Grid Value Investigation of Medium-Voltage Back-to-Back Converters

Preprint

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Grid Value Investigation of Medium-Voltage Back-to-Back Converters

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***Abstract*—This paper investigates the value that a medium-voltage back-to-back (MVB2B) converter can bring to the electric grid through two potential applications: voltage regulation powered by the reactive power adjustment function and distributed energy resource (DER) adoption enhancement powered by the quantitative power transfer function. Two groups of distribution systems have been prepared for the value investigation: the IEEE 123-bus system for the voltage regulation study and two utility-provided, realistic distribution systems for the DER adoption enhancement study. The results demonstrate that the MVB2B converter can bring significant value to the grid through these two applications. In particular, with the MVB2B converter transferring power between two feeders, a substantial amount of back-feeding solar power can be avoided, and the size of the energy storage used for extra solar power can be significantly reduced.**

Keywords—distribution system, grid application, medium-voltage back-to-back converter, value analysis.

I. Introduction

The successful integration of hundreds of gigawatts of distributed energy resources (DERs) and renewable energy systems into the electric power system requires transformative power conversion system designs that optimize various trade-offs in conflicting objectives, such as performance, reliability, functionality, and cost. The adoption of medium-voltage (between 1-kV and 35-kV AC) silicon carbide-based (SiC-based) power electronics in the electric grid would provide an important tool for ongoing efforts in grid modernization. Medium-voltage and high-voltage (greater than 35-kV ac) power converters are extensively used in grid-connected applications and motor drives. Grid-connected power converters are used in the medium-voltage distribution grid for applications such as solid-state circuit breakers, fault-current limiters, and power conditioning systems [1]–[4]. Further, the increasing penetration level of renewable generation in the electric grid has resulted in increased medium-voltage power converters as interfaces to these energy resources [5]–[7]. It is estimated that approximately 99% of the power generated by current solar photovoltaic (PV) power plants in the world is feeding into medium-voltage grids [8]–[11].

In the future electric grid, medium-voltage, SiC-based power converters would be a promising solution for several problems brought on by high penetrations of renewable generation, such as voltage violations and reverse power flow. Presently, the-state of the art focuses mostly on the control and topology design of medium-voltage converters for better functioning with lower costs [1]–[7]; however, the value and benefit that medium-voltage converters can bring to the grid have not been thoroughly analyzed. Three critical questions important to enable the widespread adoption of medium-voltage converters remain unresolved: 1) What grid applications powered by medium-voltage converters can benefit the grid? 2)What is the quantified benefit for each grid application? 3) Which grid applications are most beneficial?

Grid value analysis for medium-voltage converters is needed to answer questions. This paper discusses the initial work we have done for medium-voltage, back-to-back (MVB2B) converter grid value analysis. We investigate the grid benefits brought by MVB2B converters through two applications: voltage regulation and DER adoption enhancement. Two sets of distribution systems have been prepared for the grid value analysis: the IEEE 123-bus test system representing a single distribution system for the voltage regulation study and two utility-provided, realistic distribution systems representing a multi-feeder system for the DER adoption enhancement study. The initial investigation demonstrated that MVB2B converters can bring great benefit to the grid, especially for DER adoption enhancement.

The rest of this paper is organized as follows: Section II discusses the grid application design. Section III discusses the case studies for the designed applications. Section IV concludes the paper and discusses future work.

II. Grid Application Design

This section first introduces the MVB2B converter. Then it discusses the designed grid application and the prepared system for the application simulations.

A. MVB2B Converter

In this paper, the grid applications are enabled by a directly connected MVB2B converter. The medium-voltage, SiC-based, back-to-back AC converter analyzed in this paper operates as an asynchronous, 15-kV AC grid interconnection device (typically at 13.8 kV). Fig. 1. shows the schematic of a MVB2B converter connected to a 13.8-kV distribution system [12]. The front-end and back-end power converters are modular, multilevel power converters developed using medium-voltage SiC power semiconductor devices. The back-to-back conversions in the present electric grid entail the cascaded connection of 60-Hz transformers down to 480–600

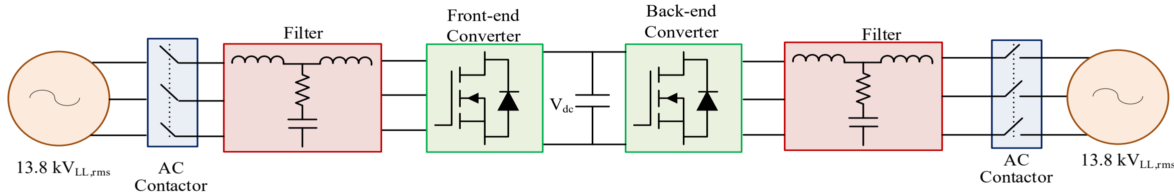

Fig. 1. Schematic of the MVB2B converter connected to electric grid.

V_{ac} and power electronic converters. The full system is heavy and expensive. A directly connected MVB2B converter will result in an approximate 80% volume reduction and 90% weight reduction compared to a conventional system used in the present electric grid. The MVB2B converter is designed to be fully capable of meeting the latest requirements for systems interconnecting to the distribution grid as defined in IEEE 1547-2018 as well as the microgrid control standards in IEEE 2030.7. These enable using MVB2B converters as an interconnection between distribution system feeders, to enable the microgrid-to-feeder connection switch, and as an interface for DERs connecting to the grid.

B. *Grid Application Design*

In this work, we design and analyze two major grid applications according to the functions of the MVB2B converter: 1) voltage support using the reactive power absorption/generation function and 2) DER adoption enhancement using the power transferring function.

In the voltage support application, we investigate the voltage regulation performance of the MVB2B converter and compare the performance with that of the voltage regulators and capacitors. As shown in (1), we leverage the voltage load sensitivity matrix (VLSM) developed in our previous work [13]–[14] to calculate the reactive power, $Q_{b2b}(t)$, that the converter needs to generate or absorb to regulate the voltage at time t. Here, $V_i(t)$ represents the measured voltage at time t, V_{obj} represents the voltage objective we aim to regulate to, $VLSM_q(i)$ represents the sensitivity factor for the reactive power at bus i, which quantifies how much the voltage will change if the reactive power at bus i change by one unit.

$$Q_{b2b}(t) = \left(V_i(t) - V_{obj}\right)/VLSM_q(i) \tag{1}$$

For the DER adoption enhancement, we transfer power between two feeders to consume more PV power with the system load instead of curtailing the extra PV power, storing the power in energy storage, or back-feeding it to the grid. In this way, we can 1) reduce the curtailed PV energy and improve the utilization rate of PV power, 2) reduce the size of the energy storage needed for extra PV energy, and 3) improve the PV hosting capacity of the system.

C. *System Preparation*

To simulate and analyze these grid applications, we prepare two systems for the study. As shown in Fig. 2, we use the IEEE 123-bus system for the voltage regulation application analysis [15]. This system has four regulators and four capacitors in the original system. The converter will be placed in the middle of the feeder and power all the downstream loads. For the DER adoption application, we prepare a two-feeder, utility-provided, realistic distribution system, as shown in Fig. 3. We connect them with the MVB2B converter and transfer power between the two feeders through the MVB2B converter to achieve the three objectives.

The load profiles for the distribution systems are modeled by the method in our previous work [16]–[17]. Instead of populating all the load nodes with profiles scaled from the substation load profile, each load node is equipped with a unique load pattern that guarantees load diversity along the distribution systems.

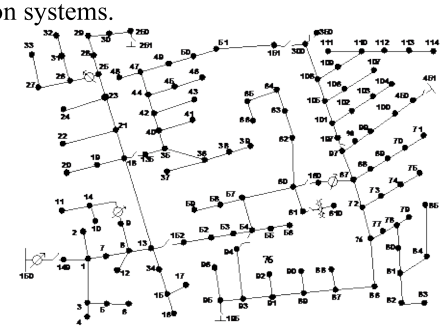

Fig. 2. Topology of the IEEE 123-bus test system.

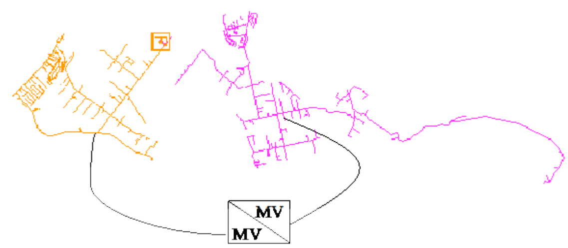

Fig. 3. Topology of the two-feeder test system.

III. Case Study

In this section, we present the case studies conducted on the prepared distribution systems to investigate the designed grid applications discussed in Section II.B. As mentioned Section II.C, the voltage regulation study is conducted on the IEEE 123-bus system, and the DER adoption enhancement study is conducted on the realistic two-feeder system.

A. *Case Study on Voltage Regulation*

Referring to Fig. 2, we place a MVB2B converter with a capacity of 2200 kVA and the primary side connected at Bus 60. This capacity is estimated by the summation of the node peak loads located in the downstream feeders after Bus 60.

To investigate the voltage regulation performance of the MVB2B converter and compare that with the voltage regulators and capacitors in the system, we conduct two case studies: a high solar penetration case where high voltages brought by the solar power need to be alleviated and a heavy loading case where the voltage sag caused by the large load needs to be saved.

As shown in Fig. 4, we conduct four simulation runs in the high solar penetration case: 1) the base case where no regulators, caps, converter, or PV are in the system; 2) a solar case where the system has a high solar penetration; 3) a solar case with regulators working to regulate the voltage profiles; and 4) a solar case where the MVB2B converter is used to alleviate the high voltage.

Similarly, as shown in Fig. 5, we present four voltage profiles for the heavy loading case as well: 1) the base case with normal loads, 2) a heavy loading case where a large load is placed at Bus 67, 3) a heavy loading case with regulators and caps, and 4) a heavy loading case with the MVB2B converter.

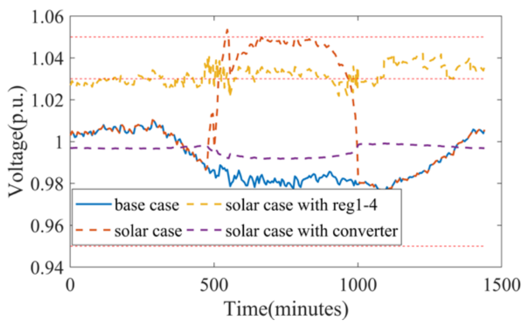

Fig. 4. Voltage regulation case for a high solar generation day.

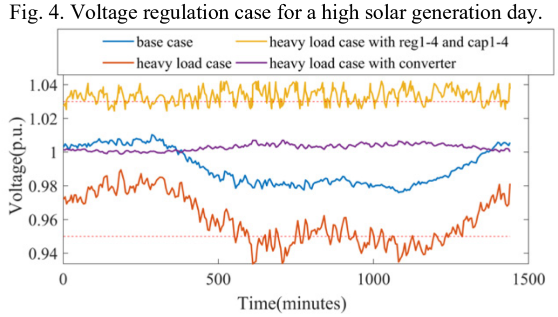

Fig. 5. Voltage regulation case for a heavy loading day.

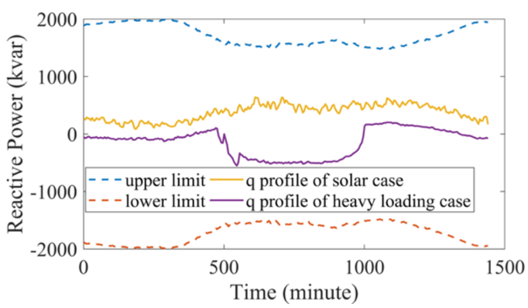

Fig. 6. Reactive power profile of the MVB2B converter.

All the simulations are conducted with 1-minute resolution for 1 day. The voltage objective (V_{obj} in (1)) is set as 1 p.u. All the voltage profiles shown in Fig. 4 and Fig. 5 are measured at Bus 67, Phase A, which is located downstream of Bus 60, where the MVB2B converter is placed.

As shown in the two figures, the MVB2B converter successfully regulates the voltage profile close to 1 p.u. in both the high solar penetration case and the heavy loading case. Fig. 6 shows the reactive power profiles of the two cases, where only a small portion of the reactive power capacity is used.

To guarantee that the voltages along the nodes located near the feeder end are not violating the lower boundary (0.95 p.u.), the voltage objective of the regulator at Bus 67 is set to a higher level. Fig. 4 and Fig. 5 show that the voltages are regulated close to 1.03 p.u. with regulators and caps. The high solar penetration case even has voltages close to or greater than 1.04 p.u at the end of the day.

This setting, however, might induce more frequent high voltages in the system when there is a high solar penetration. With voltages already boosted by the regulators, the downstream buses after the regulator bus might have more high-voltage violations because of solar generation. If we change the regulator setting to a lower voltage objective, then lower voltage violations might happen in the system when we heavy load situations occur. Changing the regulator setting in a real-time manner might be an option to resolve this problem, but it is not convenient and realistic to frequently change the regulator settings throughout a day. Therefore, the MVB2B converter might be a better option to regulate voltage for systems with high penetrations of solar or other DERs.

B. Case Study on DER Adoption Ehancement

As described in Section II.C, to investigate the benefit that the MVB2B converter can bring to enhance DER adoption, we prepared a two-feeder system. The loads in the first system are all modeled as residential, whereas the loads in the second system are all commercial. As shown in Fig. 7 (a), when the loads in the system are aggregated together, there is no obvious peak in the commercial load profile, whereas the residential load has two peaks: one in the morning and one in the evening. As shown in Fig. 3 in Section II, the two systems are connected with the MVB2B converter through the buses in the middle of the two feeders.

Three cases studies featuring different weather conditions are conducted for the investigation of DER adoption enhancement: 1) Case 1, where both feeders are experiencing a sunny day, with Feeder 1 having a larger PV capacity; 2) Case 2, where the location of Feeder 1 is sunny, but the location of Feeder 2 is cloudy; and 3) Case 3, where both feeders are experiencing a cloudy day, with clouds coming at different times of the day.

Similar to the case study on voltage regulation, all the simulations in this case study are conducted with 1-minute resolution for 1 day. We assume that all the extra PV power that is not consumed by local loads or transferred by the MVB2B converter needs to be stored. The power rating of the energy storage is decided by the maximum charge/discharge power. The energy capacity is calculated by multiplying 120% with the maximum energy needed to be stored at one time step during the 1-day simulation. We choose to oversize the energy capacity by 120% to reserve spare capacity.

As shown in Fig. 7 (b), part of the extra PV power that is not consumed by the load on Feeder 1 has been transferred to Feeder 2. In this way, the energy capacity of the energy storage can be substantially reduced, as shown in Fig. 7 (c). The MVB2B converter can help save approximately 40% extra solar energy that would be curtailed, back-fed to the grid, or stored if not transferred by the converter. Because the two feeders are all experiencing a sunny situation, there are fewer interactions between the solar generation profile and load profile, and the power rating savings is not significant in this case.

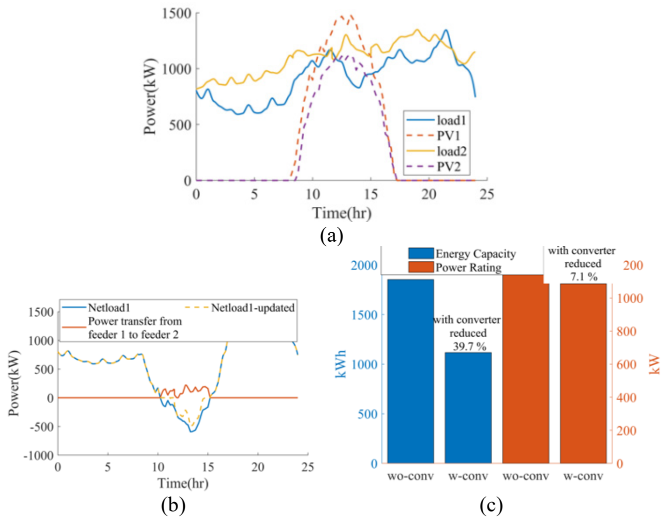

Fig. 7. Analysis results for Case 1—sunny days

Table.1. Extra energy saving analysis—Case 1

Case 2	Feeder 1	
	Without MVB2B converter	With MVB2B converter
Extra solar energy (kWh)	1482	893.75
Extra solar energy saved ratio		39.69%

Fig. 8 shows the analysis results for Case 2 where Feeder 2 is experiencing a cloudy day and Feeder 1 is experiencing a sunny day (shown in Fig. 8 (a)). Fig. 8 (b) shows the power transferred from Feeder 1 to Feeder 2 and the updated net load after the power transfer by the converter. As shown, a large portion of the extra solar energy has been transferred by the converter. As shown in Fig. 8 (c), the energy capacity reduction is significant, near 84%. Compared with Case 1, the power rating reduction is significant in this case, near 50%. As shown in Table 2, 84% of the extra solar energy can be saved by the converter, without help from the energy storage.

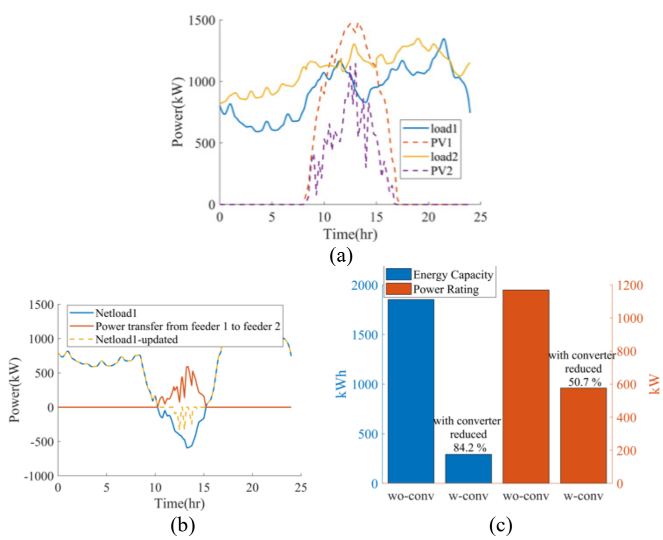

Fig. 8. Analysis results for Case 2—sunny day vs. cloudy day

Table.2. Extra energy saving analysis—Case 2

Case 2	Feeder 1	
	Without MVB2B converter	With MVB2B converter
Extra solar energy (kWh)	1482	243.3
Extra solar energy saved ratio		84.19%

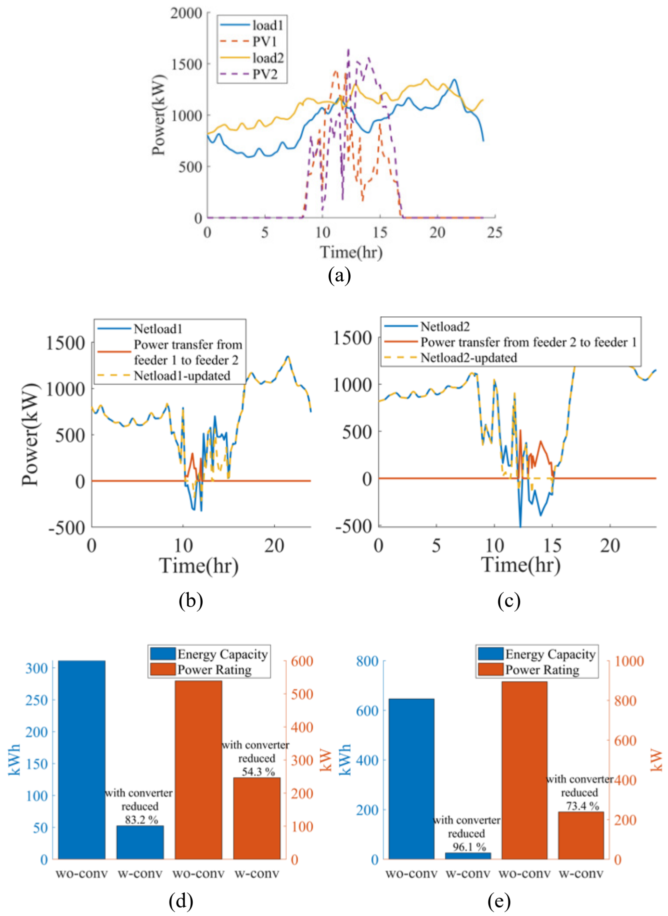

Fig. 9. Analysis results for Case 3—two different cloudy days

In Case 3, we investigate a situation where the feeders are all experiencing a cloudy day, but the clouds come to Feeder 2 first, then to Feeder 1, as shown in Fig. 9 (a). As shown in Fig. 9 (b) and (c), Feeder 1 transfers power to Feeder 2 in the morning and receives power from Feeder 2 in the afternoon. As shown in Fig. 9 (d) and (e), both feeders experience a significant reduction in energy storage size in both energy capacity and power rating. Table 3 shows that a large portion of the extra solar energy can be transferred by the MVB2B converter, which can avoid curtailment or back-feeding the solar energy.

Fig. 10 (a) and (b) show sample voltage profiles for the two feeders for Case 3. The voltages are slightly reduced when the feeders transfer power out. To further investigate the voltage changes brought by the MVB2B converter, we significantly increase the solar penetration and create a high solar penetration case on top of Case 3. As shown in Fig. 10 (c) and (d), transferring extra solar power through the MVB2B converter between the two feeders can reduce the high voltage at the sending end, which can help improve the solar hosting capacity, which was constrained by the overvoltage issues brought by the solar back-feeding power.

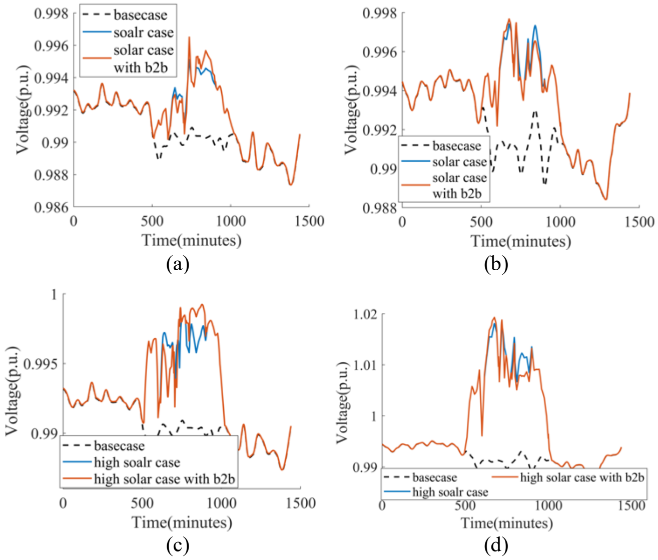

Fig. 10. Feeder simulation results for Case 3—two different cloudy days

Table.3. Extra energy saving analysis—Case 3

Case 3	Feeder 1		Feeder 2	
	Without MVB2B converter	With MVB2B converter	Without MVB2B converter	With MVB2B converter
Extra energy (kWh)	259.52	52.45	615.60	35.31
Extra energy saved ratio		79.79%		94.26%

IV. Conclusions and Future Work

In this work, we investigated two grid applications and the associated benefits the MVB2B converters can bring to the electric grid. Two sets of distribution systems were prepared for the study: the IEEE 123-bus system and two utility-provided realistic feeders, with realistic residential and commercial load profiles modeled on the feeders. The investigation and analysis results discussed in Section III demonstrated that the MVB2B converter can bring great value to the DER adoption enhancement and the voltage regulation of the grid.

To better understand and quantify the value on the DER adoption enhancement application, following this initial investigation, we will build a load and solar generation profile data pool and further quantify the value that the converter can bring under different load type combinations and weather conditions. In this way, we can provide a statistically meaningful estimation of the value that the converter can bring to improve DER adoption in distribution systems.

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