Hybrid AC Transmission System with Back-to-Back Converter Configuration and MTDC Operation Considering PV Energy Integration

Mojtaba Ahanch, Roy McCann, Alan Mantooth
Center for GRid-connected Advanced Power Electronic Systems
University of Arkansas, Fayetteville, AR 72701, U.S.A.
mahanch@uark.edu, rmccann@uark.edu, mantooth@uark.edu

2021 6th IEEE Workshop on the Electronic Grid (eGRID) | 978-1-6654-4979-3/21/$31.00 ©2021 IEEE | DOI: 10.1109/EGRID52793.2021.9662161

***Abstract*— MMC-based back-to-back (B2B) converters are promising for hybrid AC/DC transmission systems when integrating large scale PV sources. This paper proposes a novel configuration for hybrid AC transmission systems with B2B converters and multi-terminal direct current (MTDC) operation which facilitates the integration of PV energy and enhances the system stability and reliability. This is achieved by an advanced interconnection with two operation modes: 1- A bi-directional power flow via AC connections, and 2- Direct active power injection to the MTDC from PV source. Conventional outer, inner and capacitor voltage balancing control systems are utilized in this study for regulating the currents and voltages of B2B converter. Also, The Perturb and observe (P and O) technique is implemented for obtaining maximum power point tracking (MPPT) of the PV generation considering a dc-dc boost converter. The efficacy of this proposed configuration is verified through time-domain simulations carried out by MATLAB/SIMULINK.**

Keywords*— Hybrid AC Transmission System, Multilevel Converter (MMC), Back-to-Back Converter, Multi-Terminal Direct Current (MTDC), PV Integration.

I. INTRODUCTION

The increasing capacity coming from inverter-based renewable generation brings about new challenges to the power system reliability and electricity markets operation [1]. Due to the increased renewable energy generated by large scale solar PV plants along with increasing capacity in battery energy storage, hybrid AC transmission systems are gaining considerable attentions. The integration of inverter-based DC power sources via multi-terminal direct current (MTDC) configurations has potentially many benefits for meeting ever-increasing electricity demands [2].

By connecting DC renewable energy sources to HVDC systems it is expected that grid power efficiency increases, and overall system availability improves. In order to connect dc sources to a HVDC line, a rectifier and step-up transformer or dc-dc cascaded converter is required to boost the voltage to transmission or sub-transmission levels. Different kind of modular structures have been proposed to obtain a high step-up ratio [3]-[5]. Researchers have disclosed an HVDC back-to-back (B2B) voltage source converter with a 12-pulse dc circuit [6]. System reliability can be increased by connecting Two or more 12-pulse B2B converters in parallel [7]. In [8], the authors proposed a novel four-pole B2B converter for HVDC applications which can improve the system reliability through partitioning the DC circuit into 25% rated elements rather a single 100% rated circuit. Solar PV plants are usually connected to the utility grid through classical 2-level converters since the PV module insulation limits allow the plants to operate only in the range of 1.0-1.5 kV [9]. Thus, step-up transformers are needed to connect PV plants to medium voltage (MV) or high voltage (HV) lines.

To cope with the voltage limitations of PV plants, researchers propose multilevel converters to boost the PV plants' voltage. Hence, the multilevel cascaded H-bridge (CHB) inverter, Full-bridge inverter, neutral-point clamped (NPT) inverter, and the modular multilevel converter (MMC) have been used in many research projects [10-14]. New MMC topologies have also been introduced to enhance the MTDC capacity and increase system reliability and stability. In [15], the novel MMC topology improve the MTDC performance during severe DC faults. An adaptive integrated coordinated control method is suggested in [16] which boosts the response speed and stability of MMC-MTDC systems. The unidirectional hybrid converter proposed in [17] uses a new active power controller to regulate the full-bridge (FB) submodules and better control the transmitted power.

A new configuration of hybrid AC transmission system with MTDC operation is proposed in this paper which facilitates the PV energy integration into MTDC system. The new configuration and its control mechanisms are introduced in section II and III, and the simulation and results are discussed in section IV.

II. THE PROPOSED CONFIGURATION

A. Hybrid AC Transmission System with B2B converter and MTDC

This study proposes a configuration that enables hybrid AC and DC transmission operations considering large scale PV farms which improves the system reliability. The advantage of the proposed configuration is that the hybrid AC system can provide power flow control while maximizing the energy harvest from renewable resources. This can be accomplished by developing an interconnection with two operation states: 1- A bi-directional power flow through AC connections to boost the system stability; 2- Direct power injection to the grid from the PV source. Fig. 1. Illustrates the proposed B2B converter structure for hybrid AC transmission system with MTDC. The AC terminals of MMCs are connected to the step-up transformers to be connected to the utility grid. A PV source is also connected to the MTDC.

This project is supported by National Science Foundation's Fundamental Research Project NSF-FRP grant no. 1747757 as part of the NSF I/UCRC program that funds the GRAPES center.

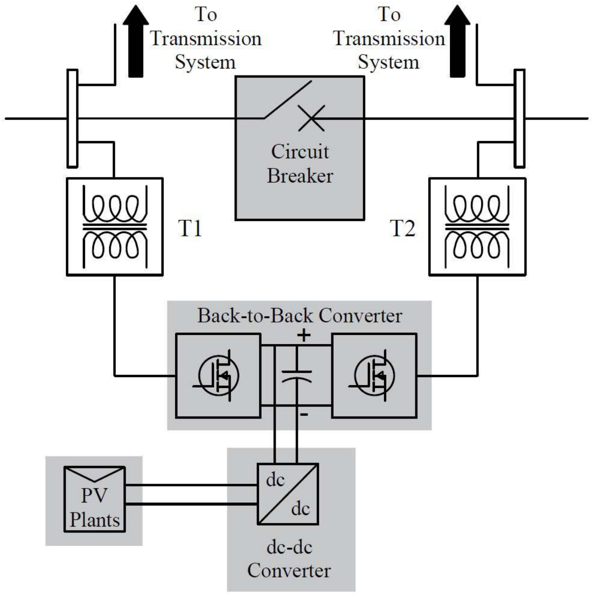

Fig. 1. Proposed hybrid AC transmission system with back-to-back configuration and MTDC.

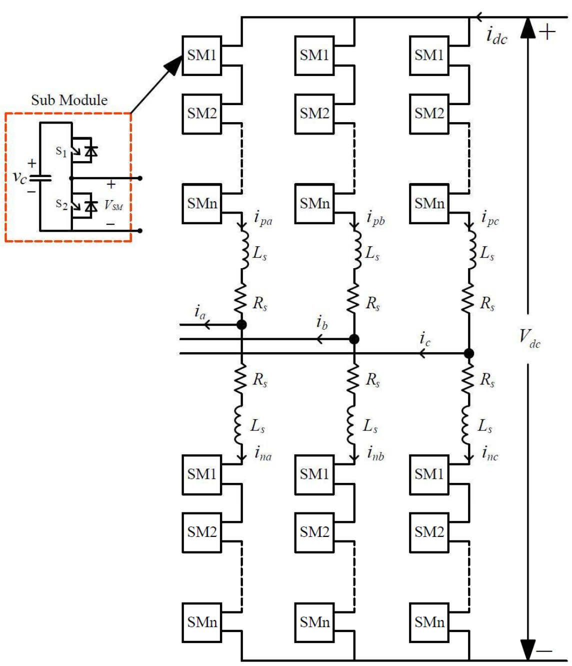

Fig. 2. Circuit diagram of n+1 level half bridge MMC and a submodule.

B. MMC modeling

Figure 2. illustrates the circuit structure of a three-phase half-bridge MMC with N+1 levels. Each MMC has six arms including N half bridge SMs (with two bidirectional switches and a capacitor), reactors (arm inductance) and resistors (equivalent resistance of MMC) connected in series. The reactors (L_S) help provide a current control for each phase arm. a staircase output voltage waveform is achieved through the modulation of converter leg submodules. The charge and discharge states of the cell capacitor can be determined by the direction of the arm current.

By switching the SM and keep it in ON state, the capacitor voltage (V_{SM}) is delivered to the SM terminals. However, by turning off the SM, the capacitor is bypassed and the voltage at SM terminals becomes zero. Such voltage variations at high frequencies causes voltage differences within the MMC arms and between the three phases which can result in a circulating current (i_{circ}) flowing through the MMC legs. This circulating current brings about some disadvantages such as increased losses, unbalance issues and disturbances.

For analyzing the currents of the circuit, the SMs can be replaced by voltage sources. By applying the Park's transformation, one can extract the d&q components of voltages and currents for the VSC.

By writing KVL at the AC side of the converter:

$$L\frac{di_i}{dt} + Ri_i = u_i - v_i, \tag{1}$$

Where v_i and u_i refer to the output voltage of MMC and system voltage, respectively.

$$\begin{cases} \dfrac{di_d}{dt} = \dfrac{1}{L}(u_d - v_d) - \dfrac{R}{L}i_d - \omega i_q \\ \dfrac{di_q}{dt} = \dfrac{1}{L}(u_q - v_q) - \dfrac{R}{L}i_q - \omega i_d. \end{cases} \tag{2}$$

Then, instantaneous real and reactive power can be expressed as:

$$\begin{cases} P = 1.5 * (u_d i_d - u_q i_q) \\ Q = 1.5 * (u_d i_q - u_q i_d). \end{cases} \tag{3}$$

Assuming the system as a three-phase balanced network, the real and reactive power can be calculated with regard to the active and reactive currents as follows:

$$u_q = 0. \tag{4}$$

$$\begin{cases} P = 1.5 * u_d i_d \\ Q = 1.5 * u_d i_q. \end{cases} \tag{5}$$

As can be seen, the real and reactive power are proportional to the decoupled currents in dq frame.

III. CONTROL OF HYBRID AC SYSTEM WITH MTDC

The control system in the proposed model is like the conventional approaches used in the HVDC system consisting of the following parts:

1- Outer control system for active and reactive power

2- Inner current control

3- Capacitor voltage balancing control

Also, a phase shifted PWM technology is employed to independently control active and reactive power and DC voltage of each converter. Besides, MPPT technique is utilized for controlling the PV output connected to the DC line. Figure 3 represents the block diagram control of the proposed model.

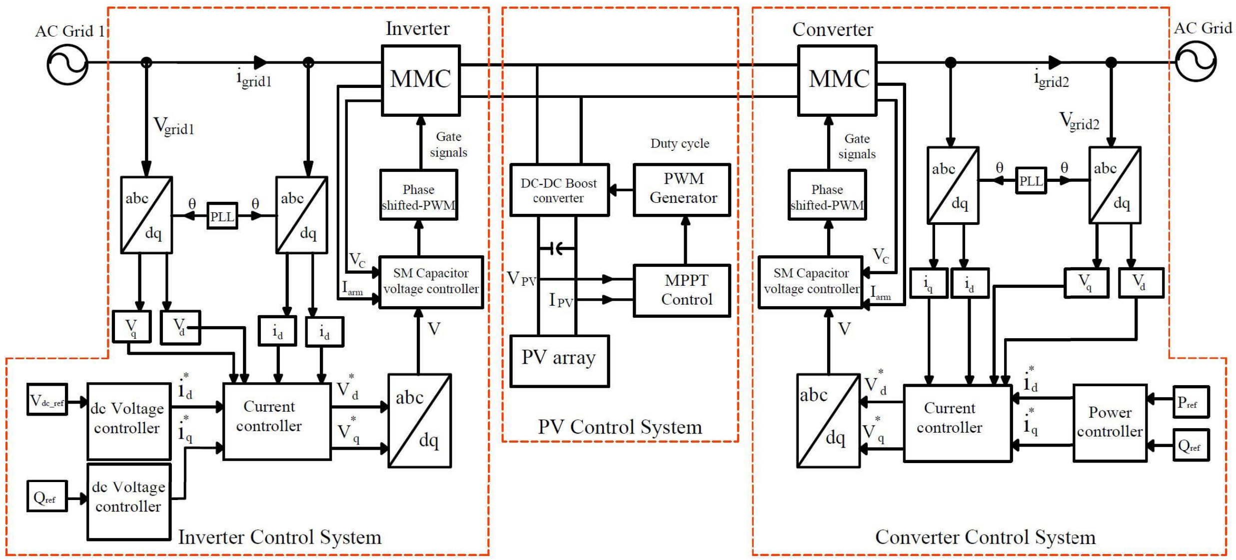

Fig. 3. Control block diagram of the proposed MMC-MTDC.

A. *Rectifier Control model*

The control system of rectifier is intended to adjust the DC voltage and reactive power. Hence, the outer control system computes the values of currents (i_d^* , i_q^*) based on the reference values of DC voltage and reactive power.

$$\begin{cases} i_d^* = k_{P1}(U_{dc}^* - U_{dc}) + k_{I1}\int (U_{dc}^* - U_{dc})dt \\ i_q^* = 2Q^* / (3u_d) + k_{P2}(Q^* - Q) + k_{I1}\int (Q^* - Q)dt. \end{cases} \quad (6)$$

Considering the reference values of the currents, the inner current control system calculates the voltage references as following:

$$\begin{cases} v_d = u_d + \omega L i_q - [k_{P3}(i_d^* - i_d) + k_{I3}\int (i_d^* - i_d)dt] \\ v_q = u_q - \omega L i_d - [k_{P4}(i_q^* - i_q) + k_{I4}\int (i_q^* - i_q)dt]. \end{cases} \quad (7)$$

B. *Inverter Control model*

The control system of the inverter keeps the stability of AC voltage when the MMC is connected to the AC network. Hence, the outer loop regulates u_d^* and u_q^*. The reference values of i_d^* and i_q^* in inner loop are found using the equations bellow:

$$\begin{cases} i_d^* = -k_{P5}(u_q^* - u_q) + k_{I5}\int (u_q^* - u_q)dt \\ i_q^* = -k_{P6}(u_d^* - u_d) + k_{I6}\int (u_d^* - u_d)dt. \end{cases} \quad (8)$$

Assuming that $u_d^* = 1$ and $u_q^* = 0$, tuned values of v_d and v_q can be obtained from the following equations:

$$\begin{aligned} v_d &= -R.PI(i_d) - \omega L.PI(i_q) \\ v_q &= -R.PI(i_q) + \omega L.PI(i_d). \end{aligned} \quad (9)$$

C. *Capacitor Voltage Balancing methodology*

The conventional voltage balancing algorithm is used in this study. The algorithm first measures capacitor voltages for each arm and defines the direction of arm current. Then, the following steps are taken for sorting the SMs:

Step 1: When the arm current discharges the arm capacitors, algorithm switches on the SMs with the highest capacitor voltages and switches of those with lowest voltage levels.

Step 2: When the arm current charges the arm capacitors, algorithm switches on the SMs with the lowest capacitor voltages and switches of those with highest voltage levels.

D. *PV converter control*

Perturb and observe (P&O) approach is employed in this study for achieving MPPT of the PV source using boost converter. The P&O approach provides better harvest of solar energy with minimum steady state oscillations. Hence, the duty cycle required for the boost converter is determined using a variable step-size to obtain MPPT precisely.

IV. Simulation Results

To verify the function of the proposed hybrid transmission system, full scale computer simulations are fulfilled in MATLAB/SIMULINK. The following table shows the parameters of the system under study.

TABLE I. CIRCUIT PARAMETERS

Parameter	***Value***
AC System	200/20 kV, 60 Hz
DC Line Voltage	40 kV
Number of SMs per arm	50
Load	100 MW, 50 MVAr
Load1	100 MW, 40 MVAr
SM Capacitance	500 µF
Switching frequency	10 kHz
Arm Inductance & Resistance	Ls= 0.15 pu, Rs=0.03 ohm
PV maximum Power	60 MW

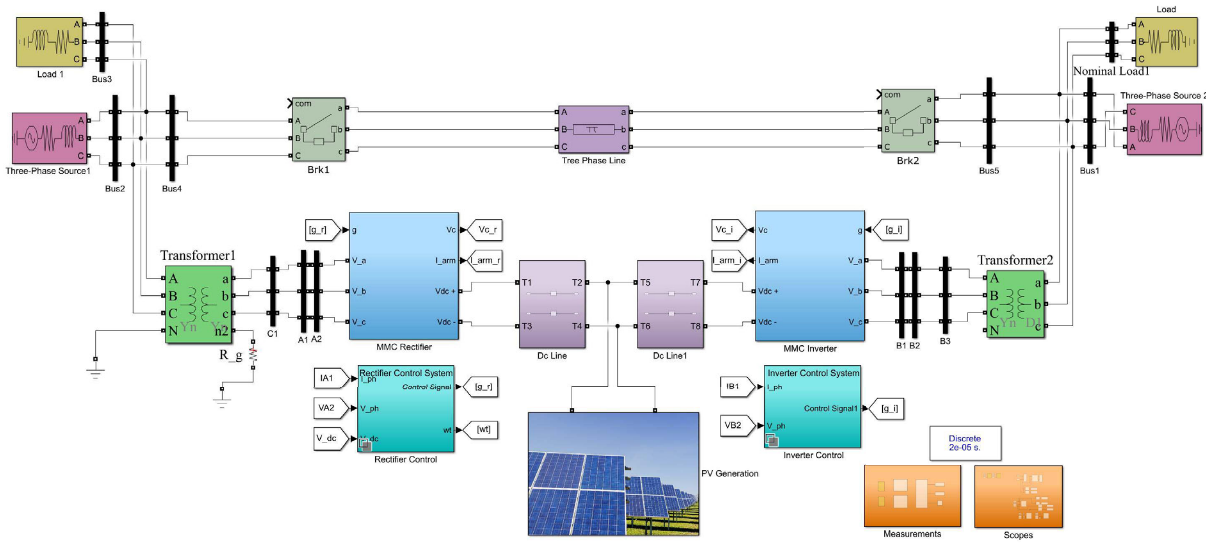

Fig. 4. The proposed configuration implemented in MATLAB/SIMULINK.

The proposed hybrid AC transmission system with back-to-back converter configuration and MTDC presented in figure 1. is simulated in Matlab Simulink. Figure 4. depicts the simulated network, and figure 5. shows the configuration of PV system with the P&O-based MPPT controller.

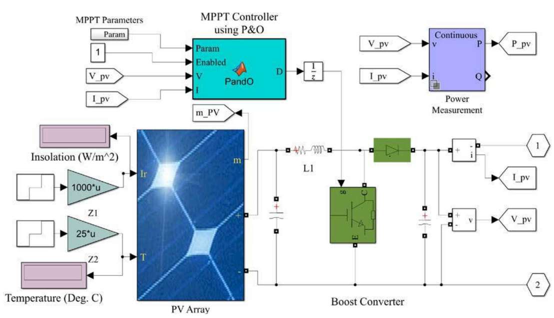

Fig. 5. Configuration of PV system performed in MATLAB/SIMULINK.

The following figures show the efficacy of the proposed configuration while maximizing the use of PV energy system. Figure 6. illustrates the generated power, current and line voltage of PV for two-second simulation, considering constant temperature value (25 Deg. C) and different levels of solar irradiance as following: %100, %50, %75 and %100, respectively (0.5 second duration for each level of irradiance). As can be seen, the MPPT controller is successful in harvesting the maximum available power during the simulation period by using P&O technique. Considering the PV output current figure, it can be observed that current fluctuations show up in the DC line due to sharp decrease or increase in irradiance. However, the PV voltage has less fluctuations because of the strong connection with the MMC rectifier output which ensures the stability of DC line voltage (40 kV). Hence, PV and rectifier controllers can support each other during any unnormal situations.

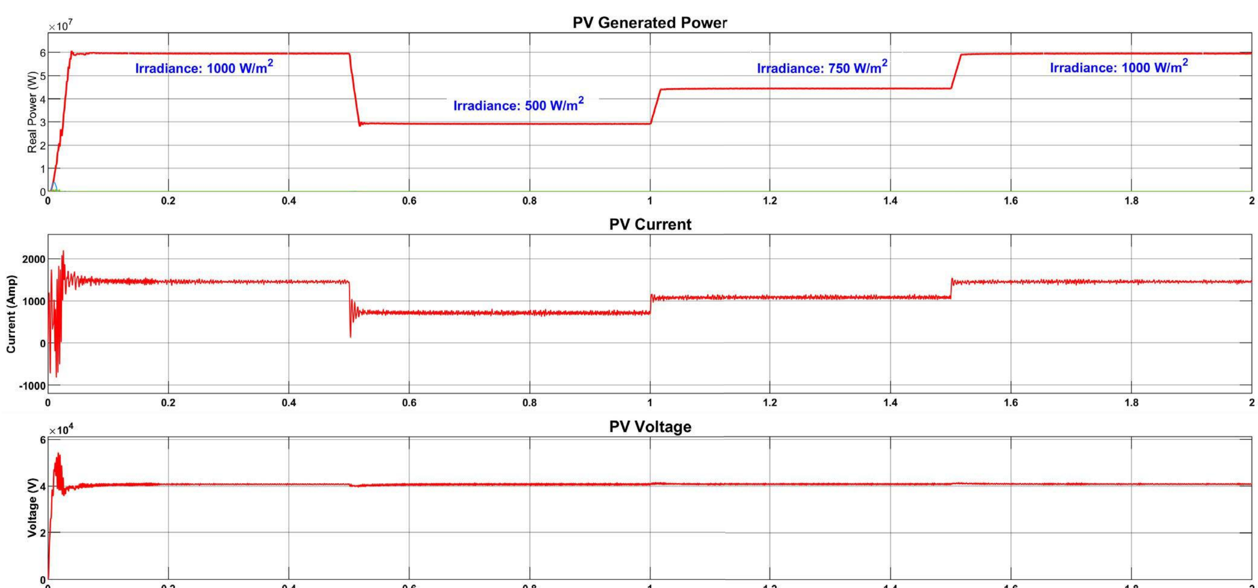

Fig. 6. PV generated power, current and line voltage.

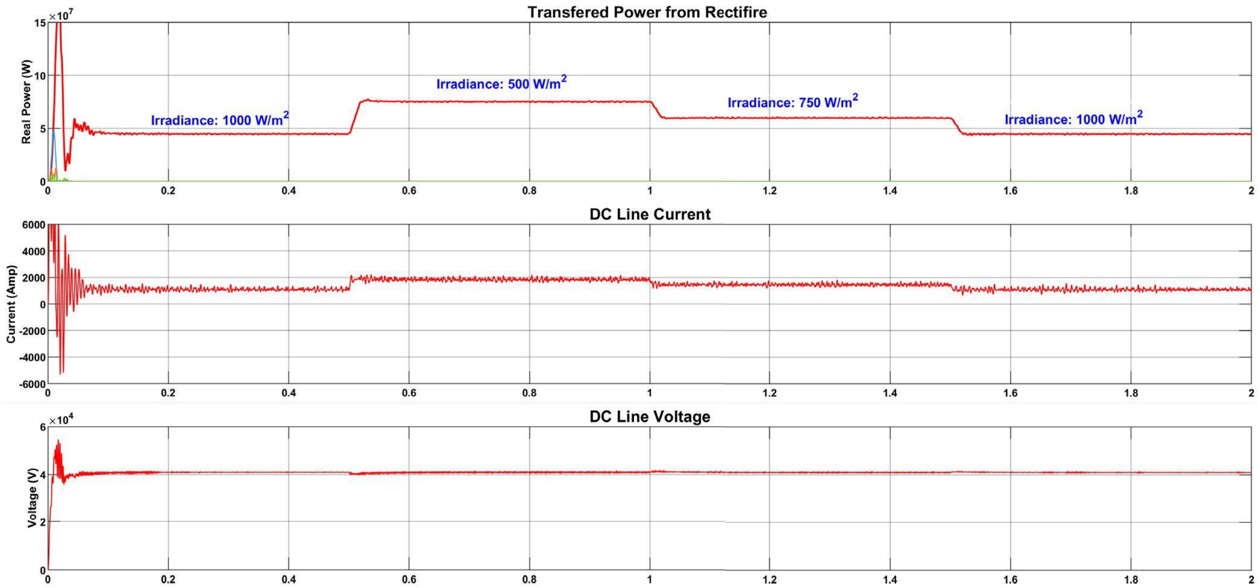

Fig. 7. DC line power, current and voltage.

Figure 7. shows the power, current and voltage of the DC line. The rectifier control system responds quickly to any variations in the PV generation (caused by different irradiance values) and provides the required power for the system loads. An advanced central control system along with filters can alleviate the fluctuations in line current. Voltages and currents of the AC sides are presented in figure 8. As can be observed, the converter input current varies largely due to the variations in PV generated power. In spite of such considerable changes, the inverter control system performs well and provides voltage and current waveforms with suitable power quality for the loads connected to the AC grid 2 (shown in figure 1.).

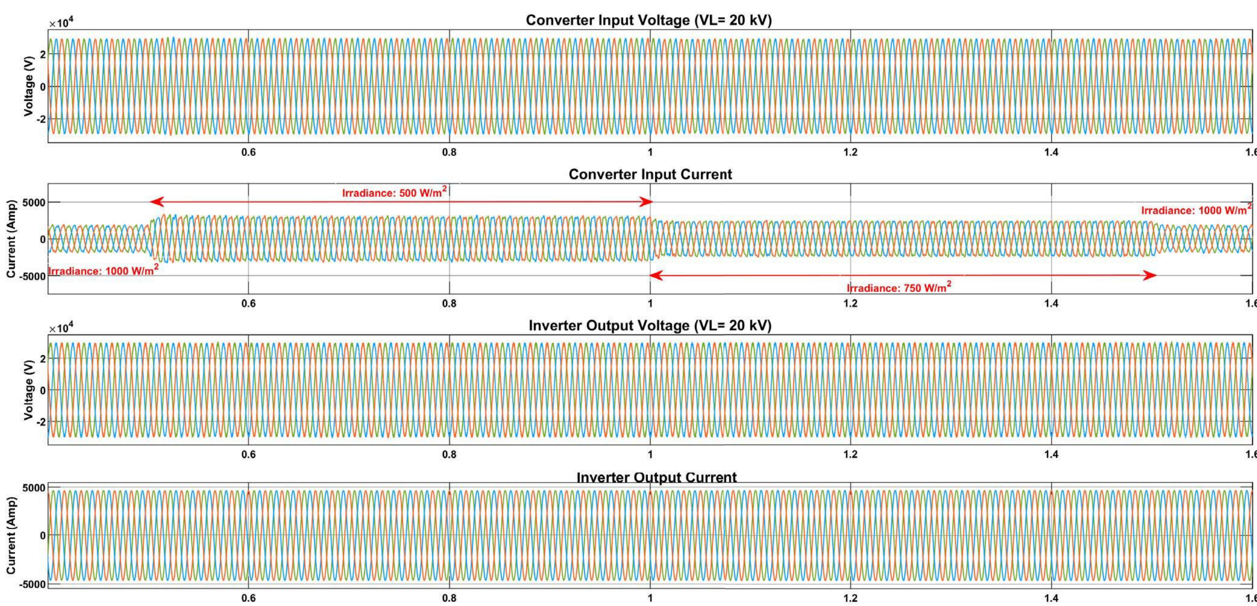

Fig. 8. Voltages and currents of the back-to-back converter ac sides.

CONCLUSION

This paper introduced a novel hybrid AC transmission System with B2B converter configuration and MTDC operation which allows the PV source to inject real power directly to the grid. The Outer control system for active and reactive power, inner current control, and capacitor voltage balancing control were used for the rectifier and converter of MMC. Besides, perturb and observe technique was applied for obtaining MPPT of the PV system connected to the MTDC through an DC-DC boost converter. The simulation results verify the efficacy of the proposed configuration in strengthening the stability of system while harvesting the maximum power from the PV source.

ACKNOWLEDGEMENT

Special thanks go to the National Science Foundation for the NSF-FRP grant no. 1747757. This project was carried out as part of the NSF Center on GRid-connected Advanced Power Electronic Systems (GRAPES).

REFERENCES

[1] Interconnections Seam Study, National Renewable Energy Laboratory, https://www.nrel.gov/analysis/seams.html

[2] J. Cao, W. Du and H. F. Wang, "An Improved Corrective Security Constrained OPF for Meshed AC/DC Grids With Multi-Terminal VSC-HVDC," IEEE Transactions on Power Systems, vol. 31, no. 1, pp. 485-495, Jan. 2016.

[3] R. Ohta, H. Matayoshi, T. Senjyu and A. M. Howlader, "LLC resonant type boost converter for HVDC interconnection of PV generation facility," 2017 IEEE 12th International Conference on Power Electronics and Drive Systems (PEDS), Honolulu, HI, 2017, pp. 156-161.

[4] C. Ju, W. Feng, H. Wang, and H. Xu, “Research on the High Voltage DC Grid-Connected Converter Based on Photovoltaic,” Applied Mechanics and Materials, Vols. 303-306, pp. 1897-1901, Feb. 2013.

[5] D Jovcic and B.T Ooi, "Theoretical aspects of fault isolation on DC transmission lines using resonant DC/DC converters" IET Generation Transmission and Distribution, Vol. 5, Issue 2, 2011, pp 153-160.

[6] T. Yoshino, "History and trends of converter technology for DC and AC transmission in Japan," 2014 International Power Electronics Conference (IPEC-Hiroshima 2014 - ECCE ASIA), Hiroshima, 2014, pp. 3834-3841.

[7] H. Bilodeau, S. Babaei, B. Bisewski, J. Burroughs, C. Drover, J. Fenn, B. Fardanesh, B. Tozer, B. Shperling, and P. Zanchette,“ Making old new again: HVdc and FACTS in the northeastern United States and Canada,” IEEE Power Energy Mag., vol. 14, no. 2, pp. 42_56, Mar./Apr. 2016.

[8] S. R. Mohammed, J. Teh and M. Kamarol, "Upgrading of the Existing Bi-Pole to the New Four-Pole Back-to-Back HVDC Converter for Greater Reliability and Power Quality," in IEEE Access, vol. 7, pp. 145532-145545, 2019.

[9] C. A. Rojas, S. Kouro, M. A. Perez and J. Echeverria, "DC–DC MMC for HVdc Grid Interface of Utility-Scale Photovoltaic Conversion Systems," in IEEE Transactions on Industrial Electronics, vol. 65, no. 1, pp. 352-362, Jan. 2018.

[10] S. Rivera, S. Kouro, B. Wu, J. I. Leon, J. Rodríguez and L. G. Franquelo, "Cascaded H-bridge multilevel converter multistring topology for large scale photovoltaic systems," 2011 IEEE International Symposium on Industrial Electronics, Gdansk, 2011, pp. 1837-1844.

[11] Y. Yu, G. Konstantinou, B. Hredzak and V. G. Agelidis, "Power Balance of Cascaded H-Bridge Multilevel Converters for Large-Scale Photovoltaic Integration," in IEEE Transactions on Power Electronics, vol. 31, no. 1, pp. 292-303, Jan. 2016.

[12] T. Kerekes, R. Teodorescu, M. Liserre, C. Klumpner and M. Sumner, "Evaluation of Three-Phase Transformerless Photovoltaic Inverter Topologies," in IEEE Transactions on Power Electronics, vol. 24, no. 9, pp. 2202-2211, Sept. 2009.

[13] L. Zhang, K. Sun and Y. Fang, "An optimized common mode voltage reduction PWM strategy for T-type three phase three level photovoltaic grid-tied inverter," 2013 IEEE Energy Conversion Congress and Exposition, Denver, CO, 2013, pp. 1623-1627.

[14] T. Soong and P. W. Lehn, "Internal Power Flow of a Modular Multilevel Converter With Distributed Energy Resources," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 2, no. 4, pp. 1127-1138, Dec. 2014.

[15] Y. Chen, S. Pan, M. Huang, Z. Zhu, Y. Liu and X. Zha, "MMC-MTDC transmission system with partially hybrid branches," in CES Transactions on Electrical Machines and Systems, vol. 5, no. 2, pp. 124-132, June 2021, doi: 10.30941/CESTEMS.2021.00016.

[16] W. Chen, W. Anna, Z. Tao and Z. Hualiang, "Adaptive Integrated Coordinated Control Strategy Based on Sliding Mode Control for MMC-MTDC," 2021 IEEE 4th International Conference on Electronics Technology (ICET), 2021, pp. 892-897, doi: 10.1109/ICET51757.2021.9451064.

[17] R. Li and L. Xu, "A Unidirectional Hybrid HVDC Transmission System Based on Diode Rectifier and Full-bridge MMC," in IEEE Journal of Emerging and Selected Topics in Power Electronics, doi: 10.1109/JESTPE.2020.3015342.