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A Buck-Chopper Based Energy Storage System for the Cascaded H-Bridge Inverters in PV Applications

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Abstract

Cascaded H-Bridge (CHB) inverter configuration is most suitable for high power solar inverters. In this work, various energy storage system (ESS) configurations suitable for CHB inverters such as AC side coupled ESS, Dual active bridge based ESS, and buck-chopper and bi-directional chopper based ESS configurations are discussed. Comparison of these configurations on the basis of cost, control complexity, controller hardware requirements are carried out and the advantages of Buck-chopper based ESS systems are listed. Operation and the dynamic response of the buck-chopper based systems are explained in detail with the help of simulation results.

Keywords: Battery; Cascaded H-Bridge; Chopper; Energy storage; Multi-level; PV inverter

1. Introduction

To meet the huge power requirements without harming the environment, large scale solar power conditioning systems are required. By incorporating the feature of energy storage, this system can be

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made operational during night time also. Due to high demand in the solar energy, a cascaded H-Bridge inverter based PV power condition systems are preferable for higher power applications. CHB inverter is having the following advantages in large scale PV applications. (a) Independent MPPT control of PV arrays can be achieved through CHB inverter (b) Due to higher number of levels in the output voltage of a CHB inverter; good THD and power quality can be achieved (c) System can be extended to higher power levels by adding additional H-Bridge units (d) Size of output filter can be reduced [1]-[4]. Since the CHB inverter is modular in construction, Design of CHB inverter is also simpler compared to other multi-level inverter configurations. A PV Inverter system will be in idle state during night time since the PV array is not able to feed the power to the grid. For continuous supply of power to the load, incorporation of energy storage is the best alternative. In such systems, Solar PV array provides power to the grid and the power required for charging the batteries. When the irradiation is weak, Batteries supply the power to the grid. When there is a fault on the grid side, still the system can supply power to the local load by working in standalone mode by isolating the grid connection. In the next section, various ESS configurations suitable for CHB inverter based systems are explained and compared.

Nomenclature

CHB	Cascaded H-Bridge
DAB	Dual Active Bridge
ESS	Energy Storage System
MPP	Maximum Power Point
PCC	Point of Common Coupling
PV	Photo-voltaic

2. ESS configurations for a CHB based PV-Inverter

Fig. 1(a) shows AC side coupled energy storage system for a CHB MLI based PV inverter. In a CHB based system the PCC voltage is usually at higher level, hence an additional transformer may be required to match the battery voltage with the voltage at point of common coupling (PCC). A bidirectional AC to DC converter is used as a battery charger in this configuration.

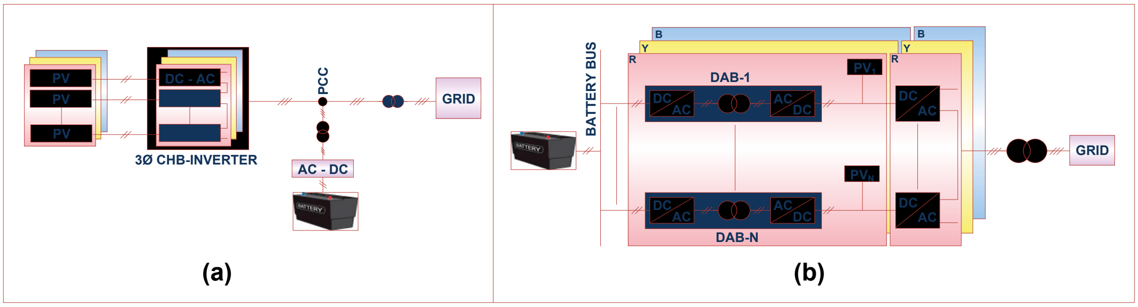


Fig. 1. (a) AC side Coupled Energy Storage System for a CHB based PV-Inverter (b) DAB based ESS for CHB Inverters

Fig. 1(b) shows DAB based ESS configurations for CHB inverter. In this system, each H-Bridge is connected to the battery through independent DC-DC converter. DAB based DC-DC converter comprises of Two single phase H-bridges isolated by high frequency (HF) transformer. DC Terminals of one H-Bridge are connected to independent DC links of CHB inverter and the DC terminals of second H-bridge are connected to a common battery bank. AC terminals of each H-bridge are connected to the primary and secondary windings of HF transformer. The Power flow through DAB converter is controlled through the phase shift control [5]-[12]. For systems having a single battery bank, AC coupled ESS, and the DAB based ESS configurations are suitable. In DAB based system can be operated with single battery bank since there is an isolation transformer available in the DAB, but the chopper based systems cannot be used, as there is no isolation transformer in DC-DC converter and CHB needs isolated DC links [8]-[12]. Cost of the DAB based system is also more due to more number of components [8]-[12]. If multiple independent battery banks are available in the system, then the chopper based configurations are more suitable. Fig. 2(a) shows a bidirectional chopper based ESS configuration for CHB inverter in which, the battery can feed power to the grid along with PV. In this system, each H-Bridge of CHB inverter is connected to the battery through independent DC-DC converter. The DC terminals of this DC-DC converter are interchangeable; hence the battery voltage can be selected higher or lower than the PV voltage levels. The block diagram of each bidirectional DC-DC converters is also shown in Fig. 2(b).

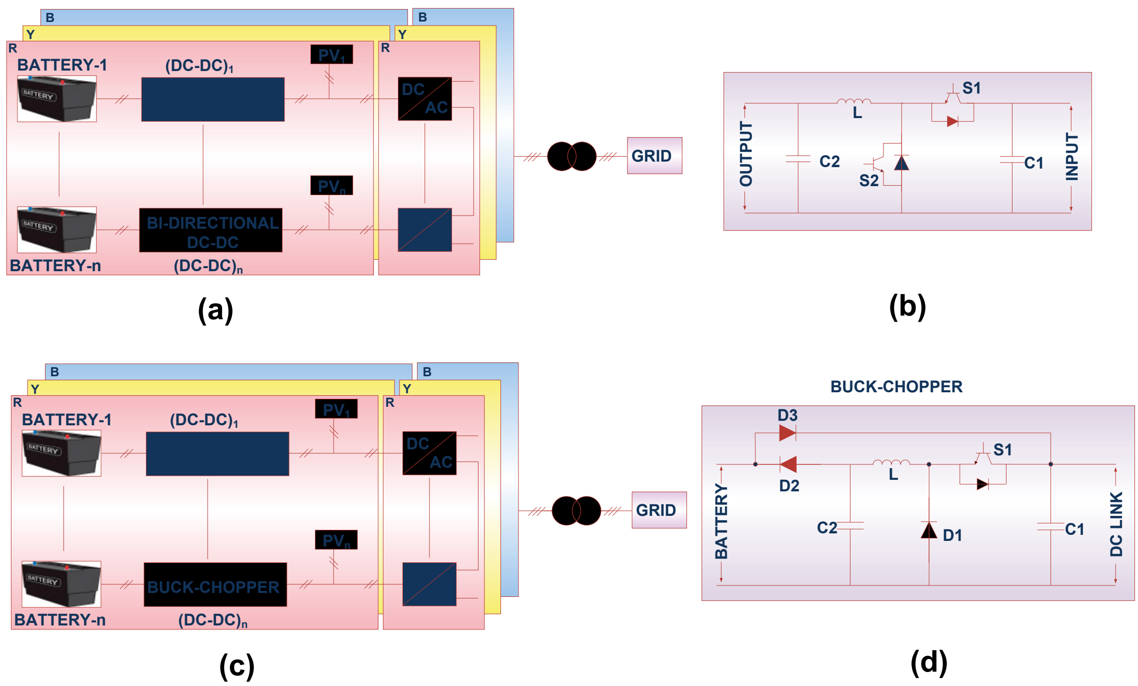


Fig. 2. (a) Block diagram of Bi-directional Chopper based ESS for CHB Inverter (b) Electrical Scheme of Bi-directional Chopper (c) Block diagram of Buck-Chopper based ESS for CHB (d) Electrical Scheme of Buck-Chopper

A Buck-Chopper based ESS configuration for CHB inverter which can reduce the cost and control complexity of the system is shown in Fig. 2(c). In this system, each H-Bridge of CHB inverter is connected to the battery through independent Buck-Chopper based DC-DC converter. Maximum battery voltage should always be less than the minimum operating PV voltage in this system. PV voltage is stepped down to match with the battery voltage during charging operation. When the irradiation is weak, the PV voltage becomes less than the battery voltage. Then the Diode D3 shown in Fig 2(d), starts conducting and Battery provides power to the grid through diode D3. D3 needs to be rated for rated battery current.

Table 1. Comparison of Different ESS Configurations suitable for CHB inverter

Parameter	AC-Side Coupled ESS	DAB based ESS	Bi-directional Chopper based ESS	Buck-Chopper based ESS
Requirement of Independent DC Sources	Not required	Not Required	Required	Required
Isolation between PV and Battery	Isolated	Isolated	Not Isolated	Not Isolated
Components required for ESS	Isolation Transformer and DC-DC converter	Independent DAB with HF Transformers	Independent DC-DC Converter	Independent DC-DC Converter
Rated Current of Charger	Equal to Battery Current	Equal to Battery Current	Equal to Battery Current	Equal to Battery Charging Current
Cost	More due to Additional Transformer	More due to more number of components	Comparatively less	Comparatively less
Control Complexity	Simple	Complex	Moderate	Moderate
Controller Hardware Requirement	Less	More	Moderate	Moderate
Limitations	Not suitable for High power Applications	Controller hardware requirement is more	Independent DC sources are required	Not Preferable for Standalone system

From Table.1., it is observed that, the Buck-Chopper based ESS configuration is having the following advantages over other ESS configurations in a grid connected PV applications

1. Each Buck-Chopper needs only one gate pulse hence the controller hardware requirement is less
2. Other ESS configurations need to be designed for rated battery power where as the buck-chopper based system needs to be designed only for the rated charging current of the battery. Hence cost of the buck-chopper based system is comparatively less.
3. Other ESS configurations need to be controlled both in charging and discharging modes of operation where as buck-chopper control is required only during charging mode and discharging is through Diode D3.

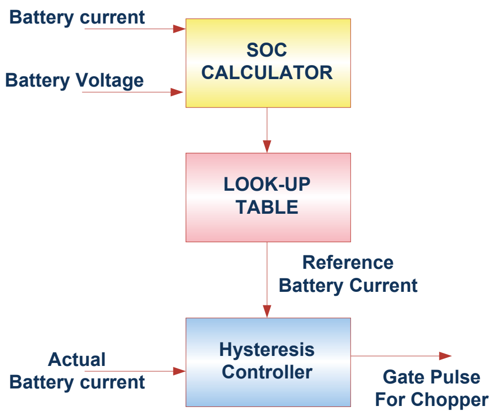
From the above discussions, It is observed that the Buck-Chopper based ESS configuration is more suitable for grid connected PV applications. The main components in this system is Buck-chopper and the PV-Inverter. In the next section, the controls and the dynamic response of the Battery charger and the PV-inverter are explained.

3. Battery Charger and PV-Inverter

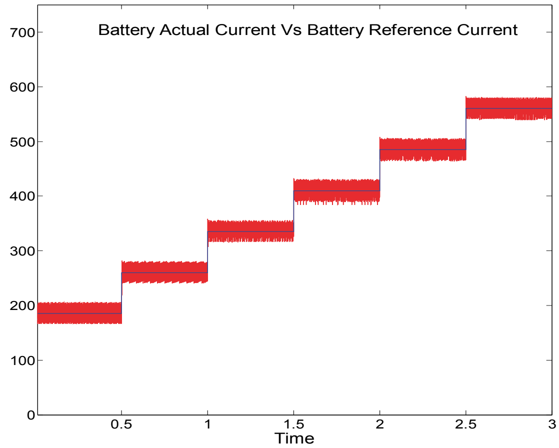
In this section, Controls for the battery charger and the dynamic response is explained. A current control shown in Fig.3(a) is used regulate the battery current during charging mode. Battery voltage and currents are monitored for obtaining the battery charging current reference. State of charge (SOC) of the battery is obtained by integrating the battery current [7].

$$\% \, SOC = 100 \text{ X } \{1- [(I*T)/Q]\} \text{ --------} \quad (1)$$

Where 'I*T' is the discharged capacity (Ah) (Obtained by integrating current) and 'Q' is ampere-hour rating. Based on SOC, the reference charging current is adjusted. A hysteresis controller based current controller is used which compares the actual battery current with the reference current and releases gate pulses to the battery charger accordingly. Fig.3 (b) shows the response of battery current with the change in reference current. A change in reference current for every 0.5 second is applied and the actual current is observed. The actual current follows the reference current within the band of hysteresis. The response of the battery current can further improved by reducing the band of hysteresis controller.



(a)



(b)

Fig. 3. (a) Battery Charger Current Control (b) Change in Battery Actual current with the change in battery reference current

In a PV-Inverter, current controllers are used for active and reactive power control through the PV-inverter as shown in Fig.4(a). Direct axis current of Inverter (Id_Inv) is controlled for the active power and the quadrature axis current of Inverter (Iq_Inv) is controlled for the reactive power flow through the PV inverter. Three phase inverter currents are converted into dq currents. Reference Id and Iq currents are obtained from the reference active and reactive powers respectively.

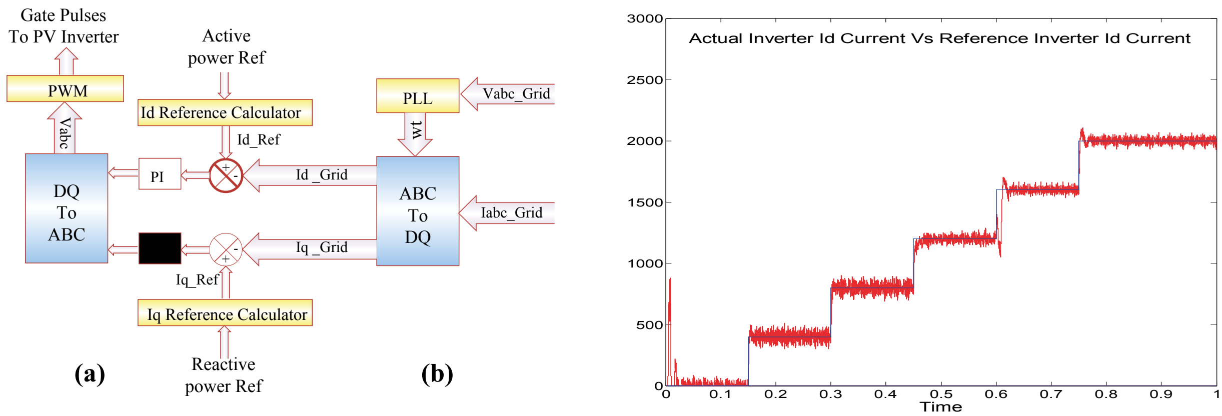


Fig. 4. (a) PV-Inverter Current Control (b) Change in Actual Inverter Id current with the change in Inverter Id reference current

In this system the reference reactive power is maintained Zero, since the reactive power compensation is not considered. Reference Id current is obtained from MPP of PV array. For analyzing the dynamic response of the system for different reference active powers is simulated. Fig.4(b) shows the response of inverter Id current with the change in reference active power i.e. reference Id current of inverter. The dynamic response of the system is good and can be improved further by tuning the PI controller parameters.

4. Results and Discussions

For better understanding of a buck-chopper based system, a single phase CHB based PV inverter fed from independent PV arrays is simulated for the specification shown in Table.2. Three independent battery banks are connected to the DC link through the Buck-chopper based battery charger as shown in Fig.5. A purely resistive local-load is connected across the Grid. In this work, Power rating of the batteries selected is lesser than the local load to study two cases of system operation.

Table 2. Electrical specification for the Buck-chopper based ESS Configurations suitable for CHB based PV- inverter

Electrical parameter	Value	Units	Description
Inverter AC Voltage	690	V	Single Phase
Frequency (F)	50	Hz	
PV array Power	1000	kW	
PV array Nominal voltage	600	V	
Battery Power	750	kW	Three Battery Banks each of 250 kW
Back Up Time	2	Hour	
Battery Nominal Voltage	500	V	
Battery Nominal Current	500	A	Power rating of each battery/ voltage
Battery Ah Rating	1000	Ah	Battery Current X Backup time

Case 1: When the irradiation is maximum (During Time Interval 0 to 0.1 Second in Fig.6.)
1. In this case PV arrays supply power to the Battery, Load and the Grid.

2. Since the PV array supply power to the Load/Grid through the inverter, inverter current and voltage and are in phase with each other.
3. Since the battery is taking the power, the battery current is Negative and it is in charging mode of operation. Since the Grid is receiving the power, Grid current is 180 degree out of phase with the Grid Voltage.
4. Since the number of H-Bridges is three, the Number of levels in the Inverter phase voltage is Seven and the each step in the PWM voltage is equal to the PV voltage.

Case 2: When the irradiation is Zero (During Time Interval of 0.1 to 0.2 Second in Fig.6.)

1. In this case Power from the PV arrays is Zero and Batteries provide power to the Load but the magnitude of current is less since the batteries are rated for lesser value.
2. Since the Batteries supply power to the Load/Grid through the inverter, inverter current and voltage and are in phase with each other.
3. Since the battery is supplying the power, the battery current is positive.
4. Since the Grid is providing additional power required for the load, Grid current is in phase with the Grid Voltage. Each step in the PWM voltage is equal to the Battery voltage.

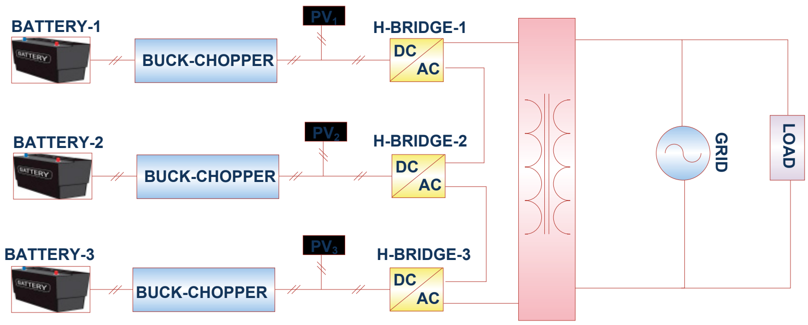


Fig. 5. Single Phase Seven-Level buck-chopper based ESS for CHB Inverter

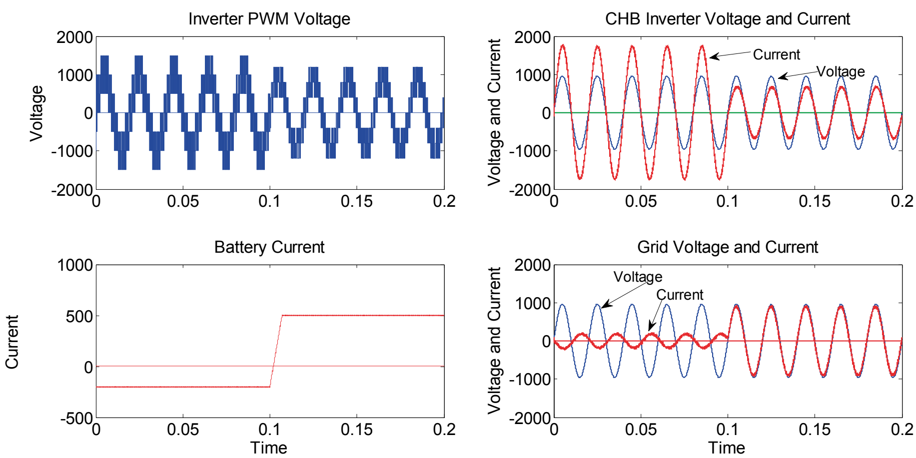


Fig. 6. Voltage and Current Waveforms of the system

5. Conclusions

In this work, various configurations of ESS for CHB inverters suitable for large scale PV applications are discussed. Advantages of the buck-chopper based ESS are explained. The buck-chopper based ESS configuration is simple to control, needs lesser controller hardware and the controls is required only during charging mode. The change over time from PV source to the battery is instantaneous as the discharging of battery is through the Diode. From the presented results, it is observed that good dynamic response can be achieved with this system. To verify the performance of the control algorithm in real time, Hardware In loop Simulations can be carried out by interfacing the real controller card with the simulated power circuit with the help of real time digital simulator (RTDS). Operation of this system can also be analyzed in standalone mode.

References

[1] V Sridhar, S Umashankar. A comprehensive review on CHB MLI based PV inverter and feasibility study of CHB MLI based PV-STATCOM. Renewable and Sustainable Energy Reviews 2017; 78:138-156.

[2] F.A.Dragonas, G.Nerrati, P.Sanjeevikumar, G.Grandi. High-Voltage High-Frequency Arbitrary Waveform Multilevel Generator for DBD Plasma Actuators. IEEE Trans. on Industry Applications 2015;51(4): 3334–3342.

[3] R.Chinthamalla, P.Sanjeevikumar, R.Karampuria, Sachin Jain, Ahmet H.Ertas, Viliam Fedak, A Solar PV Water Pumping Solution Using a Three-Level Cascaded Inverter Connected Induction Motor Drive. Engineering Science and Technology: An International Journal (JESTECH), Elsevier Journal Publications 2016;19(4): 1731–1741.

[4] P.Sanjeevikumar, Pierluigi Siano, Ahmet H.Ertas, S.Rajasekar, Kiran M. Pandav. Single-Phase Seven-Level Stack Multicell Converter Using Level Shifting SPWM Technique. in: Proceedings of IEEE conference publications. 2016.

[5] Dong-Keun Jeong, H S Kim, J W Baek, Ju-Yong Kim, Hee-Je Kim. Dual active bridge converter for Energy Storage System in DC microgrid. In: Proceedings of IEEE conference publications. p. 152-156; 2016.

[6] S Dutta, S Hazra, S Bhattacharya. A Digital Predictive Current-Mode Controller for a Single-Phase High-Frequency Transformer-Isolated Dual-Active Bridge DC-to-DC Converter. IEEE Trans Industrial Electronics 2016; 63(9): 5943-5952.

[7] Vavilapalli Sridhar, Padmanaban Sanjeevikumar, Subramaniam Umashankar, Mihet-Popa Lucian. Power Balancing Control for Grid Energy Storage System in Photovoltaic Applications-Real Time Digital Simulation Implementation. Energies Journal 2017; 10(7): 928.

[8] Sachin Jain, Ch. Ramulu, P.Sanjeevikumar, Olorunfemi Ojo, Ahmet H.Ertas. Dual MPPT Algorithm for Dual PV Source Fed Open-End Winding Induction Motor Drive for Pumping Application. Engineering Science and Technology: An International Journal (JESTECH), Elsevier Journal Publications 2016;19(4): 1771–1780.

[9] P. Sanjeevikumar, G.Grandi, Patrick Wheeler, Frede Blaabjerg, J.Loncarski. A Simple MPPT Algorithm for Novel PV Power Generation system by High Output Voltage DC-DC Boost Converter. In: Proceedings of IEEE conference publications. p. 214-220; 2015.

[10] T.Anuradha, P.Deiva Sundari, P.Sanjeevikumar, Pierluigi Siano, Zbigniew Leonowicz. Comparative Analysis of Common MPPT Techniques for Solar PV System with Soft Switched, Interleaved Isolated Converter. In: Proceedings of IEEE conference publications. 2016.

[11] Neeraj Priyadarshi, P.Sanjeevikumar, Amarjeet Sharma, Lucian Mihet-Popa. An Experimental Fuzzy SVPWM based Inverter Control Realization of Grid Integrated PV-Wind System with Hybrid FPSO MPPT Using dSPACE DS 1104 Real Time Interface. Energies Journal, MDPI AG Publications, Switzerland, 2017.

[12] S.Saravanan, N.Ramesh Babu, P.Sanjeevikumar. Comparison and Analysis of DC/DC Converters with MPPT Techniques Based PV System. Lecture Notes in Electrical Engineering, Springer Journal Publications, 2017.