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A Novel Grid-Connected PV-Battery Control Strategy for Electric-Based Power Generation

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Abstract

In this paper, a novel hybrid Voltage Source Converter (VSC) controller and battery bidirectional controller have been designed to solve the difficulties of power fluctuation on the DC-link of the grid connected Photovoltaic (PV)/battery system. The hybrid VSC controller is designed to maintain smooth power on DC-link. The hybrid VSC controller adjusted the inverter pulse signals based on the PV-generated output, which is affected by environmental climates and load variation. To achieve system stability, the charge and discharge of the battery are performed by a bidirectional controller that is synchronized with a hybrid VSC in a coordinated manner so that supply maximum power to the grid. The performance analysis of the proposed controller, the issues of DC and AC sides of the system are analyzed and these aspects are mitigated by the proposed controller that has been used to improve power quality and eliminate harmonics distribution. On the other side, the performance of the hybrid controller has been analyzed under the situation of one-day environmental climates. Finally, the simulation results in MATLAB/Simulink demonstrate that the proposed electric based power generation controller performs well on the presented grid connected PV/ battery system.

Keywords: PV-battery system; Hybrid VSC controller; Solar energy; Renewable energy sources; Energy storage; Electric based power generation

Introduction

With the rapid increase in the use of renewable energy for utility power generation over the past few decades, it is becoming a challenge for the controller to keep the system stable and reliable. One of the problems that PV systems are facing is the change in weather and on the other hand the effect of inverters, PV controllers and load demand in the system. The change in radiation and temperature is due to unpredictability in the weather, due to which energy storage batteries are being used to compensate for the fluctuation of power output on the DC side of the system. For PV system with battery, it is very important to design an effective controller that controls the inverter in such a way that the system can provide maximum power to the grid and one can only do this when the unity power factor is achieved. For Hybrid System (HS) to performer well, the energy transmitting must be designed correctly. Secondary goals such as maintaining the charge level of energy storage devices within their operational limitations, minimizing the costs of generation, working the system at high efficiency, reducing fuel consumption, and so on are fulfilled using energy dispatching strategies. A decentralized control technique based, Battery Energy Storage (BES) system is used by Kim et al. [1] to smooth PV generation and increase the scalability of microgrids. The BES is utilized by Merabet et al. [2] and Ahadi et al. [3] to stabilize the wind-PV microgrid and provide stable electricity to the loads. To control the inverter, the controller is designed in such a way that the MPPT of the PV system and the battery converter are synchronized in such a way that the power fluctuation on the DC link side and the hormone on the such side is reduced, and the maximum power inject to the grid so that the power quality of the system is improved [4-9].

The converter AC-DC connectivity is managed in the system to gives a steady AC voltage and frequency for the AC grid, while the bidirectional DC-DC converter maintains the DC bus voltage [10]. The AC-DC interlinking converter is utilized in grid-tied mode to preserve the voltage of DC bus stable and power is exchanged between the microgrid and the electric grid [11]. Traditional numerous feedback loops with Proportional Integral Differential (PID) controllers are typically employed to regulate all converters in the literatures described [12]. The BES is maintained discharging or charging at a steady rate in grid connected mode in most of the analysis presented above. This is clearly not the best technique, as overcharging or discharging may occur if the State of Charge (SOC) is not considered. A number of closed-loop methods have been proposed to achieve accurate SOC estimation. Because of their minimal computational complexity and reasonable accuracy, adaptive filters like the luenberger observer by Rahimi et al. [13] and Kalman filter are used by Wang et al. [14].

The hybrid VSC controller is designed to control the inverter in such a way that the MPPT of the PV system and the battery converter are synchronized in such a way that the power fluctuation on the DC link side and the harmonics on that DC side are reduced, and the maximum power inject to the grid is increased, resulting in improved power quality. In this paper, a hybrid converter is designed that works in a coordinated manner with the MPPT output and bi-directional converter to improve the power quality of the system so that the system is stable and reliable. In the first stage, analyses the performance of the proposed controller, the Power Quality (PQ) issues have been analyzed at each step on the DC and AC side of the grid connected PV/battery system. In the second stage, based on the performance analysis of the proposed controller, the stability of the system has been analyses under real one day solar irradiation. Finally proposed hybrid system has been modeled in MATLAB/Simulink and the simulation results as obtained are compared with an existing controller.

Design of the Proposed Methodology and Experimentation

The proposed grid connected PV/battery system configuration is shown in Figure 1. The PV/battery system is connected to the grid *via* a common DC and AC bus. The AC-DC converter connects the AC and DC buses, whereas the power electronics DC-DC converter connects the system to the DC bus. Three loads are connected to the AC bus line of the system through switches. The maximum power can be achieved by both DC and AC converter and the proposed inverter controller in such a way the power fluctuation at DC-link under environment and load variation. The proposed VSC, which maintains unity power factor and feeds the maximum power to the grid, can achieve the PQ during defective and load variation.

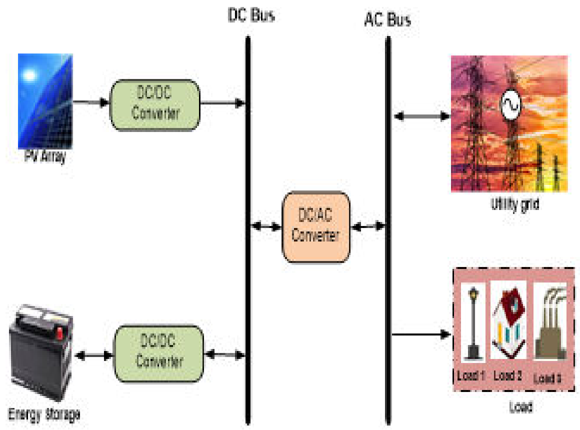

Figure 1: Equivalent model of the grid connected PV/battery systems.

PV system structure model

A photovoltaic system consists of a set of connected PV cells in parallel and series combinations. The characteristic of the PV system is characterized by a single PV cell, represents an equivalent model of the PV system and single PV cell configuration, the PV system can transform solar irradiation into electrical energy. The equivalent model of PV system IPV and VPV is the maximum generated current and voltage of PV array, where Vdc is a DC-link voltage. According to Figure 2, each PV cell has behaved like a current source (Iph) which is generated by a light source. A set of PV cells to produce the desired output power, the reverse saturation current (Is) is present in a parallel ideal diode, a shunt resistance Rsh and a series resistance Rs, using Kirchhoff's law determines the V-I as follows by Mishra et al. [15].

$$I = I_{ph} - I_o\left[\exp\left(\frac{V + IRs}{AV_t}\right) - 1\right] - \left[\frac{V + IRs}{Rp}\right] \quad (1)$$

Where is Iph:Current generated by the incident light, q:Electron charge, 1.6 × 10-19C, A:Ideality factor of diode and Vt=kT/q, is the thermal voltage in which k=1.38 × 10-23 J/K, is the Boltzmann's constant, T=p-n junction temperature in kelvin. Dependence of the photo current (Iph) on environmental parameters *i.e.,* temperature and irradiance may be expressed as:

$$I_{ph} = \left[I_{ph,n} + K\left(T - T_{ref}\right)\right]\frac{S}{S_n} \quad (2)$$

Dependence of diode saturation current is defined as:

$$I_0 = I_{0,n}\left(\frac{T}{Tref}\right)^3 \exp\left[\frac{qE_g}{AK}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right] \quad (3)$$

$$I_{0,n} = \frac{I_{sc,n}}{\exp\left(\frac{V_{oc,n}}{AV_{t,n}}\right) - 1} \quad (4)$$

Where In:Photocurrent at standard test condition, K:Temperature coefficient of short circuit current, Tref:Reference temperature, Sn:Irradiance at standard test condition, Io,n:Saturation current at reference temperature, Isc,n:Short circuit current at reference temperature and Voc,n:Open circuit current at reference temperature. The standard test conditions happen with Irradiance as 1000 W/m², cell temperature as 25°C and spectral distribution (air mass).

In this paper 'sun power SPR-305E-WHT-D' PV modules using for the hybrid system. The model parameters are given in Table 1. That the solar input (irradiation) value increases then the short circuit current of PV as shown the V-I and P-I curves at different irradiation. The generated output power increases with increasing solar irradiation as shown in Figure 2.

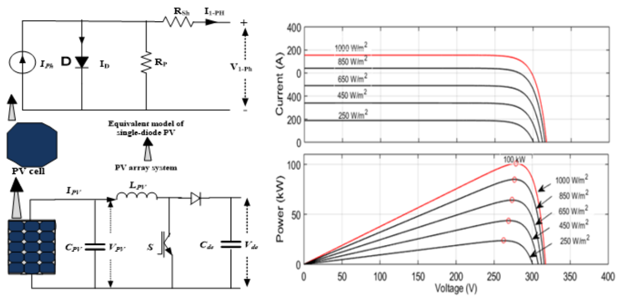

Figure 2: Equivalent model of single-diode PV cell and PV system configuration and V-I and P-V curves at different solar irradiation levels.

The basic PV cell parameters		
Module type: SPR-305E-WHT-D		
Parameter	**Symbol**	**Specification**
PV maximum output power	Pmpp	302.226 Watts
PV open circuit voltage	Voc	64 Volts
Voltage at MPP	Vmpp	54.6 Volts
Short circuit current	Isc	5.95 Amps
Current at MPP	Impp	5.58 Amps
Number of series cells	Ns	5
Number of parallel cells	Np	66
Battery parameters		

Battery type: Nickle-metal-hybrid		
Parameter	**Symbol**	**Specification**
BESS nominal voltage	VBatt	450 Volts
BESS capacity	BC	150.66 Ah
State of charge	SOC	60%

Table 1: Model parameters.

Battery model and control structure

Where the intermissive character of renewable energy resources and the fluctuating load demand are depicted in the Energy Storage System (ESS) structure Figure 3, ESS is important to smooth the gap between the generation and depletion. ESS has two important parameters, the first is terminal voltage and the second is the State of Charge (SOC) of the battery presented.

$$V_{batt} = V_0 + R_{batt} I_{batt} - \frac{KQ_{batt}}{Q_{batt} + \int I_{batt} dt} + A_{batt} \exp\left(B_{att} \int I_{batt} dt\right) \quad (5)$$

$$SOC = 100\left(1 + \frac{\int I_{batt}\, dt}{Q_{batt}}\right) \quad (6)$$

Where Vbatt:Terminal voltage of the battery, V0:The open-circuit voltage of the battery, Rbatt:Internal resistance of the battery, Ibatt:Charging current of the battery, K:Polarization voltage, Qbatt:Battery capacity, Abatt:The exponential voltage, and Bbatt:The exponential capacity. The battery can be charged or discharged by regulating the bidirectional DC-DC converter.

The ESS control block diagram is depicted in Figure 3. The discharging and charging of the battery is controlled by a bidirectional converter, which is controlled by generated switches signal obtained by the PWM generator where duty signal is the input of PWM. To obtain a duty signal, PI controllers are required afterwards; a two-loop control system should be used [16].

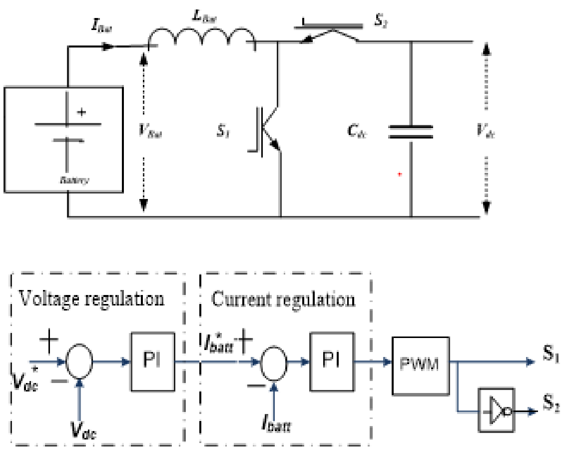

Figure 3: Battery energy storage system and its controller.

In the first scheme, we need the reference current for the inner current loop which is the output of the PI controller where the input is the error signal between the measured DC bus voltage and the reference voltage of the PI controller. In the second scheme based on current regulation in which the input is the error signal between battery current and reference current (depend on bus voltage side) of the PI controller and output is duty cycle which is given to PWM generator to control the charging and discharging of the battery. For instance, the external voltage controller generates a negative current reference whenever the dc bus voltage exceeds the reference voltage. The duty cycle is then adjusted by the internal current loop. This adjusted duty cycle then forces the flow of current into the battery through the dc bus and the battery gets charged. Subsequently, due to extra energy absorption by the battery, the dc bus voltage gets reduced in reference. Battery energy shortages should be considered when SOC limitations and charging and discharging rates are exceeded.

Proposed Inverter Control Structure Model

In Figure 4 and Figure 5 the proposed VSC control system utilizes two control loops: An exterior control loop that regulates the DC link voltage up to the appropriate limit, and an internal control loop that regulates the active and reactive current components of the id and iq grid currents. Here three-phase current converted into two-phase currents in the αβ co-ordinate system with help of abc to αβ transformation and output will be iα and iβ now it's transformed into dq co-ordinate with help of αβ to dq transformation and output will be id and iq. The error signal between id and id^*(MPPT maximum current) is input to the controller and on another side, the error signal between iq and iq^* is input to another current controller. The iq^* reference is set to zero to maintaining unity power factor. The current controller's Vd and Vq voltage outputs are converted into Vabc-ref, the three modulating signals used by the PWM generator. The voltage and current controllers, as well as the PLL synchronization unit, use a sample time in the control system. Pulse generators of boost and VSC converters use fast sampling times to obtain a suitable resolution of PWM waves [17-18].

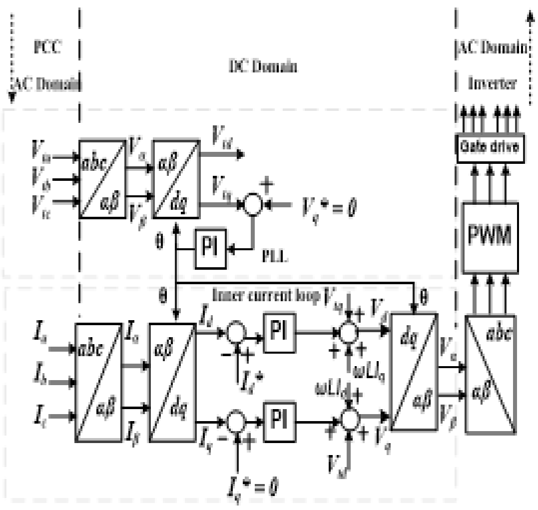

Figure 4: Proposed control strategy of VSC.

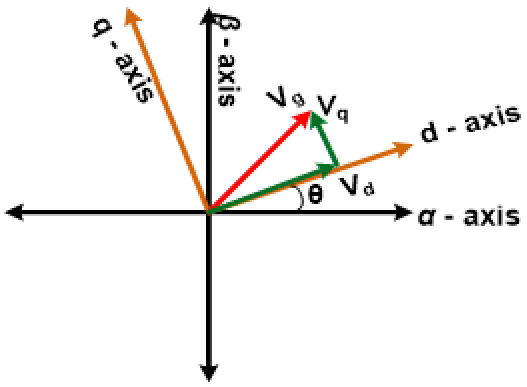

Figure 5: Pharos representation of grid voltage on two coordinate axes.

Events	Operations	Time (s)
1	Solar irradiation ramps down	1
2	Solar irradiation ramps up	1.6
3	Temperature ram up	2.4
4	Fault switched in	0.42
5	Load 1 switched in	0.58
6	Load 2+load 3 switched in	1

Table 2: Operational Events.

In brief to more robust as the closed-loop modification is suggested (PLL). The coordinate system has αβ coordinate system and has a voltage space vector (grid voltage). Now let us the d-axes are miss align means it is misaligned along among the Vg space vector and as consequence the projection on the d-axis will give the Vd and Vg, so there is a Vg component also if it had been aligned along with Vg if d-axis has been aligned along with Vg then Vq component would have been zero, now this θ is the angle between the αβ coordinate and the dq coordinate due to some reason Vq is not zero then compares with the Vq it goes to negative and the PI controller will become active and θ change in such a direction that the input to the PI controller which is the error will tend to zero then Vq have will zero to Vq^*. Where if Vq^* is equal to zero, therefore, Vg will tend to zero that means it will align the d-axes along the voltage space vector, and the value of θ will come out because the control action such that Vq here will become zero thus d-axes are aligned with the voltage space vector, this is a very robust appliance because it is the close loop so its effect will filtering the harmonics, surges and spike.

Simulation and Results

Case 1: In case first, a robust PLL-based VSC controller is designed to smooth the DC-link power. This controller synchronized the performance of the inverter and MPPT in the hybrid power generating system model, allowing the system to be stable and reliable. the controller can test under weather variation of environment and other situational conditions in terms of Figure 6 and the operational event will be shown in Table 2, it can be seen that the irradiation of the PV array was 1000 W/m2 until t=1 sec. after that, the light radiation dropped to 250 W/m2 up to 1.5 sec and about to 0.1 sec later, the irradiation gradually increases to 1000 W/m2. Where the ambient temperatures maintain 25°C from 0 to 2.4 sec. After that ambient temperature goes up from 25°C to 50°C during the time 2.4 to 2.5 sec. The d-component and q-component of the active and reactive power are controlled by the proposed controller, with the help of the controller; the active power is maintained as per the actual requirement while the reactive power is maintained at zero. As shown in Figure 7, analysis of DC side voltage, current and power of PV/battery system under variation of weather parameters, the proposed controller and PI controller performance are shown. The proposed controller-based DC link voltage is smoother than the PI controller from 1.42 to 1.9 sec and gets smooth output power and current at the dc side, as proven by the proposed controller based DC link voltage is smoother than the PI controller. Figure 8 illustrates that the inverter's 3-level output voltage outperforms the PI controller. Figure 9 shows the single-phase bus current in phase with bus voltage and a unity power factor that pumps maximum power into the grid. When the system is used in a various of weather and operating circumstances. The quality of the PV/battery system's output will decrease, as demonstrated in Figure 10, where the THD of the gird current injected using the suggested controller is 1.91%. The proposed controller can make better grid active power to improve the power quality of the PV/battery system, as shown in Figure 11 by comparing it to the PI controller. The performance analysis of the battery energy storage system under such an operational condition is shown in Figure 12. With the help of the bidirectional current controller interlink with the hybrid controller, which is controlled by generated switches signals s1 and s2, the discharge and charge of the battery can be seen to maintain the power fluctuation. Because the dc bus voltage is maintained, the charging current is properly regulated to compensate for power fluctuations. When a problem occurs between 0.42 and 0.5 sec, the bus amplitude decreases suddenly, and the bus voltage falls below the reference voltage, resulting in the battery being discharged. The duty cycle forces current flow from the dc bus to the battery for charging when a three-phase load is applied. Figure 13 shows the performance of the battery current, battery power and SOC waveform.

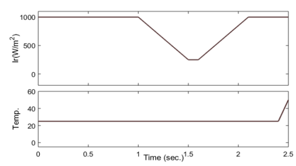

Figure 6: PV irradiation and temperature.

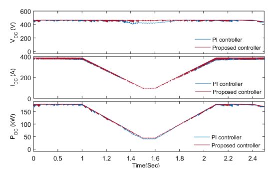

Figure 7: DC-link voltage, current, and power under the proposed controller.

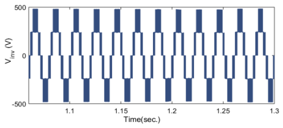

Figure 8: Inverter output voltages.

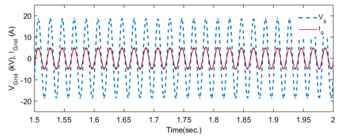

Figure 9: Bus voltage and current.

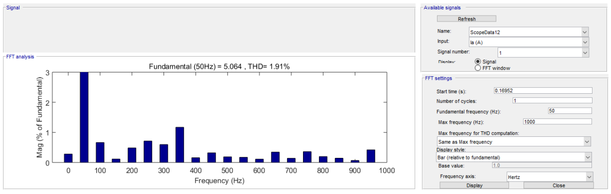

Figure 10: THD in grid current with proposed controller.

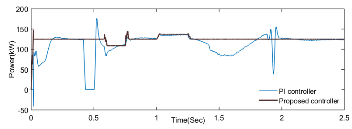

Figure 11: Active power analyses.

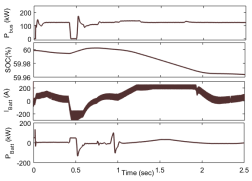

Figure 12: Performance analysis of battery energy storage system.

Case 2: The one-day solar irradiation is used to generate PV output for evaluation of the proposed method. Figure 12 shows the performance of a grid connected PV/battery system in running condition under such changing solar irradiation.

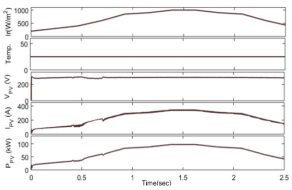

Figure 13: System performance under one day solar irradiation.

It can be seen the BES properly charges or discharges the power gap between demand and supply by the SOC and battery current. The BES maintains the dc bus voltage with outer voltage and inner current close-loop control, while the AC-DC interlinking converter generates stable ac voltage with a proposed controller.

Figure 14 and Figure 15 shows the overall system performance in a conditional situation with the proposed hybrid controller, where power at the DC-link is controlled by this controller and compared to ideal power. The hybrid power generation system can also be examined using this controller, and it can be identified that the hybrid control system's efficiency is approximately 98%.

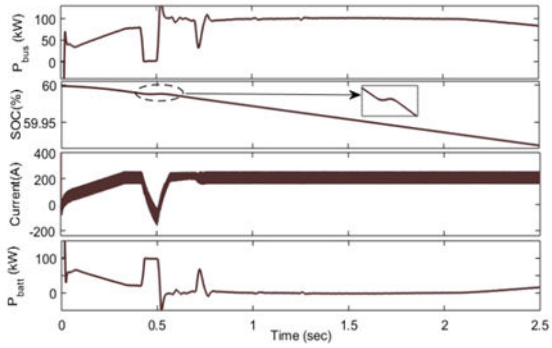

Figure 14: Variable load condition at different operation modes.

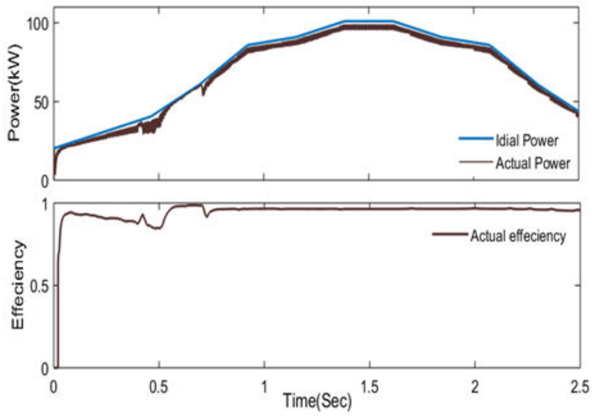

Figure 15: DC-link power and efficiency.

Conclusion

A novel hybrid VSC controller is designed in this paper. The simulation results obtained under normal, one-day solar irradiation, and variable load conditions are compared with the existing controller (PI) to evaluate the issues of system parameter uncertainty, power fluctuation, and power quality. The proposed controller can operate the PV/battery system at maximum power while maintaining unity power factor, so the DC link voltage is always kept at its nominal value. Whereas the internal system problem has been resolved through electric based power generation controller.

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