Integration of PV Generation and Battery Energy Storage System into Hybrid AC and MTDC Networks

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Abstract— **Multiterminal direct current (MTDC) networks can provide power system operators and utilities with the flexibility to connect various DC energy sources- such as inverter-based PV plants and storage systems- directly to the DC networks. However, this interesting feature requires new strategies for control of DC sources. This article introduces a new topology for AC transmission systems combined with MTDC networks considering the integration of utility-scale PV plants and Battery Energy Storage Systems (BESS). MMC-based back-to-back converters help build the MTDC network. Besides, co-located PV plant and BESS systems are integrated into the MTDC grid via DC-DC boost and bidirectional converters, respectively. The proposed configuration was simulated in Matlab/Simulink. The effectiveness of the configuration and proposed control strategies is verified during a transient AC fault.**

Keywords— MTDC, Hybrid AC Transmission Networks, BESS, PV plant, MMC, Back-to-Back Converter.

I. Introduction

Due to the considerable investment and rapid development of photovoltaic (PV) and wind generation technologies, the average levelized cost of electricity (LCOE) of these renewable energy resources (RESs) has fallen within the cost range of fossil fuel-based traditional power plants [1]. Thus, these environmentally friendly technologies are the main energy sources to meet the ever-increasing worldwide energy demand. Despite the promising achievements, the intermittent nature of large-scale RESs is still the main challenge to connecting them to transmission or distribution networks. To cope with this problem, grid-scale battery energy storage systems (BESS) are suggested that have the capability of storing and dispatching energy in the shortest period required to compensate for abrupt RESs fluctuations. Such features can significantly improve the power supply stability and reliability. In addition, energy storage systems can participate in various operation services like frequency regulation, peak shaving, power loss reduction, load management, and quality improvement [2]. Hence, interest in coupled PV and BESS is rising considerably among utilities and power system operators. On the other hand, the high transfer efficiency, and low costs of voltage source converter-based (VSC) DC networks have made them attractive solutions for RESs integration compared with their conventional AC transmission counterparts. VSC-HVDC networks provide asynchronous interconnection capability without sub-synchronous resonance issues, cable skin effect, and reactive charging current. These networks can also resist AC fault propagation and provide better active and reactive power controllability over long distances [3-5]. VSC-HVDC networks are connected to the AC grids through modular multilevel converters (MMC), including a large number of submodules. These converters can produce almost ideal sine wave voltage, considerably decreasing voltage and current harmonics and minimizing the need for filters. Researchers have investigated the application of multilevel cascaded H-bridge and Full-bridge inverters, MMCs, and neutral-point clamped inverters (NPT) during normal or abnormal situations [6-10]. Thus, some novel MMC configurations have been proposed to improve the MTDC capacity, reliability, and stability. The new MMC-based topology introduced in [11] enhances the performance of MTDC systems while faults occur in DC lines. In [12], the authors proposed an adaptive integrated and coordinated control approach that improves the MMC-MTDC system's response and stability.

Hence, a proper connection of BESS to hybrid AC/DC transmission networks can help power system operators benefit from both technologies while integrating RESs. Research efforts have been investigating the connection of BESS to VSC-HVDC systems, resulting in various configurations. The methods of integrating BESS in hybrid AC/DC networks can be divided into two fundamental categories: 1- separate RESs and BESS units integrated through their DC-DC converters [1-3,12], 2- embedded BESS into MMCs in HVDC systems [14-19]. Dominant configurations of the first category were described in detail in [2], including 1- loosely DC coupled, 2- tightly DC coupled, and 3- AC-coupled.

This paper investigates the performance of co-located but independent PV and BESS systems integrated into MTDC links that connects two parts of an AC transmission network through back-to-back (B2B) converters. PV can be connected to the MTDC lines through DC-DC converters, while BESS is connected to the MTDC network by a bidirectional DC-DC converter. The performance of the proposed configuration is evaluated through a transient AC fault analysis.

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II. The Proposed Topology

This section discusses the proposed hybrid AC and MTDC transmission system topology and implemented control systems.

A. *Hybrid AC/MTDC Transmission Networks*

The proposed AC/MTDC transmission configuration allows the system operators and utilities to integrate large-scale PV plants and battery energy storage systems (BESS) into the MTDC networks, which enhances the system's availability and reliability. This new topology provides a bidirectional power flow control while maximum energy can be harvested from solar farms. Fig. 1. shows the introduced topology of the hybrid AC transmission system with an MTDC network. MMC-based B2B converters provide the MTDC system with connecting PV plants and BESS. B2B converters are connected to the AC transmission lines through step-up and step-down transformers. In this study, it is assumed that PV plants and the BESS system are co-located units having independent control strategies.

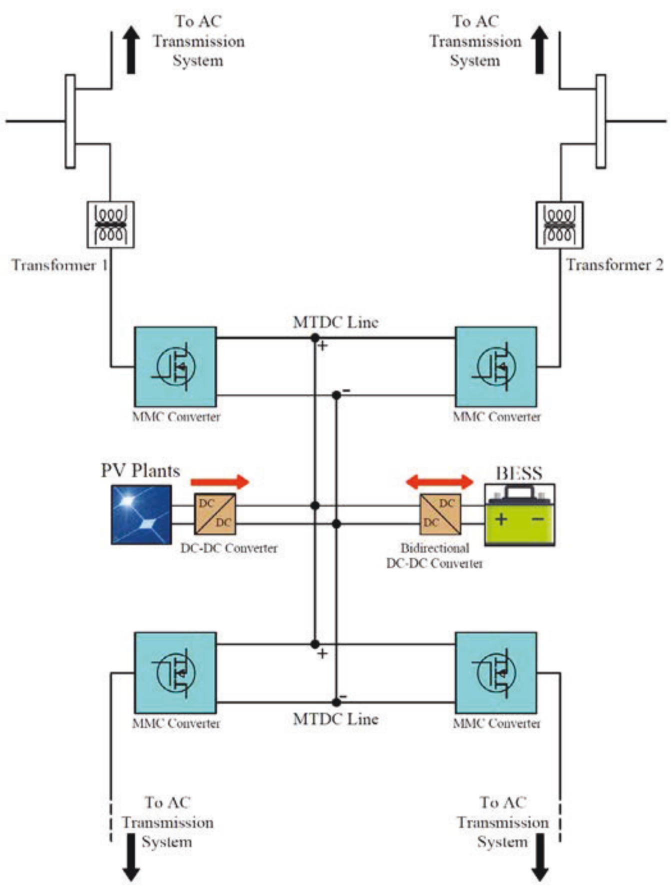

Fig. 1. *Suggested AC/DC transmission network with MTDC operation.*

Figure 2. depicts the structure of N+1 level MMC. As can be seen, MMCs have six arms consisting of N half bridge SMs, including two bidirectional power switches, capacitors, reactors, and resistors (representing the equivalent resistance and inductance of MMC arms) which are connected in series.

A staircase output voltage (with N+1 levels) can be obtained via proper modulation of MMC submodules. The arm current direction determines the capacitors' charging and discharging states. Switching SMs allows the capacitor voltage to be delivered to the terminals, and the capacitors are bypassed -and terminals have zero voltages- when SMs switches are off. However, these voltage changes at high frequencies result in unwanted voltage changes within the MMCs and voltage unbalance between the three phases that cause a circulating current within the legs. This unwanted current leads to drawbacks like increased losses and disturbances. An inner control approach is often applied to cope with this problem.

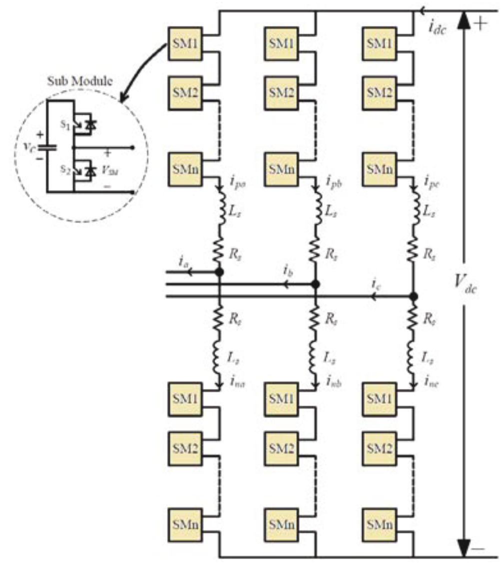

Fig. 2. *N+1 level half-bridge MMC.*

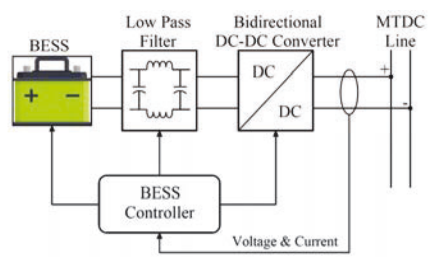

Fig. 3. *BESS control modeling.*

III. Modeling and Simulation

This section introduces the control system implemented for the control of converters, inverters, maximum power point tracking (MPPT) technique, and the BESS control strategies. In this study, typical control methods for the B2B controls include 1- an outer control technique for regulating active and reactive power, 2- an inner current technique for reducing the circulating current, and 3- a voltage balancing approach for the capacitor voltage. In addition, a PWM (with phase-shifted) technique is used for controlling to control the power and each leg of MMCs. For PV plants, the MPPT method is employed to control the output of PV modules. Fig. 4. illustrates the implemented control system.

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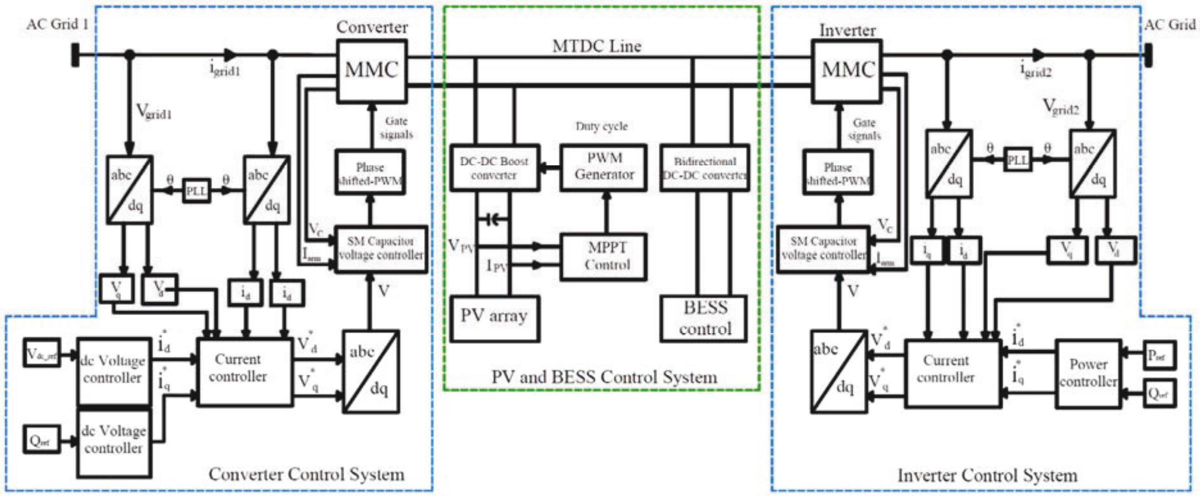

Fig. 4. *Control system of the proposed configuration.*

Fig. 3. also shows the control strategy applied for BESS. As an independent unit, the BESS controller continuously measures the bidirectional DC-DC converter output and sends control signals to BESS, filter, and converter. Hence, a closed-loop control system is carried out to control the current, voltage, and state of charge (SOC) of the BESS. The control signals are sent to gate drivers of the bidirectional DC-DC converter that connects the BESS unit to the MTDC network.

MATLAB/SIMULINK-based simulations are carried out by fulfilling an AC transient fault analysis to approve the performance of the suggested configuration and control strategies. Table I. represents the case study network parameters. Fig. 5. shows the hybrid AC transmission network with the MTDC network simulation implemented in the SIMULINK environment. A transient fault is applied to one of the buses of the lower AC network while PV is producing its maximum available power and BESS is charging at %70 of its nominal capacity.

TABLE I. CASE STUDY NETWORK PARAMETERS

Parameter	***chosen Values***
AC System	200/20 kV, 60 Hz
MTDC Line Voltage	40 kV
Number of SMs (for each arm)	50
AC Loads	Upper Buses: 100 MW, 50 MVAr - 100 MW, 40 MVAr Lower Busses: 40 MW, 30 MVAr - 30 MW, 20 MVAr
Capacitance values of the SMs	500 µF
Switching frequency	10 kHz
Inductance & Resistance of Arms	Rs=0.03 ohm, Ls= 0.15 pu
Maximum Power of PVs	60 MW
BESS Capacity	20 MW

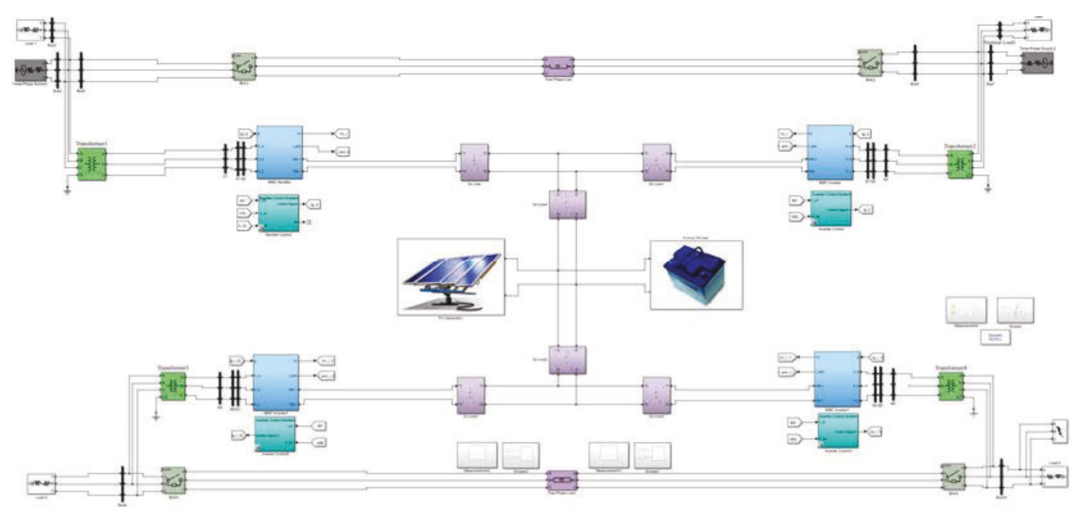

Fig. 5. *The implemented case study in MATLAB/SIMULINK.*

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IV. Results and Discussion

Figures 6-11 illustrate the simulation results of the suggested topology and control systems when a transient AC fault occurs in the lower AC network (right side). Fig. 6 shows the AC bus voltage experiencing the transient fault with and without BESS. When there is no BESS, voltages become unstable for a few seconds after the fault (upper figure). Considering BESS for the same fault scenario, there is a slight voltage increase after the fault, but the system is completely stable (lower figure). Fig. 7 shows the B2B inverter voltages and currents (upper AC network) during and after the fault, with and without BESS. It is evident that BESS can considerably improve the inverter outputs (voltages and currents) after the fault.

Before the fault happens, BESS is in the charging state (starting from 70%). However, during the fault, the BESS control system switches to discharging state to keep the MTDC voltage within standard limits. Fig. 8. represents the voltage, current, power, and SOC of BESS during and after the fault. Due to the appropriate performance of BESS and MMCs control systems, voltages and currents of the upper AC network and MTDC are not much affected during the fault. Fig. 9. represents the MTDC line voltage and current (flowing from the converter side to the inverter side) without and with BESS, respectively. PV plant outputs (including generated power, grid voltage, and line current) are also illustrated in Fig. 10.

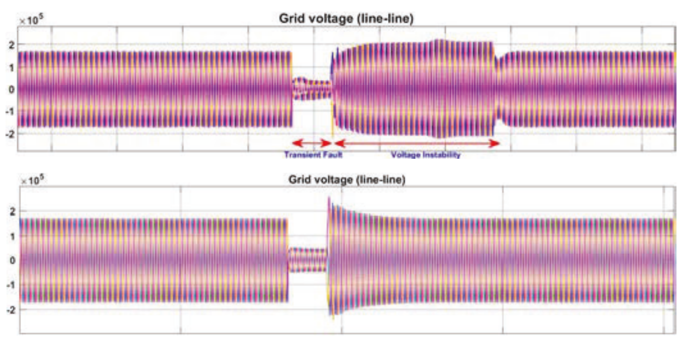

Fig. 6. *Voltages of the AC Bus experiencing the fault; upper figure) without BESS, lower figure) with BESS.*

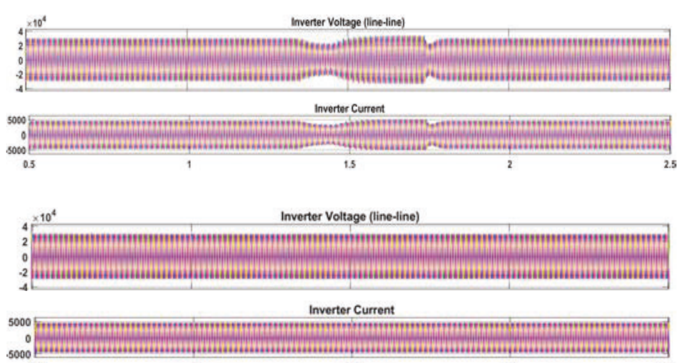

Fig. 7. *Inverter Voltages and currents (upper AC network); upper figure) without BESS, lower figure) with BESS.*

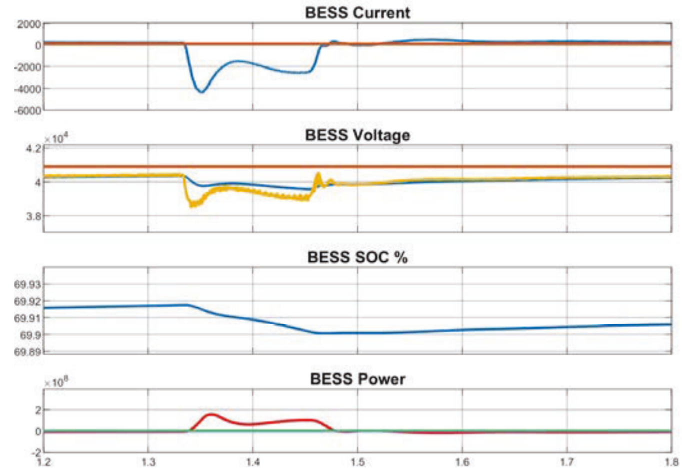

Fig. 8. *BESS line voltage, current, and power.*

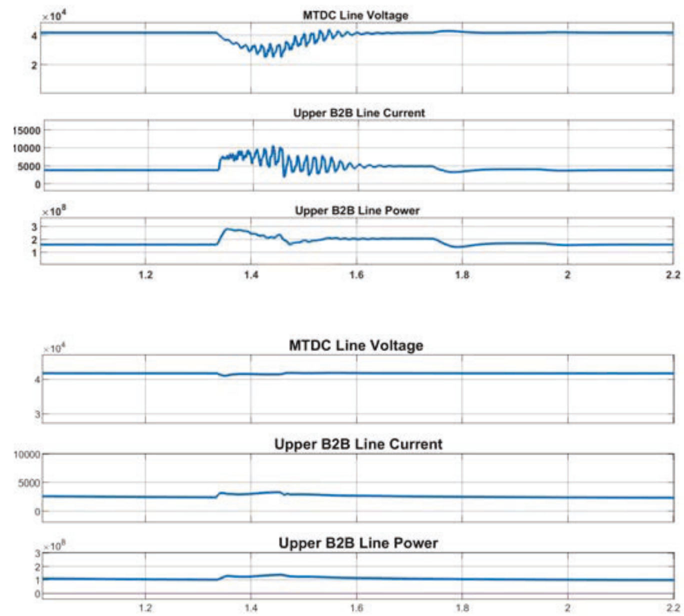

Fig. 9. *MTDC line Voltage, Current, and Power; upper figure) without BESS, lower figure) with BESS.*

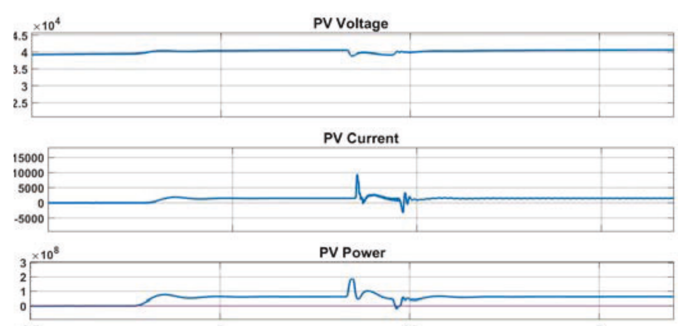

Fig. 10. *PV plant output: Voltage, current, and power.*

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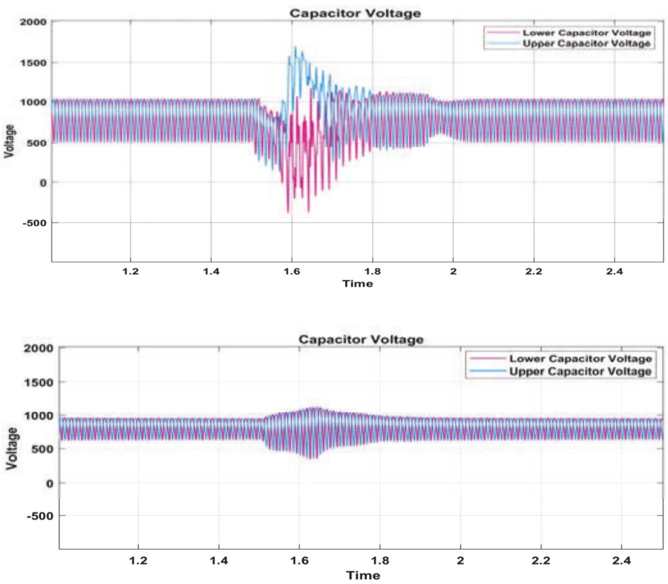

Fig. 11. *Capacitor voltage of the MMC Rectifier; upper) without BESS, lower) with BESS.*

Without BESS, the upper AC source should provide the fault current during the transient fault. However, this fault current causes remarkable undervoltage and overcurrent problems in the MTDC network and considerable overvoltages on the MMC capacitors (shown in fig. 11. upper figure). By considering BESS, the fault current can be supplied by the batteries, and the BESS controller can guarantee MTDC network voltage stability and avoid any outages or damage to the MMCs and transformers (shown in fig. 11. lower figure).

V. Conclusion

This article presented a new topology for hybrid AC and MTDC networks while integrating PV plants and BESS. An MMC-based B2B converter is used to provide the MTDC connection, and DC-DC boost and bidirectional converters facilitate connections of PVs and BESS to the DC grid. Outer and inner controllers were applied to regulate the active and reactive power of B2B converters and decrease the circulating current, respectively. The unbalance issue of converters was also dealt with by a capacitor voltage balancing control strategy. MPPT technique helps harvest the maximum accessible energy from the PV farm. Simulation results verify the effectiveness of the suggested topology during a transient AC fault.

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