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Published in:
Proceedings of the 5th IEEE International Symposium on Environment Friendly Energies and Applications (EFEA)

DOI (link to publication from Publisher):
10.1109/EFEA.2018.8617110

Publication date:
2018

Document Version
Accepted author manuscript, peer reviewed version

Citation for published version (APA):
Lashab, A., Sera, D., Martins, J. P. R., & Guerrero, J. M. (2018). Multilevel DC-link converter-based photovoltaic system with integrated energy storage. In *Proceedings of the 5th IEEE International Symposium on Environment Friendly Energies and Applications (EFEA)* (pp. 1-6). IEEE Press. https://doi.org/10.1109/EFEA.2018.8617110

Multilevel DC-link converter-based photovoltaic system with integrated energy storage

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***Abstract*—This paper presents a multilevel topology of photovoltaic (PV) system with integrated energy storage system (ESS). In this proposed topology, half of the cells are connected to PV panels, the rest are connected to batteries. The sum of the cells are connected in series to form a dc-link, which is then connected to an H-bridge to convert the dc voltage to an ac one. The advantage of the proposed topology compared to the modular multilevel converter (MMC) as well as compared to the cascaded H-bridge converter is that less active switches are needed here. More switches are saved as the level of the output voltage increases, which results to a cheaper and less sizable converter. A local maximum power point tracking (MPPT) algorithm is proposed for this converter, which requires the voltage and current of each sub-module. Hence, there are no losses related to partial shading effect here. The excess of power in case of high irradiation levels is stored in the batteries, and is recovered when needed. A detailed simulation program has been built to test the effectiveness of the proposed converter; the obtained results are shown in the paper.**

Keywords— Battery, grid connected, High power, H-bridge, MMC, MPPT, Multilevel converter, Partial shading, PV, P&O.

I. INTRODUCTION

The conventional centralized PV grid tie inverter has a lower efficiency, requires a high filter size, and suffers from limited depth of operation for remaining connected to the grid particularly under lower irradiance/partial shading condition [1]. Consequently, multilevel converters are becoming the most suitable choice for power processing in medium and high power applications, due to their superior efficiency and modularity [2]. In PV application specifically, the solar power harvesting increases by installing PV arrays in parallel with each submodule, and operating each one at its maximum power [3]. As found in the literature, several types of multi-level converters have been proposed for PV applications, such as, modular multilevel converters (MMC) [4], cascaded H-bridge converter [5], cascaded Z-source converter [6], cascaded Quasi Z-source converter [7], [8], and multilevel dc-link converter [9].

In fact, in multilevel converters, the submodules that operate during the positive sequence do not operate during the negative one. On the contrary, the multilevel dc-link converter is able to use the same submodules during both positive and negative sequence by adding just an H-bridge. Hence, the multilevel dc-link uses almost 50% less submodules in high output voltage levels [9].

The solar photovoltaic systems are contributing as a major part of renewable energy resources in micro-grid applications, as well as, in large power system networks in recent years [9]. However, as the power generated by the PV resources is continually changing in an unpredictable manner, the integration of energy storage systems became indispensable for an interruptible service [10]. In addition, the PV systems with energy storage can provide ancillary services to the grid such as, voltage and frequency support [11]. In [12], MMC for PV systems with energy storage has been proposed, where each submodule has a PV panel in parallel and the batteries are installed on the dc side of the MMC. However, the state of charge control of the batteries is not discussed. In [13], cascaded H-bridge for PV systems with energy storage is presented; the state of charge control is not discussed here as well. In [14], the dc-link capacitor of each submodule in a cascaded H-bridge is paralleled with a boost converter and buck-boost converter, the boost converter is fed by a PV panels, whereas the buck-boost is connected to a battery. The configuration is flexible and offers full control of both MPPT and the state of charge of the batteries, but a high number of half bridges is used. A small battery in cascaded H-bridge configuration has been added in [15]; the objective of this design is to mitigate high order harmonics in case of partial shading. The previously developed quasi z-source inverter with energy storage in [16], has been used in cascaded configuration in [17]. A thorough analysis of a state of charge balancing in cascaded quasi z-source has been presented in [18]. This paper proposes PV system with storage integration using a modified multilevel dc-link converter. The dc-link is formed with series connection of PV and battery sub-modules. The PV panels are connected in parallel with the capacitor of each PV sub-module. Local maximum power point tracking (MPPT) algorithm is used to track the maximum power point (MPP) of each submodule independently, which guarantees that the global MPP is tracked even under partial shadowing. A battery is connected in parallel with the capacitor of each battery submodule through a buck-boost converter. The proposed converter saves submodules compared to the cascaded H-bridge as shown in Table 1, which reduces the price and size of the converter.

II. CONVERTER CONFIGURATION

The proposed PV multilevel grid connected converter with integrated energy storage is shown in Fig 1. During high

TABLE I.
COMPARISON OF MULTLEVEL CONVERTERS FOR PV APPLICATIONS WITH INTEGRATED ENERGY STORAGE IN TERMS OF USED ACTIVE SWITCHES

	Cascaded H-bridge	*Proposed Topology*
3 PV submodules	*24*	*17*
5 PV submodules	*40*	*23*
20 PV submodules	*160*	*68*
80 PV submodules	*640*	*248*

irradiance levels, when the power generated by the PV panels is larger than the power required by the grid, the three PV sub-modules inject power into the grid, and the surplus of power will be used to charge the batteries. If the power generated by the PV modules is equal to the power required by the grid, then the batteries will be bypassed. During low insolation levels, when the power generated by the PV panels is less than the power required by the grid, all the submodules of both the PV panels and batteries will contribute to inject the required power to the grid. In all the aforementioned cases, all the submodules are connected in series to form the dc-link. The submodules of the PV panels are half-bridge type, whereas the submodules of the batteries are a full-bridge one. The submodules operate with phase shifted PWM (PSPWM) at 2.5kHz switching frequency.

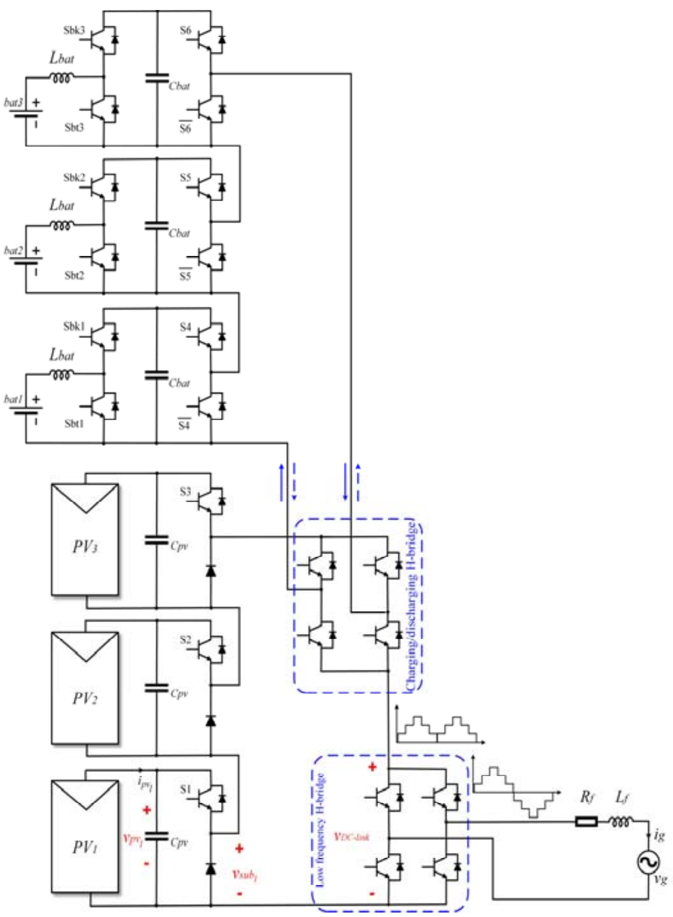


Fig 1. The proposed multilevel topology for PV systems with built-in energy storage.

Each PV submodule produces the voltages of either V_{pv} or *0* to the dc-link. Each battery submodule produces either V_{bat} or $-V_{bat}$ or *0*. The status of the battery' submodules voltage changes from V_{bat} to $-V_{bat}$ by using the charging/discharging H-bridge. The whole dc-link voltage will be inverted by using a low frequency H-bridge that operates at the grid fundamental frequency as shown in Fig 1. Local maximum power point tracking algorithm is used for each PV submodule to prevent the losses caused by the partial shading effect. The proposed multilevel converter can be used in 3-phase application by adding two similar converters for the remaining phases.

The i^{th} submodule is inserted when the switch S_i is ON. For the case of PV, and when the submodule is inserted,

$$\Delta V_{pvi} = \frac{1}{C_{pv}} \int \left(I_{pvi} - I_g \right) dt \quad (1)$$

Where, V_{pvi} is the voltage at the terminals of the i^{th} PV panel, I_{pvi} is the current going through the i^{th} PV panel, C_{pv} is the capacitor of the PV submodules, and I_g is the current injected to the grid.

When the PV submodule is bypassed,

$$\Delta V_{pvi} = \frac{1}{C_{pv}} \int I_{pvi} \, dt \quad (2)$$

For the case of both battery and capacitor C_{bat} are in discharging mode or both are in charging mode, and when the submodule is inserted,

$$\Delta V_{Cbat_i} = \frac{1}{C_{bat}} \int \left(I_g - I_{bat_i} \right) dt \quad (3)$$

Where, $VCbat_i$ is the voltage at the terminals of the capacitor of the i^{th} battery submodule, $Ibat_i$ is the current going into the i^{th} battery, and C_{bat} is the capacitor of the battery submodules. Whereas in case of either the battery or the capacitor are in discharging mode, and when the submodule is inserted,

$$\Delta V_{Cbat_i} = \frac{1}{C_{bat}} \int \left(I_{bat_i} - I_g \right) dt \quad (4)$$

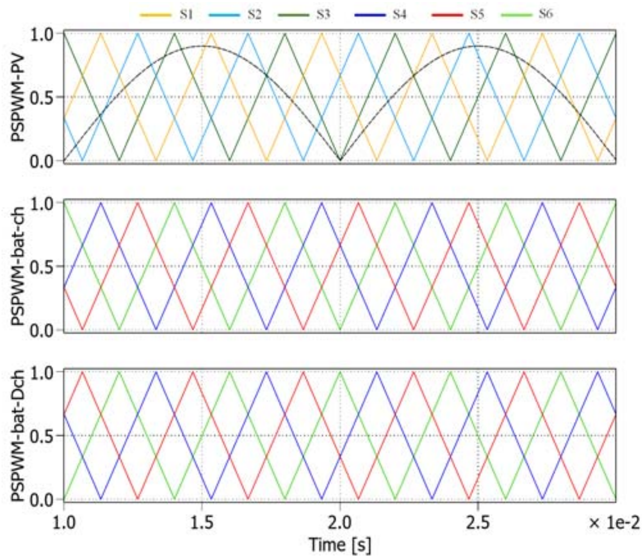


Fig. 2. PWMs used for the proposed converter.

In case the battery submodule is bypassed and the battery is discharging,

$$\Delta V_{Cbat_i} = \frac{1}{C_{bat}} \int I_{bat_i}\, dt \tag{5}$$

Whereas in case the battery submodule is bypassed and the battery is charging,

$$\Delta V_{Cbat_i} = -\frac{1}{C_{bat}} \int I_{bat_i}\, dt \tag{6}$$

III. Control Strategy of the Proposed Topology

The overall control design of the proposed PV multilevel grid connected converter with integrated energy storage is shown in Fig 3. Since there are many scenarios of operating conditions of the proposed topology, three Phase Shifted PWMs are used. The first PWM ($PSPWM_{pv}$) is used for the control of the PV modules, the second ($PSPWM_{bat-ch}$) is used to control the batteries during charging mode, and the third one ($PSPWM_{bat-Dch}$) is used to control the batteries in discharging mode as shown in Fig. 2. A local MPPT algorithm is used for each PV submodule to extract the maximum power from its PV panel at any meteorological conditions. In this paper, the conventional Perturb and Observe (P&O) is implemented [19]. However, any MPPT can be used for the proposed converter.

The voltage in each PV submodule is regulated by using a PI controller from the error between the reference obtained by the MPPT voltage (V^*_{pv}) and the submodule voltage (V_{pvi}) as the following,

$$I^{ref}_{sub_i} = KP_{PVv}\cdot(V_{pv_i} - V^*_{pv_i}) + KI_{PVv}\int (V_{pv_i} - V^*_{pv_i})\, dt \tag{7}$$

where, KP_{PVv} and KI_{PVv} are the proportional and integral gains of the voltage regulation loop in the PV submodules. The reference of the grid current can be defined by using the classical decoupled PQ control method. Due to the various possible scenarios, an energy management algorithm has been designed for the control of the proposed system.

1)During high insolation levels, the excess of power generated by the PV panels is injected into the batteries, the charging/discharging H-bridge is set to charging mode. As the duty cycle of the PV submodules is larger than the duty cycle required to inject the active power to the grid, a fraction from it is exploited to charge the batteries as shown in Fig. 4. In this case, the batteries are controlled by $PSPWM_{bat-ch}$, which implies that the PV submodules are synchronized with the battery submodules in order to charge them. The current injected to each battery is determined as,

$$I^*_{bat} = \frac{P_{bat}}{3\cdot V_{Cbat}} \tag{8}$$

where:

$$P_{bat} = P^* - P_{PV} \tag{9}$$

Such as, P_{bat} is the power exchanged by the batteries, P^* is the active power reference, and P_{pv} is the power generated by all PV submodules. By using Kirchhoff voltage law, the dc-link voltage can be found as follows:

$$V_{DC-link} = \sum_{i=1}^{n} V_{pv_i}\cdot S_i - \sum_{i=n}^{m} V_{bat_i}\cdot S_i \tag{10}$$

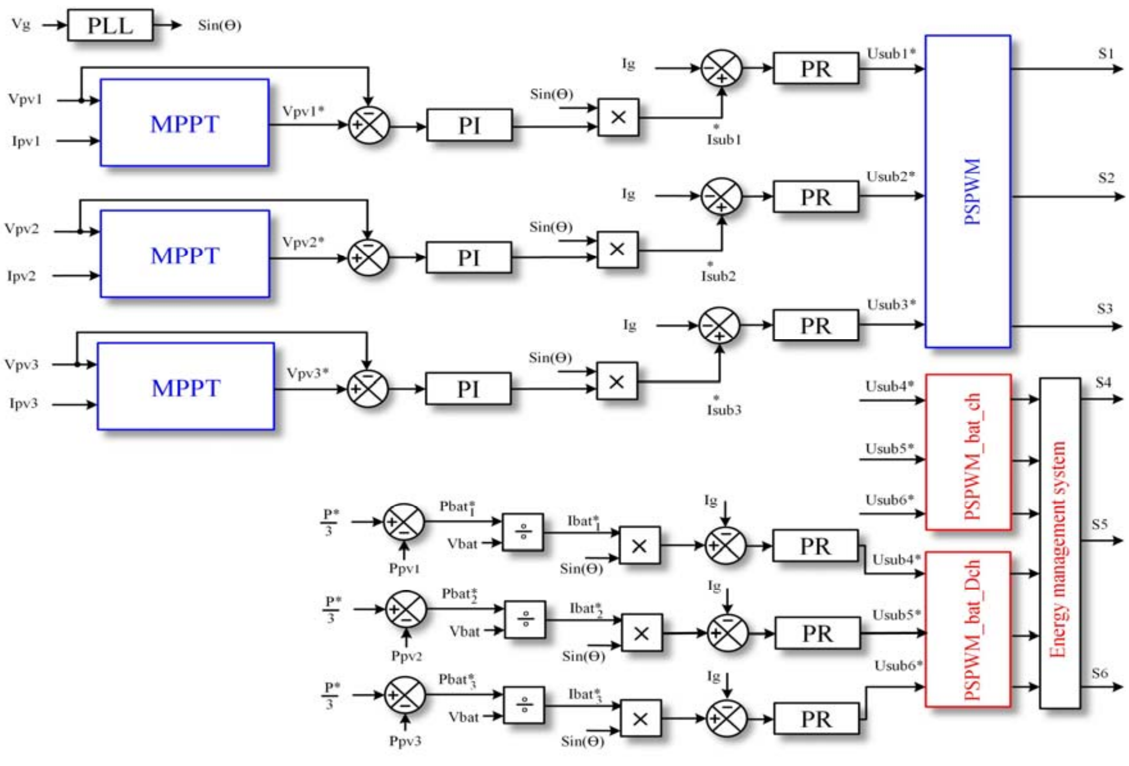
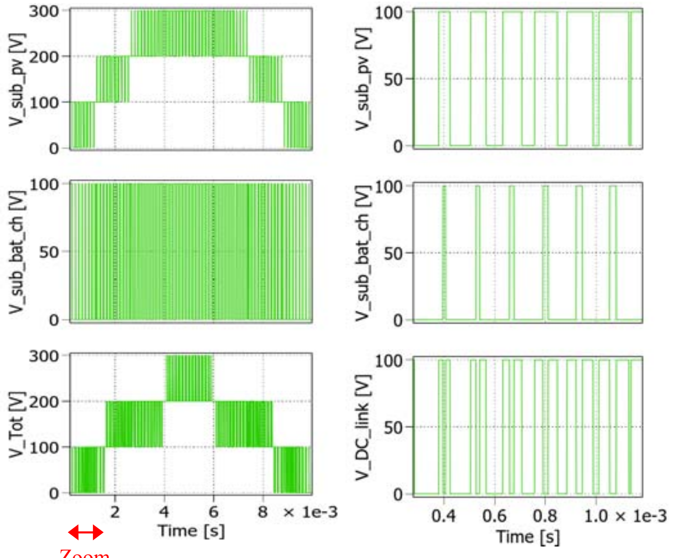
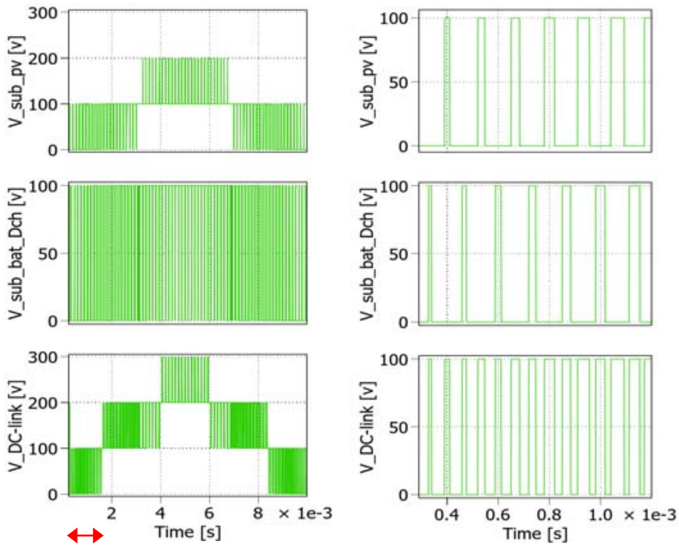


Fig 3. The overall control structure of the proposed multilevel converter



(a) (b)

Fig. 4. (a) The voltages across the PV and battery submodules, and the total voltage of the DC-link during charging the batteries, (b) a Zoom on the voltages across the PV and battery submodules, and the total voltage of the DC-link during charging the batteries.



(a) (b)

Fig. 5. (a) The voltages across the PV and battery submodules, and the total voltage of the DC-link during discharging the batteries, (b) a Zoom on the voltages across the PV and battery submodules, and the total voltage of the DC-link during discharging the batteries.

The grid voltage was found similarly as:

$$V_g = V_{DC-link} - R_f \cdot I_g - L_f \frac{dI_g}{dt} \quad (11)$$

Where V_g is the grid voltage, L_f is the inductance of the output filter, and R_f is the internal resistance of the filter. By substituting the dc-link voltage in (11), the grid voltage can be found as follows:

$$V_g = \sum_{i=1}^{n} V_{pv_i} \cdot S_i - \sum_{i=n}^{m} V_{bat_i} \cdot S_i - R_f \cdot I_g - L_f \frac{dI_g}{dt} \quad (12)$$

2) During low insolation levels, the deficit of power generated by the PV pannels is compenstated by the batteries. Thus, the charging/discharging H-bridge is set to discharging mode, and the batteries are controlled by $PSPWM_{bat\text{-}Dch}$. Here the battery submodules are not inserted at the same time the PV submodules are inserted. By applying Kirchhoff voltage law on the proposed converter during discharging mode, the dc-link voltage can be found as follows:

$$V_{DC-link} = \sum_{i=1}^{n} V_{pv_i} \cdot S_i + \sum_{i=n}^{m} V_{bat_i} \cdot S_i \quad (13)$$

The grid voltage will be then expressed as,

$$V_g = \sum_{i=1}^{n} V_{pv_i} \cdot S_i + \sum_{i=n}^{m} V_{bat_i} \cdot S_i - R_f \cdot I_g - L_f \frac{dI_g}{dt} \quad (14)$$

IV. Simulation Results and Discussion

To demonstrate the features of the proposed converter topology, a detailed simulation model has been built in MATLAB/Simulink according to the schematic shown in Fig 1. The chosen PV panels have the specifications shown in Table. II under the standard test conditions (STC). In each PV submodule, three PV panels are connected in series. Table. III shows the parameters of the converter, filter, and batteries.

Test1. High irradiance level, in this test, all PV panles are subjected to 1000W/m^2 of solar irradiance, which genrates 2.49kW. The active power required by the grid is 2.1kW. Hence, the surplus of 390W will be used to charge the batteries. The voltages of PV submodules, the voltages of battery submodules, the output voltage, and the injected current to the grid are shown in Fig. 6(b), Fig. 6(c), Fig. 6(d), and Fig. 6(e), respectively.

Test2. PV power less than the required one, all PV panels are subjected to 500W/m^2 of solar irradiance in this test, which produces 1.24kW. As 2.1kW is the active power required by the grid, the batteries will be used to provide the deficit of power of 0.86kW. The voltage of PV submodules, the voltage of battery submodules, the output voltage, and the current injected to the grid are shown in Fig. 7(b), Fig. 7(c), Fig. 7(d), and Fig. 7(e), respectively.

Test3. Gradually decreasing solar irradiance, all the PV sub modules are subjected to gradually decreasing irradiance from 1000W/m^2 to 300W/m^2 in this test. Thus, the PV panels will provide larger power than the needed at the beginning of the test, and this power will gradually decrease until the PV

TABLE II.
DATA SHEET OF THE USED PV PANEL

Parameter	Value
Voltage at maximum power, *VMPP*	*35.6V*
Current at maximum power, *IMPP*	*7.77A*
Open circuit voltage, *VOC*	*39.9V*
Short circuit current, *ICC*	*8.56A*

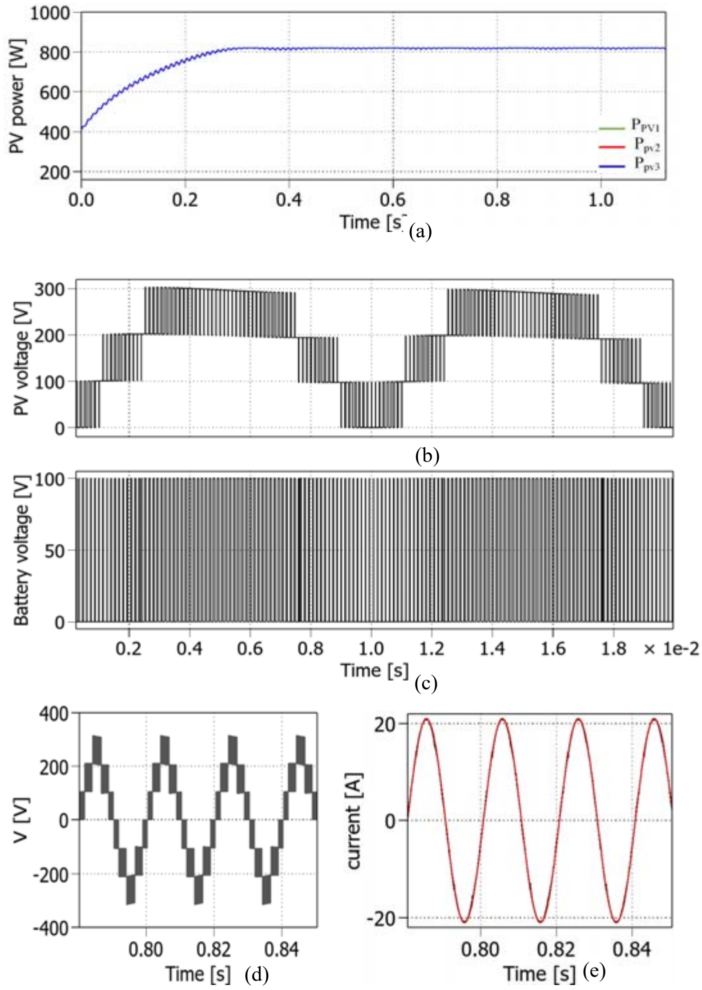


Fig. 6. (a) The power of the PV submodules, (b) the voltage generated by the PV submodules, (c) the sum of the voltage at the terminals of battery submodules, (d) the output voltage, and (e) the current injected to the grid, when the PV panels are subjected to 1000W/m^2 of solar irradiance.

TABLE III.
SYSTEM PARAMETERS

Parameter	Value
Gird frequency, *f*	*50Hz*
Filter inductance, *Lf*	*2mH*
Internal filter resistor, *Rf*	*0.1Ohm*
Switching frequency	*2.5KHz*
PV submodule capacitor, C_{pv}	*1000µF*
Battery submodule capacitor, C_{cap}	*600µF*
Batteries nominal voltage, *Vbat_nom*	*34V*
Rated capacity of the batteries, *Q*	*6Ah*

panels reach to a point where they produce less power than the needed one as shown in Fig. 8(a). On the batteries side, the batteries will start by absorbing a gradually decreasing power until they reach a point where they convert to discharging mode to compensate the lack of power. The voltage of PV submodules, the battery submodules voltage, the DC-link voltage, the output voltage, and the current injected to the grid are shown in Fig. 8 (b), Fig. 8 (c), Fig. 8(d), Fig. 8 (e), Fig. 8(f) and Fig. 8(g),

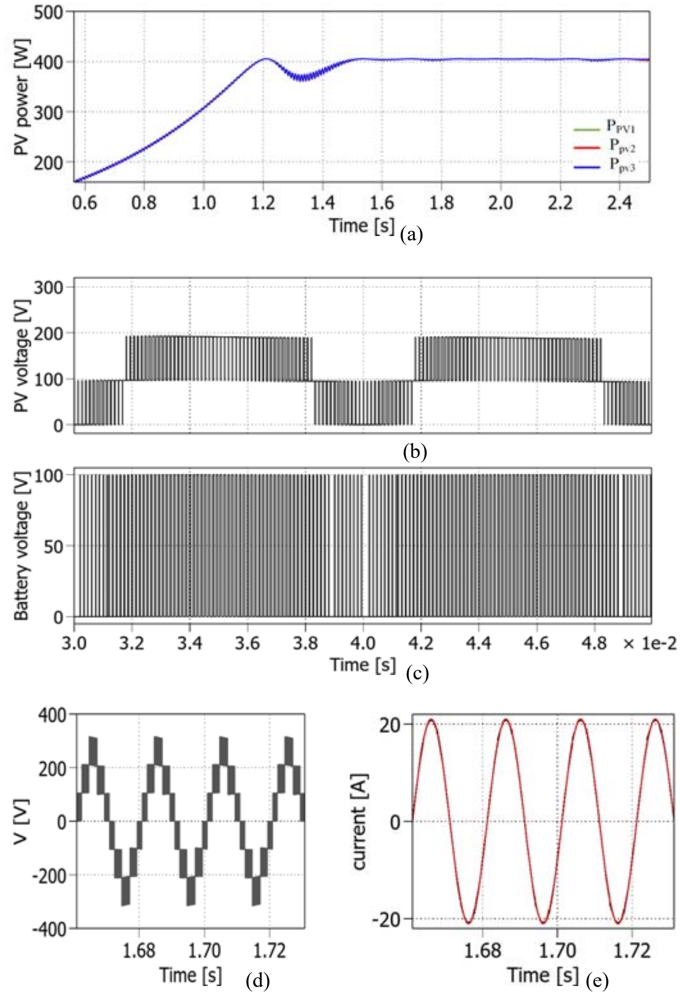


Fig. 7. (a) The power of the PV submodules, (b) the voltage generated by the PV submodules, (c) the sum of the voltage at the terminals of battery submodules, (d) the output voltage, and (e) the current injected to the grid, when the PV panels are subjected to 500W/m^2 of solar irradiance.

respectively. Please note that the voltage of the battery is positive in Fig. 6(c) and Fig. 8(c), but it is negative at the dc-link since the charging/Discharging H-bridge is set to charging mode.

V. CONCLUSION

A multilevel converter for PV system with integrated energy storage has been presented in this paper. The proposed multi-level converter requires less active switches compared to the cascaded H-bridge converter. The proposed multilevel converter is able to provide a constant power whatever the meteorological conditions are present. The surplus of power during high irradiance levels is used to charge the batteries, and is recovered later when the power generated by the PVs is less than the required one due to low solar irradiance. The simulation results show also that the proposed multilevel converter presents a smoothness when changing from charging mode to discharging mode.

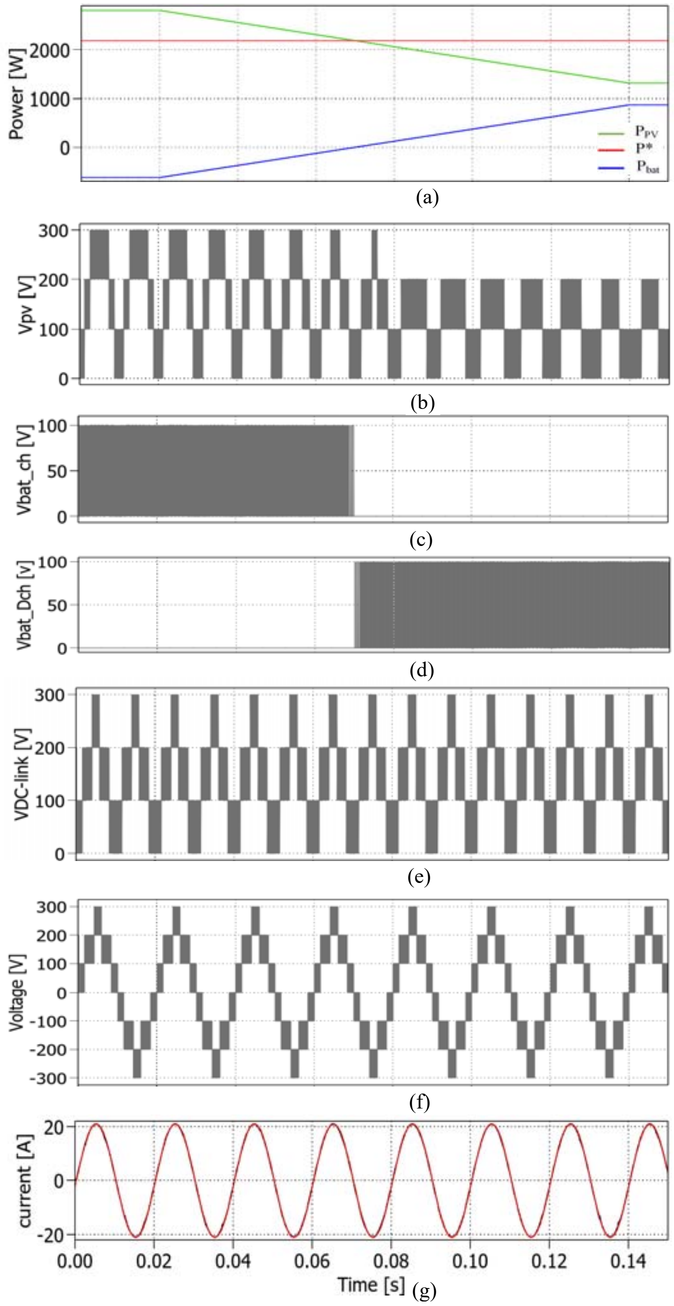


Fig. 8. (a) The power of PV submodules, (b) the voltage generated by the PV submodules, (c) the sum of the voltage at the terminals of battery submodules when charging, (d) the sum of the voltage at the terminals of battery submodules when discharging (e) the voltage at the dc-link, (f) the output voltage, and (e) the current injected to the grid, when the PV panels are subjected to gradually decreasing solar irradiance.

VI. References

[1] A. Kumar and V. Verma, "Performance enhancement of single phase grid connected PV system under partial shading using cascaded multilevel converter," *2016 IEEE 1st Int. Conf. on Power Electron., Intelligent Control and Energy Systems (ICPEICES), Delhi,* 2016, pp. 1-6.

[2] S. Debnath, J. Qin, B. Bahrani, M. Saeedifard, and P. Barbosa, “Operation, control, and applications of the modular multilevel converter: A review,” *IEEE Trans. Power Electron*., vol. 30, no. 1, pp. 37–53, Jan. 2015.

[3] Liming Liu et al, "Decoupled Active and Reactive Power Control for Large-Scale Grid-Connected Photovoltaic Systems Using Cascaded Modular Multilevel Converters," *IEEE Trans. Power Electron*., vol.30, no.1, pp.176-187, Jan. 2015.

[4] K. Shen, D. Zhao, G. Zhao and S. Wang, "Photovoltaic supplied grid-connected modular multilevel converter with active power injection and reactive power compensation capability," *IECON 2017 - 43rd Annual Con. of the IEEE Ind. Electron. Society*, Beijing, 2017, pp. 7837-7842.

[5] H. Jafarian, N. Kim and B. Parkhideh, "A distributed active and reactive power control strategy for balancing grid-tied cascaded H-bridge PV inverter system," *2017 IEEE Energy Conversion Congress and Exposition (ECCE)*, Cincinnati, OH, 2017, pp. 1667-1672.

[6] Y. Fayyad and L. Ben-Brahim, "Multilevel cascaded Z source inverter for PV power generation system," *2012 Int. Conf. on Renewable Energy Research and Applications (ICRERA)*, Nagasaki, 2012, pp. 1-6.

[7] Y. Liu, B. Ge, H. Abu-Rub and F. Z. Peng, "An Effective Control Method for Three-Phase Quasi-Z-Source Cascaded Multilevel Inverter Based Grid-Tie Photovoltaic Power System," *IEEE Trans. Ind. Electron*, vol. 61, no. 12, pp. 6794-6802, Dec. 2014.

[8] A. Lashab, D. Sera, J. M. Guerrero, L. Mathe and A. Bouzid, "Discrete Model-Predictive-Control-Based Maximum Power Point Tracking for PV Systems: Overview and Evaluation," *IEEE Trans. Power Electron*., vol. 33, no. 8, pp. 7273-7287, Aug. 2018.

[9] T. S. Basu, S. Maiti, and C. Chakraborty, “A Hybrid Modular Multilevel Converter for Solar Power Integration,” *2016 IEEE 7th Power India Int. Conf.*, pp. 1–6, 2016.

[10] W. Yuan, J. Yang, Y. Sun, H. Han, X. Hou and M. Su, "A novel operation mode for PV-storage independent microgrids with MPPT based droop control," *2017 IEEE 3rd International Future Energy Electronics Conference and ECCE Asia (IFEEC 2017 - ECCE Asia),* Kaohsiung, 2017, pp. 936-941.

[11] N. Saxena, I. Hussain, B. Singh, and A. L. Vyas, “Implementation of Grid Integrated PV-Battery System for Residential and Electrical Vehicle Applications,” *IEEE Trans. Ind. Electron.*, vol. 46, no. c, 2017.

[12] H. Nademi, Z. Soghomonian and L. Norum, "A robust predictive MPPT strategy: An enabler for improving the photovoltaic conversion source," 2017 *IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA),* San Diego, CA, 2017, pp. 1086-1091.

[13] Qinghao Zhang, "Control of PV battery hybrid system using Cascaded H Bridge converter," *2017 IEEE 3rd International Future Energy Electronics Conference and ECCE Asia (IFEEC 2017 - ECCE Asia), Kaohsiung*, 2017, pp. 2008-2012.

[14] V. Verma and A. Kumar, "Power balanced cascaded multilevel inverter fed scalar controlled induction motor pump sourced from photovoltaic source," 2012 *IEEE International Conference on Power Electronics, Drives and Energy Systems* (PEDES), Bengaluru, 2012, pp. 1-6.

[15] A. Marquez, J. I. Leon, S. Vazquez, L. G. Franquelo and S. Kouro, "Operation of an hybrid PV-battery system with improved harmonic performance," IECON 2017 - *43rd Annual Conference of the IEEE Industrial Electronics Society*, Beijing, 2017, pp. 4272-4277.

[16] D. Sun, B. Ge, W. Liang, H. Abu-Rub and F. Z. Peng, "An Energy Stored Quasi-Z-Source Cascade Multilevel Inverter-Based Photovoltaic Power Generation System," *IEEE Trans. Ind. Electron*, vol. 62, no. 9, pp. 5458-5467, Sept. 2015.

[17] D. Sun, B. Ge, W. Liang, H. Abu-Rub and F. Z. Peng, "An Energy Stored Quasi-Z-Source Cascade Multilevel Inverter-Based Photovoltaic Power Generation System," *IEEE Trans. Ind. Electron*, vol. 62, no. 9, pp. 5458-5467, Sept. 2015.

[18] B. Ge, Y. Liu, H. Abu-Rub and F. Z. Peng, "State-of-Charge Balancing Control for a Battery-Energy-Stored Quasi-Z-Source Cascaded-Multilevel-Inverter-Based Photovoltaic Power System," *IEEE Trans. Ind. Electron*, vol. 65, no. 3, pp. 2268-2279, March 2018.

[19] H. Bounechba, A. Bouzid, H. Snani, A. Lashab, “Real time simulation of MPPT algorithms for PV energy system,”*International Journal of Electrical Power & Energy Systems*, Vol. 83, Pages 67-78, 2016.