

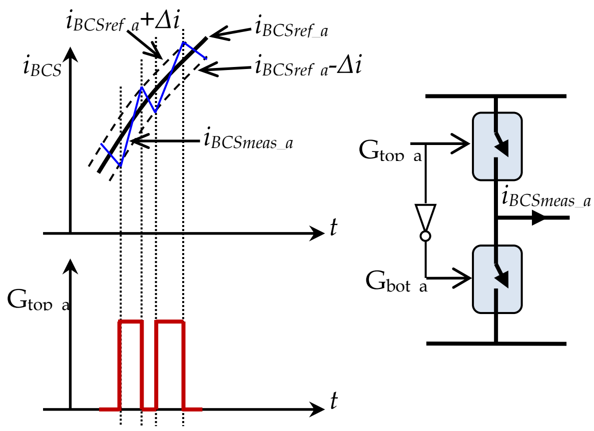

Fig. 7: Hysteresis controller technique for the BCS VSC

In this controller, the calculated output currents (reference currents i_{BCSref_abc}) is compared with the measured BCS output currents ($i_{BCSmeas\_abc}$) and the error is sent through hysteresis controller, as shown in Figure 7, to produce gate pulses to the converter switches. A signal (G_{Open_switch}) is used to block all signals going to the switches by opening the switches.

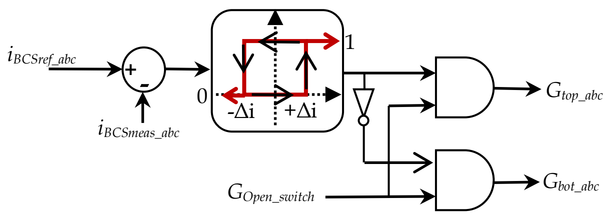

Fig. 8: Hysteresis current controller with gate blocking technique

The blocking signal is operated by logic AND circuit with the output to produce top and bottom switches' gate signals (G_{top_abc} or G_{bot_abc}). This helps to eliminate to startup transients in the simulations. In practice, it can be used for protecting the device.

e) Developed battery model at the PSCAD to represent its characteristic

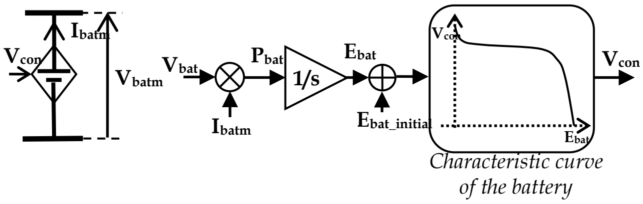

Fig. 9: Developed Battery model for simulation

Battery model was developed to use in simulation is shown in Figure 9. The measured battery terminal voltage (V_{batm}) and output current (I_{batm}) were multiplied to get the output power (P_{bat}) from the battery. It was integrated to get the energy (E_{bat}) in the battery. If the battery had some initial energy then a signal was ($E_{bat\_initial}$) added to represent it in the simulation. Finally base on the battery energy and according to the battery characteristic graph, the battery terminal voltage (V_{con}) was taken. This was used as external input to the dc source in the model to generate the battery terminal voltage.

5. Simulation results

The proposed system in Figure 1 was simulated with the complete control technique. Results are presented in this section with detail discussions. In overall, it has proved that the proposed control technique worked excellently. The grid reactive power was maintained at constant and zero. Grid active power is maintained at constant based on the available power from wind and solar plants and system control set point.

a) Operation of the hysteresis current controller of the converter

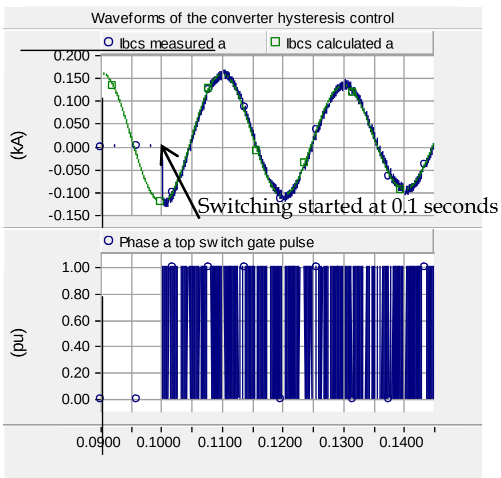

Fig. 10: Converter hysteresis current control – phase a measured and calculated (or reference) currents and switching pulse

Figure 10 shows the result of the hysteresis converter control. The switching operation started at 0.1 seconds of the simulation. It confirms that the calculated current is exactly followed by the measured current and accordingly converter switches are operated.

b) Operation battery model implemented in the simulation

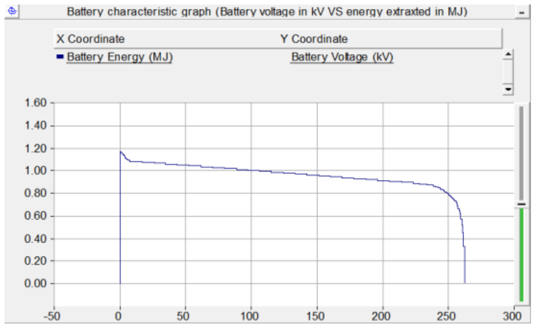

Fig. 11a: Battery characteristic graph of voltage vs energy extraction

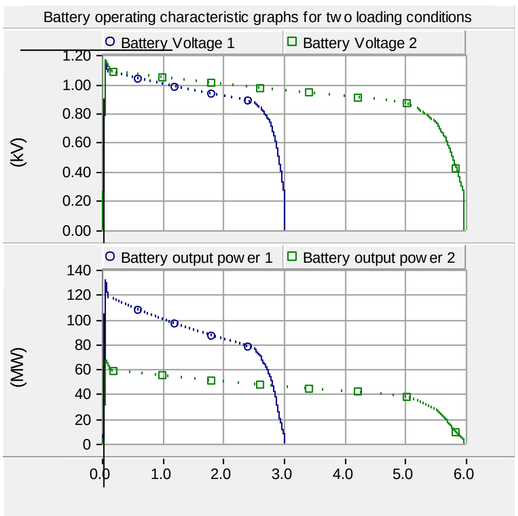

Fig. 11b: Battery model performance for two discharge rate (power)

Figure 11 shows the performance of the battery model developed in the simulation. Figure 11a shows the battery characteristic on voltage variation with energy extraction. This shows that this battery model is made to be having the capacity of 250MJ of energy with 1kV voltage rating. Further its performance with two different discharging powers is shown in Figure 11b.

c) *Performance based on system operators' control requirements*

To study the performance of the proposed system based on system operators' control requirements, the system control set points were varied in ramp as well as step. This is to check the worst case performance for fast variations. During this study, the power from solar and wind was kept at constant to clearly illustrate the response for system control. Figure 12 shows the performance of the proposed complete system for varying the system control set points

(P_{SC_set} and Q_{SC_set}). The ramp and step changes were made as given in the top graphs of both Figures 12a and 12b.

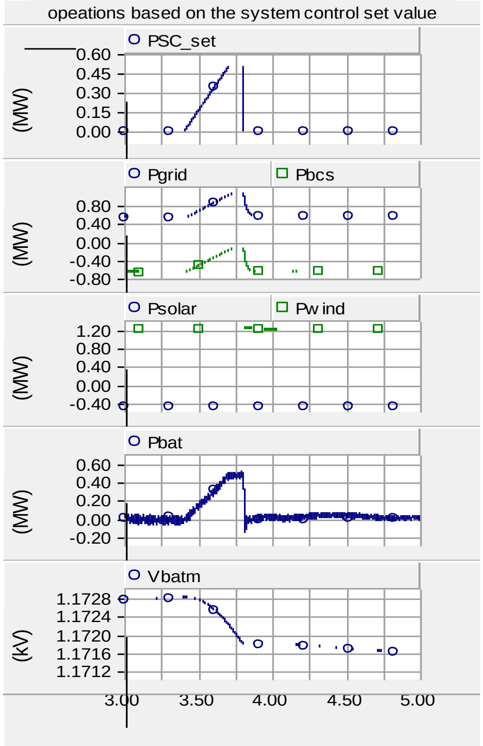

Fig. 12a: Performance of the proposed system with change in system control set point of the active power (P_{SC_set})

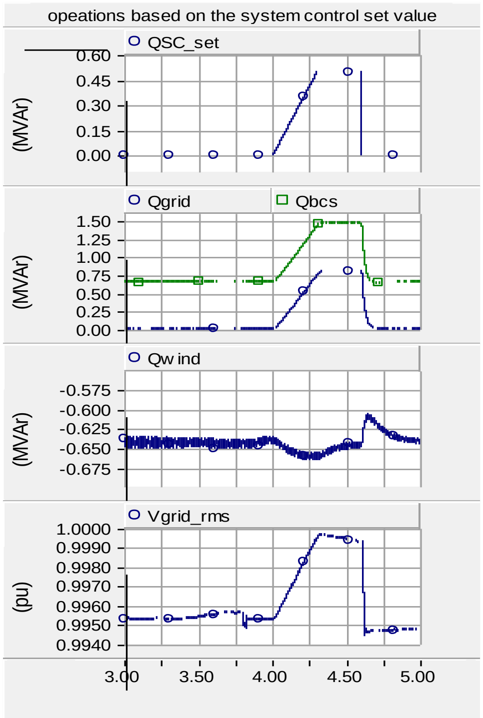

Fig. 12b: Performance of the proposed system with change in system control set point of the reactive power (Q_{SC_set})

As shown in Figure 12a, the battery voltages changes as expected with the active power injection based on system control requirement. Battery rapid charging can be controlled through this control signal. Further grid active power variation confirms accordingly the load shifting control can also be made by varying this system control set signal. As shown in Figure 12b, this confirmed that proposed control technique working as expected while maintaining power factor at the grid connection at unity when Q_{SC_set} is set to zero. The grid terminal voltage varies as expected with the reactive power injection based on system control requirement. This also confirmed that the power factor at the grid connection point or the grid terminal voltage control can be achieved using this system control set signal.

d) *Performance for eliminating the power fluctuation at the grid network due to wind and solar plants*

Figure 13a shows the performance of the proposed control system for eliminating the power fluctuation due to intermittent nature of the renewable energy technology. The fluctuating components on the wind and solar power were engaged at 2 and 2.5 seconds of the simulation study respectively. Here the constant active power is send to the grid and fluctuating active power is used to charge the battery at the BCS. Here the battery power is always in negative so that it charges always by absorbing total fluctuating power from wind and solar above from its minimum power. This increases the battery energy thus increases the battery terminal voltage accordingly.

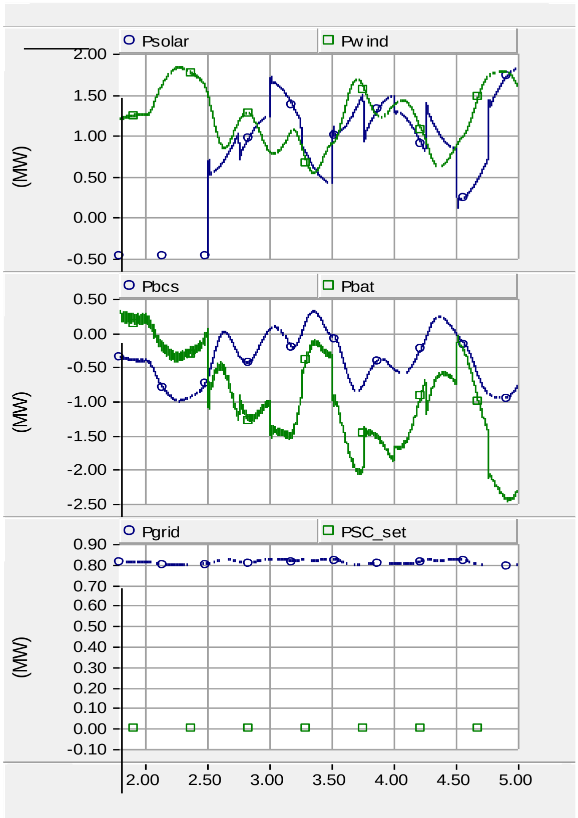

Fig. 13a: Performance on active power injection of the proposed system with fluctuating wind and solar power inputs

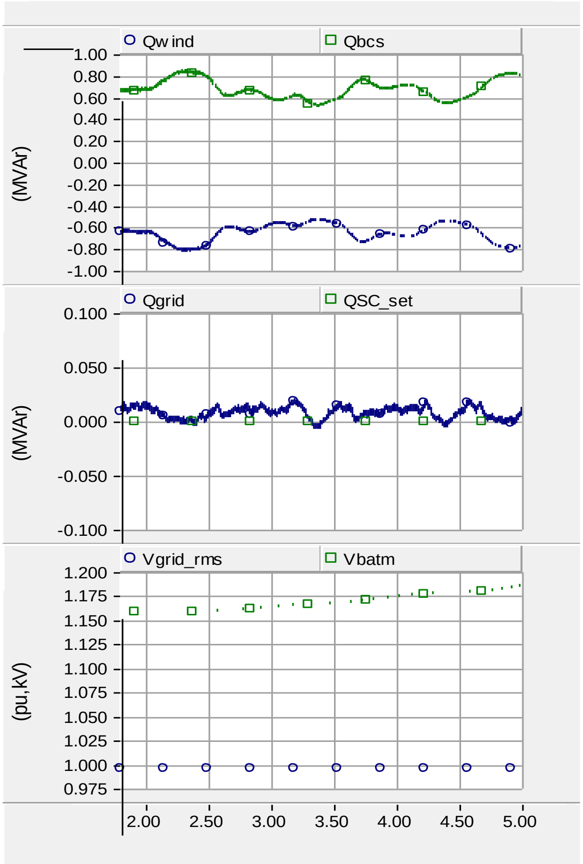

Fig. 13b: Performance on reactive power injection of the proposed system with fluctuating wind and solar power inputs

Figure 13b shows the reactive power variation in the system. The complete reactive power absorbed by the wind farm is supplied by the BCS converter. This confirmed the proposal control system is working as expected.

An additional control loop was added to maintain the battery voltage around 1 pu. This was achieved by varying the system control active power set value. The simulation was repeated with the battery voltage control. Wind and solar fluctuations engaged at 2 and 2.5 seconds respectively. Further to check the possibility of power factor control the system control reactive power set value was change to match the power factor at 0.9 lagging. The performance study was made on lagging and leading power factor operation. This was done by gradually changing the 0.9 lagging power factor into 0.9 leading power factor starting from 3 seconds in the simulation.

The average battery charging rate is adjusted by changing the grid power through the system control set value. This maintains the battery voltage within the allowable range thus can be seen from Figure 14a. Further the added control loop on the system control reactive power set value, keeps the reactive 0.9 lagging power factor operation till 3 seconds as shown in Figure 14b. Then it changes from lagging to 0.9 leading power factors gradually.

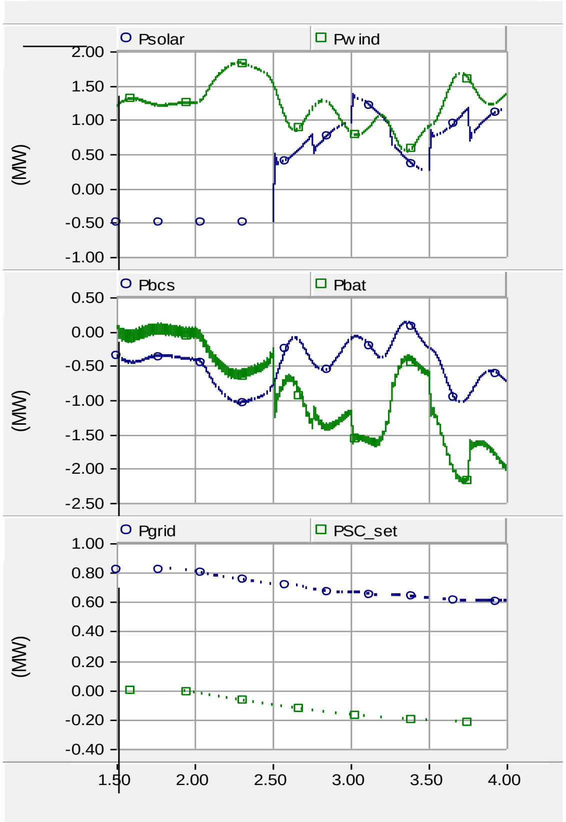

Fig. 14a: Performance on battery voltage regulation control through active power system control set value

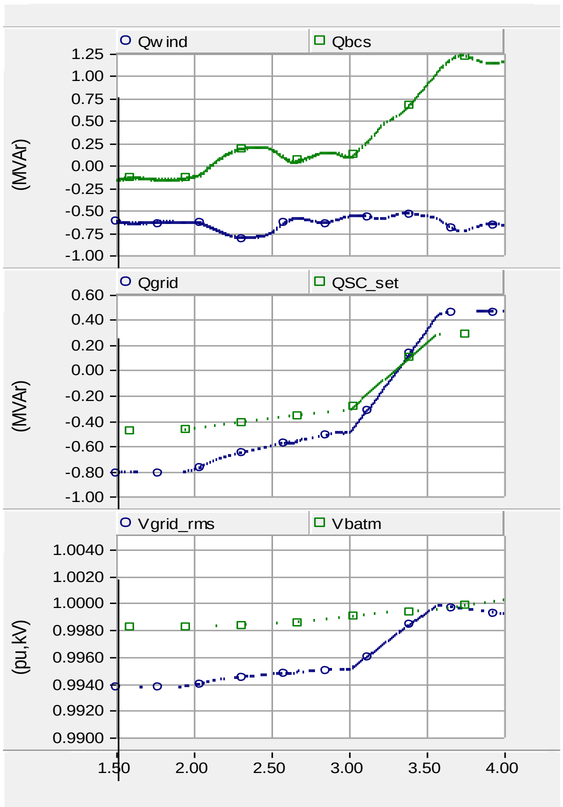

Fig. 14b: Performance on lagging-leading power factor control through reactive power system control set value

This can be summarized that the proposed control technique with proposed operating concept of electric vehicle battery charging station together with wind-solar power plants worked very well. The requirement from the controller is achieved and all simulation results confirmed the performance of the proposed system.

6. Conclusions

This paper proposes the effective integrated concept for a battery charging station for electric vehicle together with integrating renewable energy technologies such as wind and solar to the power system grid. A coordinated control system was developed and modeled in simulation. The results confirmed that the proposed system has number of benefits such as (i) eliminates power fluctuations in the grid, which generated due to intermittent nature of wind and solar, (ii) charges the batteries by absorbing all fluctuating active power components, which eliminates voltage flicker at the grid, (iii) compensates the entire reactive power, including fluctuating component, absorbed by the wind farm, (iv) allows facility for load shifting if system operator requires, (v) allows grid voltage or reactive power control, by controlling the reactive power system control set value, if it is required by the system operator and (vi) finally fast charging of battery is also possible by adjusting the active power system control set value. This coordinated control technique helps to utilize the power electronic devices to achieve number of operations together or separately. This is a real value addition for any of the existing power electronic converters/inverters used in renewable energy applications. Further it increased the applications of the same energy storage device used in electric vehicle to the solar power plants and power systems.

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