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Increasing Dispatchability of a PV Power Plant through Modular Multilevel Converter-Based Embedded Battery Energy Storage (MMC-EBES)

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SUMMARY

Solar PV power has become increasingly popular as widely abundant source of renewable energy. However intermittency of solar irradiance remains an issue when providing reliable baseload power through solar PV systems. Battery energy storage has been introduced by utilities to address the intermittent nature of PV power. This paper discusses how a battery energy storage system (BESS) based on modular multilevel converters (MMC) can be used to minimize the effect of solar intermittency on a solar PV system. This novel converter includes battery units within the submodules (SM) of the converter for proper battery management. In the suggested scheme, BESS communicates with the PV farm and calculates a moving average of the PV power to determine the BESS power output. A droop controller is used for better performance of the overall system. PSCAD/EMTDC simulations results are presented to show and validate the proposed control system.

KEYWORDS

Solar PV, MMC-EBES, intermittent power, droop, dispatch power
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INTRODUCTION

Modern power systems are increasingly including renewable energy sources such as wind, solar PV, thermal power, and tidal waves [1]. From these technologies, wind and solar PV have become the most popular in the race to harness more green energy at a lower cost. Due to the ease of installation, transportation, and relatively low capital and operation expenses, solar PV power has become a highly attractive energy source. However compared to conventional synchronous machines, solar PV plants introduce several challenges to the power system and power system operators [2], [3].

The power output of a solar PV plant is dependent on the solar irradiance and the temperature of the PV panels. Throughout the day, the solar irradiance is subjected to change due to cloud movement, accumulation of dust, etc. [4]. Sudden irradiance variations could result in large changes in the output power of a PV power plant where a large number of PV panels are used. This could lead to inadvertent effects on the power system with respect to frequency, voltage and power quality. Therefore it is vital to make necessary arrangements to reduce these power fluctuations as much as possible.

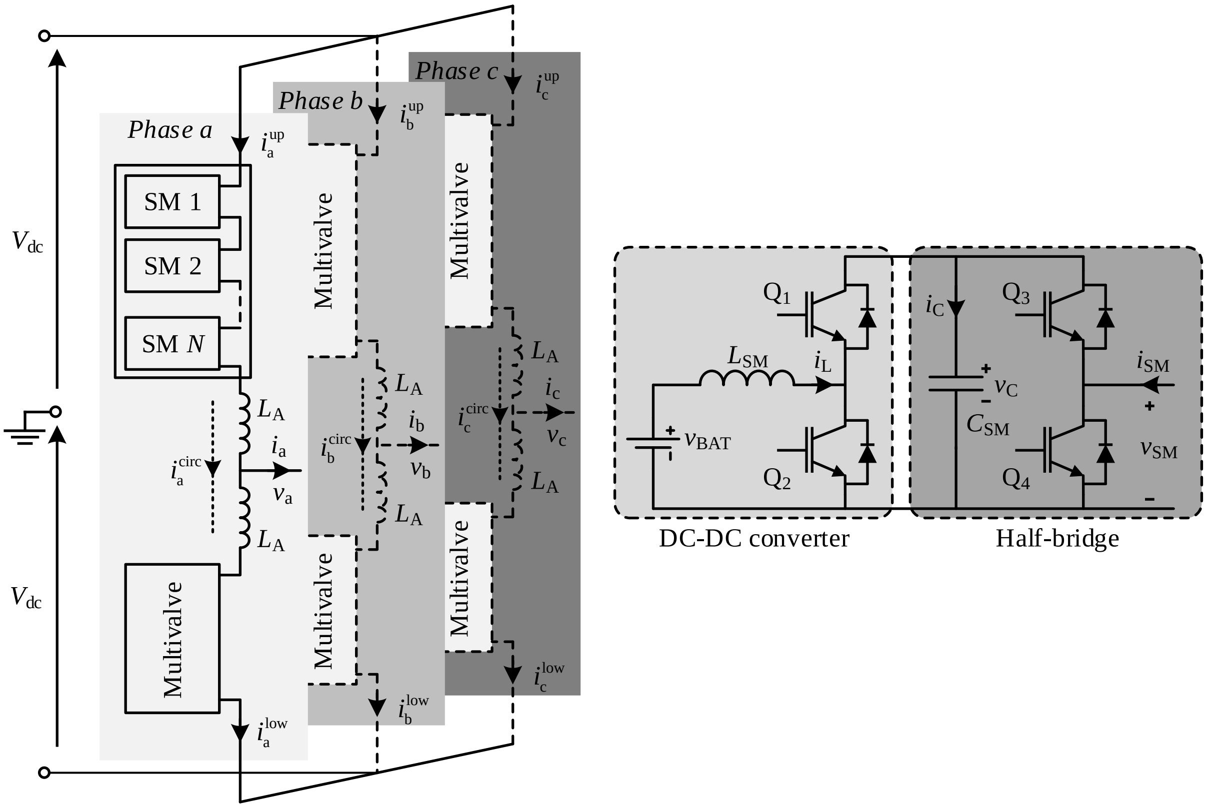
Many researchers around the world are working on the power intermittency and dispatchability issues related to PV power plants. Irradiance prediction based on highly complex computer-based environmental models has become popular, but have proven to be expensive and of low accuracy [4], [5]. De-rating the PV power output [6], [7] has also become a popular research topic where the power output from the PV plant is curtailed at a given operating point that is lower than the maximum available power to leave some energy reservoir to support frequency variations as well as to enable dispatchability of the PV power plant. This control procedure provides a low-cost solution with regards to hardware requirements but is considered highly inefficient due to low utilization factors. As an alternative approach to the above methods, energy storage can be installed with PV plants for improving dispatchability and intermittency [8]–[10].

In current installations, commercial BESS have been implemented mainly based on two- or three-level converters with large battery banks formed with several parallel connected battery strings (e.g., ABB's DynaPeaQ® system). These systems have known issues with uniformly charging and discharging batteries. The low number of converter levels at the ac interconnection requires heavy filtering to reduce harmonic distortions introduced to the connected network. Fairly low voltages are required in the converter due to limitations of power electronic switches. To address these problems an MMC-EBES (Multi-Modular Converter – Embedded Battery Energy Storage) system is considered [11]–[13]. This converter disperses the battery units in number of submodules (SMs) and generates an output voltage with good harmonic performance. Additionally, the converter provides a medium voltage dc (MVDC) link, which can be further used for MVDC transmission. Individual battery currents can be controlled for uniform charging and discharging. Therefore, this converter has attracted the attention of many researchers as a means of introducing battery energy storage to the grid.

In this paper, a basic introduction for the converter along with its main control systems are presented. The converter is integrated with a PV farm to smooth out the power generated from the PV power plant. The power order for the ac power output of the BESS is determined by a moving average calculation of the PV power plant's output along with a droop function. The converter operation is also validated in a scheme where the converter is used to interchange power with an MVDC link.

CONVERTER STRUCTURE AND CONTROL SYSTEMS

The MMC-EBES is formed with two multivalves and two arm inductors per phase where a multivalve is formed with several series connected SMs as shown in Fig. 1. Each SM is formed with a capacitor and a half-bridge switching arrangement, which allows the capacitor to be inserted with the rest of the SMs. A battery is connected across the SM via a bi-directional dc-dc converter. Proper switching of each of the SMs ensures that the ac voltage at the terminal is developed with multiple steps.



(a) (b)

Fig. 1. MMC-EBES (a) converter's schematic diagram (b) SM's schematic diagram.

MMC-EBES ac currents can be controlled similar to a conventional inverter. Decoupled synchronous reference frame current controllers can be designed and can be further augmented with outer active power and ac voltage or reactive power controllers. Fig. 2(a) shows a block diagram of such a controller. The dc-dc converters in the SM provide a boost action on the battery voltage and controls the average capacitor voltage. Fig. 3 shows the dc-dc converter's average capacitor voltage controller.

Due to voltage mismatch between the multivalves and dc link, circulating currents of different harmonic frequencies are generated within the converter. These currents circulate within the converter consuming valuable current capacity of semiconductors and causing power losses. However, these currents can be controlled as shown in Fig. 2(b) and be used to transfer power between and among phases and help in balancing the state-of-charge (SOC) between battery units [11], [14]. The same controller topology can be used to supress unwanted harmonic currents to reduce losses by making the reference zero.

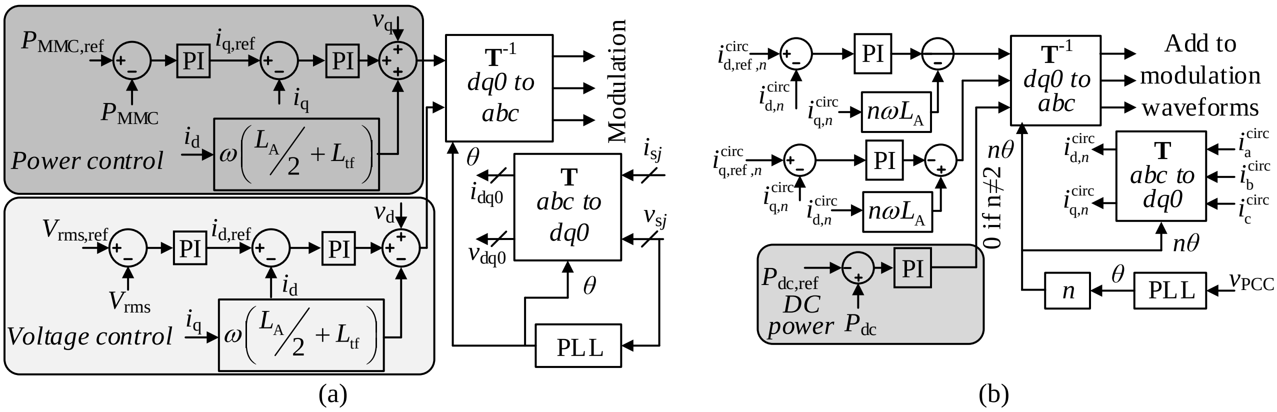


Fig. 2. Control systems (a) power and voltage control (b) circulating current control.

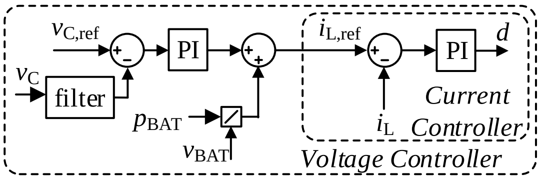


Fig. 3. DC-DC converter voltage controller.

The converter's power transfer with the dc link can be manipulated by controlling the zero sequence component of circulating current. This is useful when the converter is also connected to an MVDC system for power transmission.

PV PLANT POWER SMOOTHING WITH MOVING AVERAGE WINDOW

As indicated in the introduction, solar insolation on a land area varies throughout the day due to cloud movement and, as a result, the power output of the PV plant fluctuates. In large PV installations, these variations could translate into high power variations injected to the power system, resulting in frequency deviations.

As a solution, this paper proposes a moving averaging (MA) window based control system to smoothen out the power fluctuations due to variations in solar insolation. The MA window samples PV plant power output at a certain sampling rate (e.g. 2 Hz) and store the sample values. The output of this block is the average of the samples and is held constant until a new sample is available. At the arrival of new sample, the oldest sample is discarded and the remaining samples shift in the averaging window data storage. The power data samples from the PV plant are sent to the MMC-EBES through a communication channel.

The power order from the moving averaging power smoother ($P_{ac,ref1}$) is augmented with a droop controller. The droop controller measures the frequency of the system obtained from the phase locked loop (PLL) and generates a reference power order ($P_{ac,ref2}$), which aims to minimize the deviation of power system frequency due to fluctuations in generation. The ac power order reference setting ($P_{ac,ref\ set}$) provides the reference level for power to be dispatched from the PV plant at the point of connection. The control block diagram associated with the moving average and the droop controller is shown in Fig. 4.

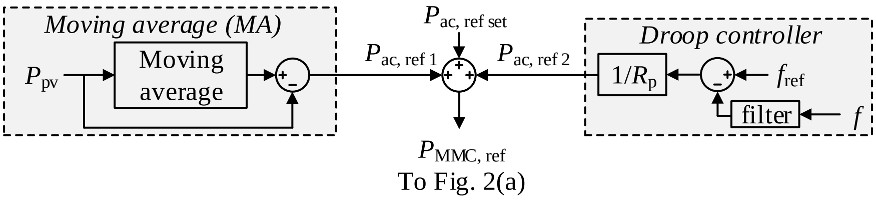


Fig. 4. Power smoothing controller.

VERIFICATION OF CONTROLLERS USING SIMULATIONS

The proposed controller and converter operation are validated using PSCAD/EMTDC. A small power system as shown in Fig. 5 was implemented. The MMC-EBES is modelled as shown in [15] for efficient simulation. The grid is simulated using a synchronous machine with relatively low inertia to observe the variations of frequency. The parameters of the MMC-EBES, PV system, and synchronous machine are shown in Table I.

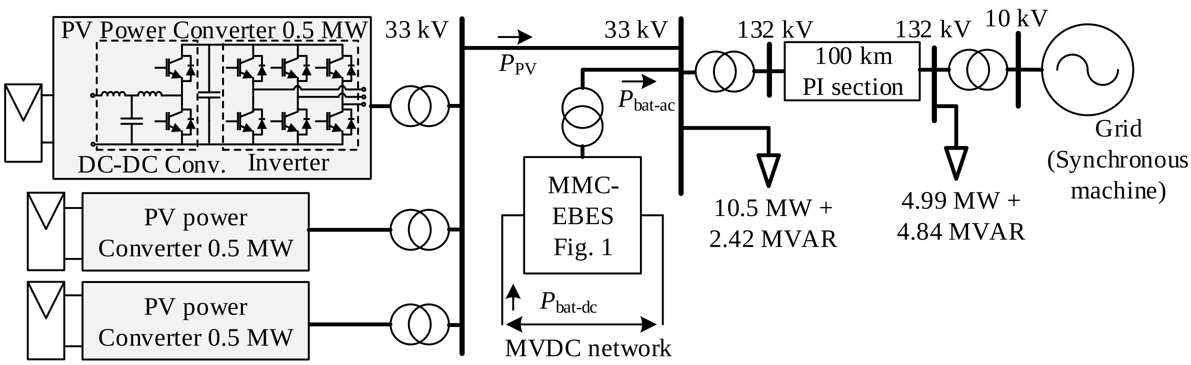


Fig. 5. Study simulation system.

TABLE I

MMC-EBES PARAMETERS	
Parameter	**Value**
Power rating	10 MW
No. of SMs per arm	15
SM capacitor	15 mF
MVDC voltage	±7.5 kV
Battery voltage	500 V
Arm inductor	0.5 mH
AC voltage	8 kV_{ll-rms}
PV SYSTEM PARAMETERS	
Parameter	**Value**
PV Module	KU330-8BCA
No. of modules in a string	15
No. of strings in parallel	100
Power converter rating	0.5 MW
DC link voltage	1 kV
Inverter ac voltage	480 V
Total rated PV power	1.5 MW
SYNCHRONOUS MACHINE PARAMETERS	
Parameter	**Value**
Inertia	5 s
Governor droop	5 %
Power rating	20 MVA
Frequency	60 Hz

The first test is the verification of the ability of the MMC-EBES to operate as a three-port converter. Solar irradiance is kept constant at 1000 Wm^{-2} and the droop function on the MMC-EBES is disabled during this test. After reaching steady state in the simulation, the ac power reference is changed from 0.3 pu to 0 pu at t = 1 s and to -0.3 pu at t = 3 s. The dc power reference is changed from -0.3 pu to 0 pu at t = 2 s and to 0.3 pu at t = 4 s. Small power steps are used as the synchronous machine is operating near its rated power capability. In Fig. 6, the MVDC line current, ac voltage at the converter's point of common coupling (PCC), and power distribution within the MMC-EBES are shown. It can be seen that when ac power command variation happens the battery power also rapidly settles at the required value. Very little disturbance can be seen in dc system's power or current. A dc power change does not affect the ac power transfer as expected. However one could observe slow transitions in dc power and battery power during rapid power command changes. The dc power controller is required to be made slow as rapid changes in circulating currents could result in instability of the MMC-EBES.

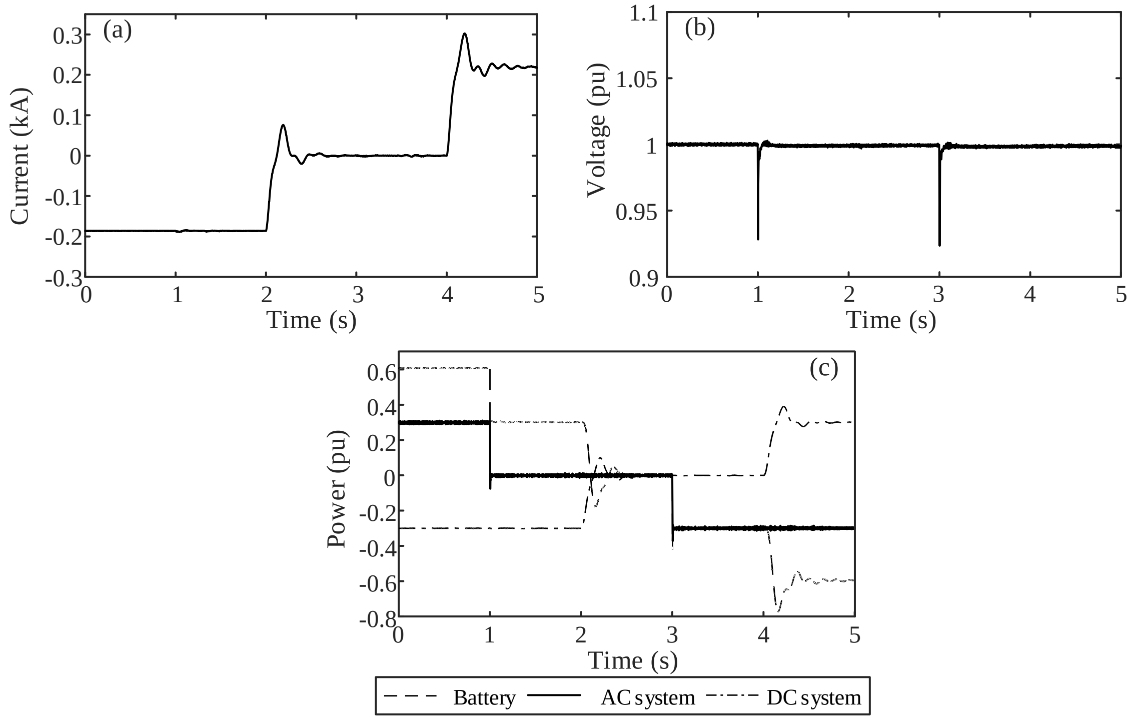


Fig. 6. Simulation results of independent power control (a) dc current (b) converter ac voltage (c) power distribution within the converter.

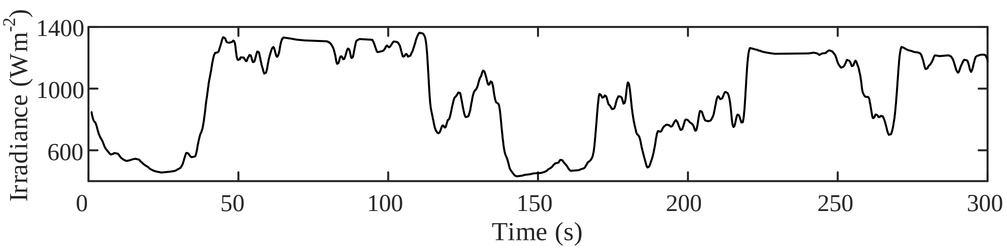


Fig. 7. Irradiance profile.

The second test is performed with real solar insolation data over a period of 300 s (Fig. 7). The solar irradiance data is obtained from [16]. The impact of the solar irradiance variation over power system frequency and synchronous machine model speed is observed. The test is performed without any ancillary support from MMC-EBES (constant 0.5 pu power supplied), with moving average (MA) power smoothing controller only, droop controller only, and finally with both MA and droop controllers. Fig. 8 shows the power system frequency and machine speed variations at different settings. As expected the average frequency is different due to the droop function. Large rapid variations in the frequency can be observed without any support actions. The MA controller reduces the frequency spikes partially and smooths out the frequency change. With only the droop function, the frequency spikes are reduced although sudden changes still happen. When both the MA and droop controller are enabled, very smooth frequency and machine speed can be observed.

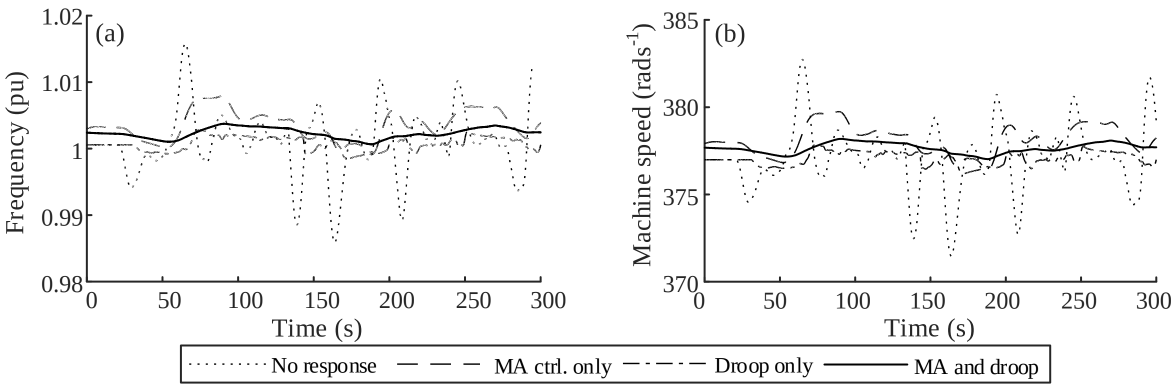


Fig. 8. Response for different control systems. (a) frequency (b) machine speed.

CONCLUSION

An MMC-EBES has been used to smoothen power output fluctuation in a PV plant due to variations in insolation. The proposed converter is able to rapidly control ac power and also transfer power into a MVDC network. Control systems for power and voltage, dc power, circulating current, and the dc-dc converter were presented. The EMT simulations validated that the MMC-EBES is able to operate as a three-port converter interchanging power between a MVDC network, an ac network, and the battery units. Further simulations based on the MA power smoothing controller and droop controller show the ability of the proposed control system in damping the frequency deviations due to variation of solar irradiance in a power system with high penetration of PV power. The MMC-EBES also has the ability to discharge/absorb active power based on a power order setting given by the system operator.

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