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A Novel Hybrid Control Strategy for Grid-Connected PV- Battery System under Different Operating Conditions

***Abstract**. This paper presents a new hybrid controller for grid-connected photovoltaic (PV)/Battery systems to handle power fluctuations. To lessen the difficulties brought on by power fluctuations at the DC-link of grid-connected PV/Battery systems, a novel hybrid voltage source converter (VSC) controller and bi-directional battery controller have been designed. The suggested controller efficiently handles problems on the DC and AC sides of the system through performance analysis, improving power quality and reducing harmonic dispersion. In this paper, three cases of PV input environments are analyzed. Furthermore, the performance of the hybrid controller is assessed under a range of environmental situations, indicating its versatility. The MATLAB/Simulink simulation results verify that the suggested controller is effective in improving the grid-connected PV/Battery systems' performance.*

***Streszczenie**. W artykule przedstawiono nowy sterownik hybrydowy do systemów fotowoltaicznych (PV)/baterii podłączonych do sieci, umożliwiający obsługę wahań mocy. Aby zmniejszyć trudności spowodowane wahaniami mocy w obwodzie prądu stałego systemów fotowoltaicznych/akumulatorów podłączonych do sieci, zaprojektowano nowatorski hybrydowy sterownik konwertera źródła napięcia (VSC) i dwukierunkowy sterownik akumulatora. Proponowany sterownik skutecznie radzi sobie z problemami po stronie prądu stałego i przemiennego systemu poprzez analizę wydajności, poprawę jakości energii i redukcję rozproszenia harmonicznych. W tym artykule przeanalizowano trzy przypadki środowisk wejściowych PV. Co więcej, wydajność sterownika hybrydowego ocenia się w różnych sytuacjach środowiskowych, co wskazuje na jego wszechstronność. Wyniki symulacji MATLAB/Simulink potwierdzają, że sugerowany sterownik skutecznie poprawia wydajność systemów PV/baterii podłączonych do sieci. (**Nowa hybrydowa strategia sterowania dla systemu baterii fotowoltaicznych podłączonego do sieci w różnych warunkach pracy**)*

Keywords: PV-Battery system, hybrid VSC controller, solar energy, renewable energy sources, energy storage
Słowa kluczowe: System PV-Battery, hybrydowy sterownik VSC, energia słoneczna, odnawialne źródła energii, magazynowanie energii

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 [1-3]. 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 [7-9]. 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 [5]. For hybrid system (HS) to performer well, the energy dispatching must be designed correctly [9]. A decentralized control technique based, battery energy storage (BES) system is used in [1] to smooth the PV output and raise the level of micro grid scalability. The BES is utilized in [11-12] to stabilize the wind-PV micro grid 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 [10-15].

The AC-DC interlinking converter is managed in the system to provide a steady ac voltage and frequency for the ac grid, while the bidirectional dc-dc converter maintains the dc-bus voltage [13]. The AC-DC interlinking converter is utilized in grid-tied mode to preserve the DC-bus voltage stable and to exchange power between the micro grid and the utility [14]. Traditional multiple feedback loops with proportional integral differential (PID) controllers are typically employed to regulate all converters in the literatures described above [16]. The BES is kept 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 is not considered (SOC). 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 [4-6].

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 synchronised 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 [16-18]. 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 [19-25].

Methodology & Experimentation

The proposed grid-connected PV/Battery system features a PV/Battery system connected to the grid via a common DC and AC bus [18]. The AC/DC converter links the AC and DC buses, while the DC/DC converter connects the system to the DC bus. Three loads are connected to the AC bus line through switches. The DC/AC converter and inverter controller maximize power output, maintaining unity power factor and feeding maximum power to the grid, achieving PQ during defects and load variations, shown in figure 1.

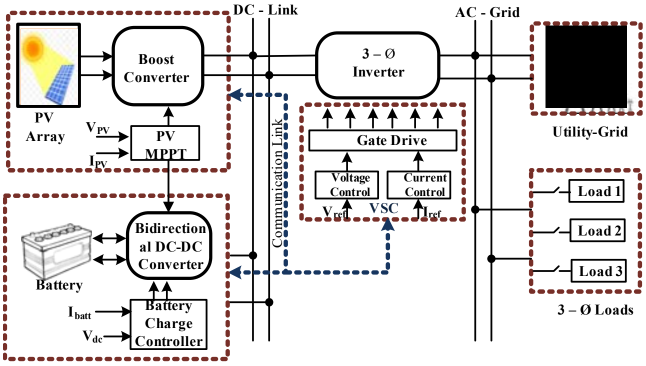

Fig.1. Equivalent model of the grid-connected PV/Battery systems.

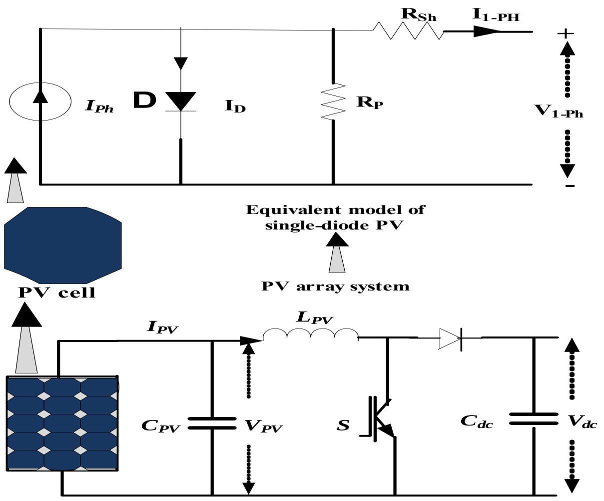

Fig. 2. Equivalent model of single-diode PV cell & PV system configuration.

PV system structure model

A PV system comprises PV cells connected in series and parallel. Its characteristic is determined by a single PV cell, represented by an equivalent model in Figure 2(a). The PV system converts solar irradiation into electrical energy. IPV and VPV represent the maximum generated current and voltage of the PV array, while Vdc is the DC-link voltage. Each PV cell behaves like a current source (Iph) generated by light. To produce the desired output power, a set of PV cells includes a reverse saturation current (Is), parallel ideal diode, shunt resistance Rp, and series resistance Rs. Kirchhoff's law determines the V-I characteristic as follows [26-28].

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

Where Iph is the current generated by incident light, q is the electron charge (1.6x10^-19 C), A is the diode ideality factor, and Vt = kT/q is the thermal voltage, with k = 1.38x10^-23 J/K as the Boltzmann constant and T as the p-n junction temperature in Kelvin. The photocurrent (Iph) dependence on environmental parameters like temperature and irradiance is expressed as:

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

Dependence of diode saturation current is defined as:

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

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

Where $I_{o,n}$ is the photocurrent at standard test condition, K is the temperature coefficient of short circuit current, T_{ref} is the reference temperature, Sn is the irradiance at standard test condition, $I_{o,n}$ is the saturation current at reference temperature, $I_{sc,n}$ is the short circuit current at reference temperature, and $V_{oc,n}$ is the open circuit current at reference temperature. The standard test conditions are 1000W/m² irradiance, 25°C cell temperature, and standard spectral distribution (Air Mass).

Proposed inverter control structure model

The proposed VSC control system employs two control loops: an outer loop regulating the DC link voltage to the appropriate level, and an inner loop controlling the active and reactive current components (id and iq) of the grid currents. Three-phase currents are transformed into two-phase α-β coordinates using abc to αβ transformation, yielding iα and iβ. These are then transformed into d-q coordinates via αβ to dq transformation, producing id and iq. The error between id and id* (MPPT maximum current) is fed to one controller, while the error between iq and iq* (set to zero for unity power factor) is input to another current controller. The current controllers' outputs, Vd and Vq, are converted into $V_{abc\text{-}ref}$, the three modulating signals for the PWM generator. The voltage and current controllers, along with the PLL synchronization unit.

Simulation and results

Case 1: In this case, a robust PLL-based VSC controller is designed to smoothen the DC-link power. This controller synchronizes the performance of the inverter and MPPT in the hybrid power generation system model, ensuring system stability and reliability. Initially, the PV array irradiation was 1000 W/m^2 until t = 1 sec, then it dropped to 250 W/m^2 until 1.5 sec, and gradually increased back to 1000 W/m^2 after 0.1 sec. The ambient temperature was maintained at 25°C from 0 to 2.4 sec, then rose from 25°C to 50°C during 2.4 to 2.5 sec. The proposed controller regulates the d-component (active power) as per actual requirement while maintaining the q-component (reactive power) at zero. Figure 3 analyzes the DC side voltage, current, and power of the PV/battery system under varying weather parameters, comparing the proposed controller's performance with a PI controller. The proposed controller-based DC link voltage is smoother than the PI controller from 1.42 to 1.9 s, providing smoother output power and current at the DC side.

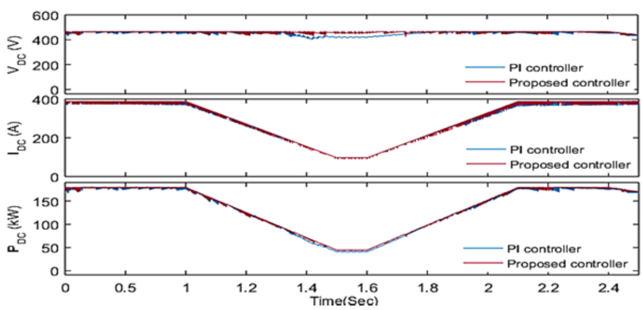

Fig. 3. DC-link voltage, current, and power under the proposed controller

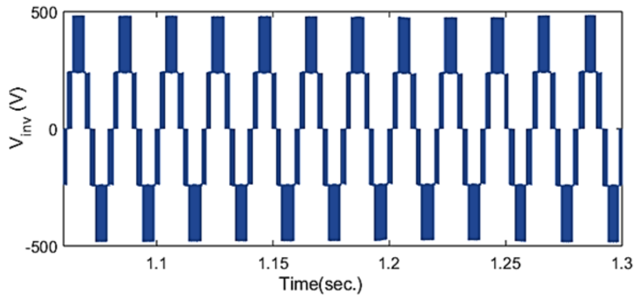

Fig. 4. Inverter output voltage

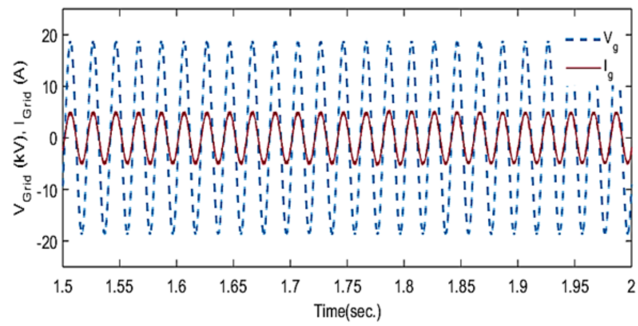

Fig. 5. Bus voltage and current.

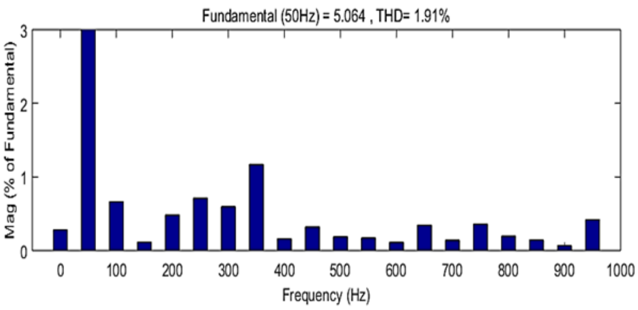

Fig. 6. THD in grid current with proposed controller

Figure 4 shows that the inverter's 3-level output voltage performance surpasses the PI controller. Figure 5 depicts the single-phase bus current in phase with bus voltage, maintaining unity power factor and pumping maximum power into the grid. However, when the system operates under various weather and conditions, the PV/Battery system's output quality degrades, as evident in Figure 6, where the THD of the grid current injected using the proposed controller is 1.91%. Nonetheless, the proposed controller enables better grid active power injection to improve the PV/Battery system's power quality, as demonstrated in Figure 7 by comparing it with the PI controller. Figure 8 illustrates the battery energy storage system's performance analysis under such operational conditions. With the aid of the bidirectional current controller interlinked with the hybrid controller, controlled by generated switching signals s1 and s2, the battery's discharge and charge can be observed to maintain power fluctuation. As the DC-bus voltage is maintained, the charging current is properly regulated to compensate for power fluctuations. When a disturbance occurs between 0.42 and 0.5 seconds, the bus amplitude decreases suddenly, and the bus voltage falls below the reference, resulting in battery discharge. The duty cycle forces current flow from the DC bus to the battery for charging when a three-phase load is applied. Figure 8 shows the battery current, power, and SOC waveform performance."

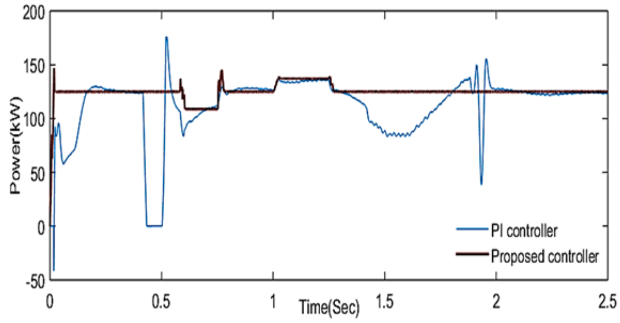

Fig. 7. Active power analyses

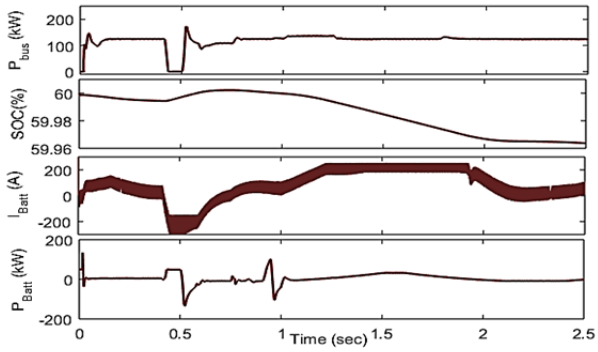

Fig. 8. Performance analysis of battery energy storage system

Case 2: To verify the proposed method with practical consideration, one-day solar irradiation data is used to generate the PV output, plotted in Figure 9. Figure 12 this is the demonstrates the performance of a grid-connected PV/Battery system in operation under such varying solar irradiation conditions. As evident from the battery current and SOC, the BES appropriately charges or discharges to bridge the power gap between generation and consumption. The BES maintains the DC-bus voltage through outer voltage and inner-current double-loop control, while the AC-DC interlinking converter generates stable AC voltage with the proposed controller. Such as shown in figure 10, the demonstrations the complete system with the planned hybrid controller. And also hybrid power generation system can also be examined using this controller, and it can be observed that the hybrid control system's efficiency is approximately 98 %.

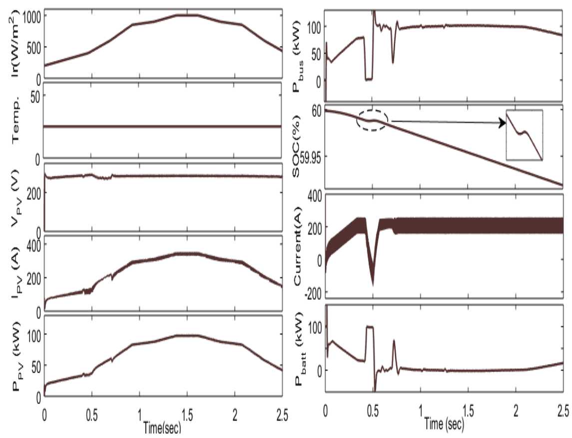

Fig. 9. System performance under one-day solar irradiation

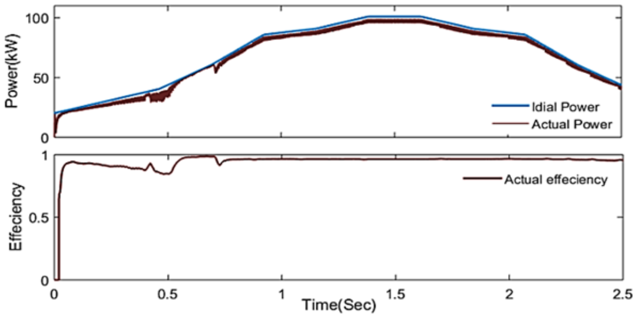

Fig. 10. DC-link power and efficiency

Case3. The controller has been tested under weather variation of environment for four years (2010-2013) at Delhi. For easy consideration annual variable data of irradiation is represented in terms of time as shown in figure 11. The ambient temperatures maintain 250C from 0 to 2 sec.

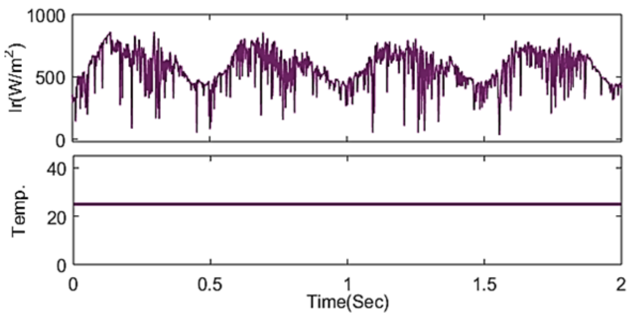

Fig. 11. PV irradiation and temperature

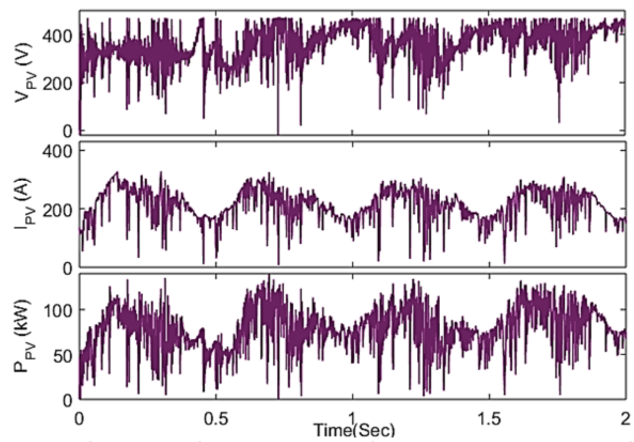

Fig. 12. System performances under four year solar irradiation & variable load condition

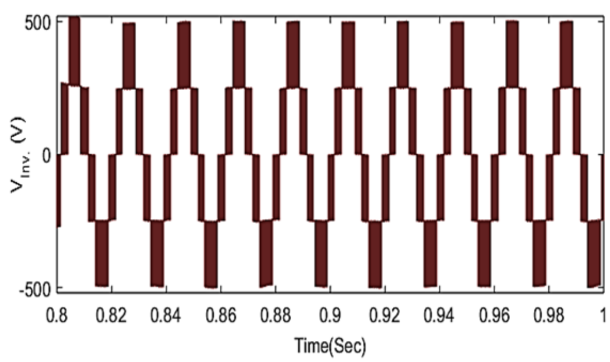

Fig. 13. Inverter output voltage

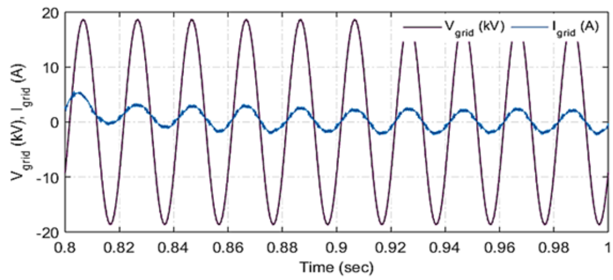

Fig. 14. Bus voltage and current

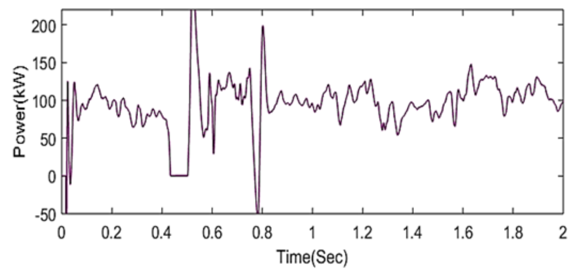

Fig. 15. Active power analyses

The PV system has been assessed on the basis of the results generated on dc-link as per the conditions mentioned above. Here the voltage, current and power of the PV system on the dc-link is estimated as the performance of the proposed controller is shown in Figure 12. The proposed controller provides a controlled switching input signal to the inverter, due to which the inverter converts the DC supply into the required AC supply. The performance of the controller can be estimated by the 3-level output voltage of the inverter as shown in Figure 13. The most important function of the proposed controller is to stabilize the power fluctuations in the system under any situation, thereby providing stability to the system. This is possible only when the controllers provide the correct signal to the inverter as per the parameters of DC side and AC side. So that as a result unity power factor is obtained and maximum power can be supplied to the grid. Accordingly, the Unity Power Factor has been achieved as shown in Figure 14. Here the grid voltage and current are in the same phase. Figure 15 shows the performance of great active power as per the given condition, which shows the best performance of the controller.

Conclusion

The effectiveness of the proposed hybrid controller model has been thoroughly examined in a variety of operating stages and environmental circumstances. It has been shown via extensive testing that the controller efficiently maximises the PV/Battery system's performance, allowing it to perform at maximum power while maintaining a unity power factor. System stability and efficiency are enhanced by this steady performance, which guarantees that the DC connection voltage stays at its nominal value. In addition, the incorporation of battery state-of-charge (SOC) management effectively addresses internal system problems, augmenting the entire system's dependability and efficiency.

Conflict of Interest

The authors declare no conflict of interest.

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