Grid Value Analysis of Medium-Voltage Back-to-Back Converter on DER Hosting Enhancement

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Abstract—This paper presents an analysis of the value that can be realized by medium-voltage back-to-back (MVB2B) converters in terms of the increased utilization rate of distributed energy resources (DERs) and the improvement in operational conditions. A systematic, transferrable, and scalable methodology has been designed to analyze and quantify the increased DER value from three perspectives: 1) curtailment reduction of the DER generation, 2) size reduction of the energy storage needed to otherwise realize DER hosting levels, and 3) hosting capacity improvement of the DERs compared to the base distribution circuit capability. In the case study, the proposed methodology is applied to two utility distribution systems for analysis and quantification of the grid value of the MVB2B converter, installed in the distribution circuit, and provided to the solar photovoltaic (PV) DERs. The analysis results demonstrate that the MVB2B converter can deliver significant value to the PV hosting enhancement of two adjacent distribution systems when they are connected by the MVB2B converter. Based on this case study, this paper analyzes and summarizes the approximate realized grid value of the MVB2B converter for distribution systems dominated by different shares of customer classes.

Index Terms—DER, distribution system, grid value, medium-voltage back-to-back (MVB2B) converter, PV.

NOMENCLATURE

- $C_{\text{DER}}$: DER hosting capacity without MVB2B converter (kW)
- $C_{\text{DER}}'$: DER hosting capacity with MVB2B converter (kW)
- $E_{c}$: Curtailed DER energy without MVB2B converter (kWh)
- $E_{c}'$: Curtailed DER energy with MVB2B converter (kWh)
- $E_{ES}$: Energy storage capacity needed without MVB2B converter (kWh)
- $E_{ES}'$: Energy storage capacity needed with MVB2B converter (kWh)
- $E_{t_{ES}}$: Energy level of the energy storage at time $t$ (kWh)
- $i$: Node number
- $j$: Node number
- $m$: Number of seasons
- $n$: Number of nodes in the system
- $n_{s}$: Number of profiles
- $P_{12}^{\text{limit}}$: Power transferred from feeder 2 to feeder 1 (kW)
- $P_{21}^{\text{limit}}$: Power transferred from feeder 1 to feeder 2 (kW)
- $P_{\text{DER}}$: DER power generation (kW)
- $P_{\text{ES}}$: Energy storage power rating with MVB2B converter (kW)
- $P_{\text{ES}}'$: Energy storage power rating with MVB2B converter (kW)
- $P_{\text{ES}}(t)$: Energy storage power output/input at time $t$ (kW)
- $P_{\text{load}}$: Power of load (kW)
- $P_{\text{net}}$: Netload of feeder 1 before converter power transfer (kW)
- $P_{\text{net}}'$: Netload of feeder 1 after converter power transfer (kW)
- $P_{\text{net}}''$: Netload of feeder 2 before converter power transfer (kW)
- $P_{\text{net}}'''$: Netload of feeder 2 after converter power transfer (kW)
- $P_{\text{net}}^{{\text{limit}}_{\text{net}}}$: Power transferred from feeder 1 to feeder 2 (kW)
- $p_{ij}$: Reactive power sensitivity factor
- $q_{ij}$: Real power sensitivity factor
- $r_{C_{\text{DER}}}$: DER hosting capacity improvement rate
- $r_{C_{\text{net}}}$: DER energy curtailment reduction rate
- $r_{C_{\text{net}}}$: DER energy curtailment reduction rate for the Nth data set
- $r_{C_{\text{mean}}}$: Average DER energy curtailment reduction rate among the N data set
- $r_{C_{\text{min}}}$: Minimum DER energy curtailment reduction rate among the N data set
- $r_{C_{\text{max}}}$: Maximum DER energy curtailment reduction rate among the N data set
- $r_{C_{\text{ES}}}$: Energy storage energy capacity reduction rate among the N data set
- $E_{\text{Cmax}}$: Maximum DER energy curtailment reduction rate among the N data set
- $E_{\text{Cmean}}$: Average DER energy curtailment reduction rate among the N data set
- $E_{\text{Cmin}}$: Minimum DER energy curtailment reduction rate among the N data set
- $E_{\text{CES}}$: Energy storage energy capacity reduction rate among the N data set

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**I. INTRODUCTION**

Distributed energy resources (DERs), such as photovoltaics (PV), have become a promising solution to transform renewable energy to satisfy the increasing electricity demand [1]. The energy need has transformed this period with the disruption of changing power systems focused on a few centralized resources toward arcades dominated by extensive assortments of variable DERs.

For a long time, the inherent intermittency of DERs transforming renewable energy has posed challenges to their adoption [2]. Solutions to address those challenges have been widely studied in the literature, such as demand response [3], [4], and [5] and large energy storage systems [6] and [7]. One promising solution has rarely been researched, however: power exchange among distribution feeders. If distribution feeders can have controlled power flow exchange, the value of the DERs in the feeders is expected to be effectively enlarged by using the load-DER interaction differences between the feeders. The connections among the feeders would require the insertion of power converters or line-frequency transformers [8], [9], and [10], whose main responsibility is to harmonize the different operating conditions between the feeders. But line-frequency transformers cannot control power flow, which will greatly limit the flexibility and value that the connections can bring to the feeders. On the other hand, power converters can help feeders maintain a radial structure, and they have functions controlling the power flow that can be used to develop effective solutions for problems brought by high penetrations of DERs; therefore, adding power converters is a more universal approach that is likely to draw more interest. Further, power converters have controls that can enable multiple functions, such as reactive power support, which is not possible using traditional connections [11], [12], [13], and [14]. Use of back-to-back power converters for interconnection of microgrids has been studied in [12], [13]. These studies have been focused on the control of the back-to-back power converters and their stability analysis [13], [14], and [15]. Recently some work has been done that demonstrates the design and development of such back-to-back converters for medium voltage grid-connected operation [14], [15], [16], and [17]. The feasibility of these power converters beyond academic space is just beginning [15], [18]. Today, the technology to build a medium-voltage back-to-back (MVB2B) converter is moving beyond the academic research level to becoming commercially viable; therefore, value analysis of the MVB2B converter is critical to aid market adoption [14], [18], [19].

Currently, most research in the literature focuses on the design and control of power converters to achieve a smaller size and better performance with reduced costs [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], and [20]; however, not enough work in the current state of the art analyzes questions about the benefits of implementing these converters on the electric grid and the value they can bring because of functions that traditional transformers do not have. Resolving these questions can help grid operators and converter vendors have a comprehensive understanding of how to properly design the functions of the MVB2B converter and effectively scheme the grid applications.

Our work in [21] investigated the value of some grid applications that can be enabled by MVB2B converters. In the initial investigation of several representative scenarios, the quantified power transfer function of the MVB2B converter demonstrated great potential benefit. To obtain a statistically meaningful quantification of the benefit and to provide effective value analysis conclusions and suggestions, this paper develops a systematic, transferrable, and scalable methodology to analyze and quantify the value that the MVB2B converter can bring to distribution system DER hosting enhancement. The developed methodology is applied to a case study that uses utility-provided, realistic load and PV profiles and system models for analysis. The analysis results provide not only a quantification of the value that the MVB2B converter can bring to various aspects but also insight into converter size selection and implementation.

The main contributions of this paper are threefold:

1) Beyond the initial investigation in our previous paper into different grid applications [21], this work is a deep dive into the power transfer application. The presented statistical meaningful distributions of the technical value (e.g., reduce DER curtailment) that the MVB2B converter can bring to connected distribution systems covers many diverse, comprehensive scenarios.

2) The technical value analysis results and the instructive information on the potential economic value the MVB2B converter can bring to the grid are beneficial for its market evaluation and implementation.

3) The developed systematic, transferrable, and scalable value analysis methodology can be applied to the evaluation of other grid applications of the MVB2B converter and to the value analysis of other advanced grid devices.

The remainder of this paper is organized as follows: Section II briefly introduces the MVB2B converter. Section III presents the methodology developed for the value analysis. Section IV discusses the data preparation method, and Section V presents the case study. Section VI concludes the paper and discusses future work.

**II. MVB2B CONVERTER INTRODUCTION**

This section briefly introduces the architecture of the MVB2B converter controls and the advanced grid support functions embedded in the controls.

The full controller block diagram for the MVB2B converter system is shown in Fig. 1. The MVB2B converter is controlled...
by implementing two forms of generic switching-level control and voltage/current control [22]. The applications of the controls are in the form of an averaged current control setup, with an outer voltage loop and an inner current loop. The voltage control is further split into three different controllers: active power, reactive power, and dc-link control. Because this control diagram is for demonstration purposes only and not for technical discussion in the paper, the variables in this control diagram are not explained in detail; these can be found in [22].

The decentralized hierarchical controller architecture encompasses two levels of control: the central control and the local control. The central controller contains the advanced grid support functions for integration into the grid, whereas the local controllers contain the lower-level current control and switching controls. The grid measurements are used to generate the voltage reference points for the system to implement the grid support controls. The grid support controls, along with the local controls (see, Fig. 1), allow asynchronous power flow between the two sides and provide additional services to the grid that are not possible through a line-frequency transformer or a line as used in classical electricity connections. These developed controls enable various functions that are used for the value analysis presented in this paper.

III. ANALYSIS METHODOLOGY

This section introduces the methodology developed for the grid value analysis of the MVB2B converter on DER hosting enhancement, including the analysis metrics, the metrics quantification approach, and the preparation of a statistically meaningful data set for simulation and demonstration.

A. Analysis Metrics

To effectively quantify the value to the grid that could be realized via the use of an MVB2B converter within a distribution system with high shares of DERs, three analysis metrics have been designed:

1) Curtailment reduction of the DER generation
2) Size reduction of the energy storage needed for excess DER generation
3) Voltage-constrained hosting capacity improvement of the DER.

As shown in (1), the curtailment reduction is measured by the reduction rate, \( r_{E_{\text{c}}} \), which is calculated based on the difference between \( E_c \) and \( E'_c \), which are the curtailed DER energy before and after placing the MVB2B converter as a connection between the two feeders. The energy storage size reduction is measured by two sub-metrics: energy capacity reduction rate, \( r_{E_{\text{ES}}} \), and power rating reduction rate, \( r_{P_{\text{ES}}} \), as calculated in (2) and (3), respectively. Here, \( E_{\text{ES}} \) and \( E'_{\text{ES}} \) represent the energy capacity needed for the energy storage before and after the converter implementation, and \( P_{\text{ES}} \) and \( P'_{\text{ES}} \) represent the energy storage power rating needed with and without the converter. The hosting capacity improvement rate, \( r_{C_{\text{DER}}} \), is calculated in (4), where \( C'_{\text{DER}} \) is the improved hosting capacity, and \( C_{\text{DER}} \) is the hosting capacity without the MVB2B converter connecting the two feeders.

\[
\begin{align*}
    r_{E_{\text{c}}} &= \frac{(E_c - E'_c)}{E_c} \quad (1) \\
    r_{E_{\text{ES}}} &= \frac{(E_{\text{ES}} - E'_{\text{ES}})}{E_{\text{ES}}} \quad (2) \\
    r_{P_{\text{ES}}} &= \frac{(P_{\text{ES}} - P'_{\text{ES}})}{P} \quad (3) \\
    r_{C_{\text{DER}}} &= \frac{(C'_{\text{DER}} - C_{\text{DER}})}{C_{\text{DER}}} \quad (4)
\end{align*}
\]

B. Metrics Quantification Approach

The new variables in equation (5)–(16) are explained as follows: \( t \) represents the time step, and \( P_{\text{net}}(t) \) represents the net load, which is the difference between the load, \( P_{\text{load}}(t) \), and the DER generation, \( P_{\text{DER}}(t) \). \( P_{\text{net}}^1(t) \) and \( P_{\text{net}}^2(t) \) represent the net load for feeder 1 and 2, respectively, where \( P_{\text{net}}^1(t) \) and \( P_{\text{net}}^2(t) \)
represent the updated net load after the power exchange through the MVB2B converter. $E_{ES}(t)$ represents the instant energy stored in the energy storage system, and $P_{ES}(t)$ represents the instant power flows into the energy storage system. $E_c$ represents the curtailed DER energy, where $P_{net}^{limit}$ represents the maximum back-feeding DER power allowed. $P_{B2B}^{12}(t)$ and $P_{B2B}^{21}(t)$ represent the power exchange between the two feeders through the MVB2B converter, where $P_{B2B}^{12}(t)$ represents feeder 1 to 2, and $P_{B2B}^{21}(t)$ represents feeder 2 to 1. $P_{net}^{limit}$ represents the maximum power exchange allowed by the converter.

As shown in (5)–(7), for a specific time period that covers $n$ time steps with a resolution of $\Delta T$, the energy storage connected with the DER is assumed to store excess generation if the load, $P_{load}(t)$, is smaller than the DER generation, $P_{DER}(t)$, and vice versa—when the DER generation is not able to power the load, the energy storage will be discharged to power the load. The energy capacity and the power rating of the energy storage are decided by the maximum instant energy stored in the energy storage and the maximum instant excess generation needed to be charged to the energy storage, as shown in (8)–(9). For cases where the cost-benefit balance allows some tolerance on the energy storage size, a coefficient, $\eta$, can be applied to reduce the size.

The DER generation curtailment is calculated in (10). The assumption is that there would be a back-feeding limit, $P_{net}^{limit}$, when there is high DER penetration in a distribution system to avoid potentially jeopardizing the grid stability; therefore, if there is neither energy storage nor an MVB2B converter in the system, when the net load, $P_{net}(t)$, exceeds the limit, the excess generation will be curtailed.

When the two distribution systems are connected by the MVB2B converter, the power transfer through the MVB2B converter between the two systems is calculated in (11)–(12). When System 1 has excess DER generation and the DER generation in System 2 is not enough to cover the load, the excess power from System 1 will be transferred to System 2, and vice versa. Note that when the excess DER generation from one system is much higher than the net load in the other system, only the power amount needed to cover the load or up to the converter capacity limit, $P_{B2BC}^{limit}$, will be transferred, and the remaining excess DER generation will be back-fed to the grid or stored in the local energy storage system if it exceeds the limit, $P_{net}^{limit}$.

$$P_{net}(t) = P_{load}(t) - P_{DER}(t)$$ (5)

$$E_{ES}^{t}(t) = E_{ES}^{t}(t-1) - P_{net}(t) \cdot \Delta T$$ (6)

$$P_{ES}^{t}(t) = P_{net}(t)$$ (7)

$$E_{ES} = \eta \cdot \max (E_{ES}^{t}(t))$$ (8)

$$P_{ES} = \eta \cdot \max (P_{ES}^{t}(t))$$ (9)

$$E_c = \sum_{t=1}^{n} P_{net}(t)$$

where $P_{net}(t) \not< 0$, $P_{net}(t) \not< P_{net}^{limit}$
can bring to the two connected systems because there are many different combinations between various weather conditions and load types, as shown in Fig. 3.

Therefore, a comprehensive database that can cover various weather and load type combinations is needed. In this paper, the Monte Carlo method is used to prepare a statistically meaningful database with limited data resources. This data preparation approach is introduced in Section IV.

As shown in (17)–(20), for a database that includes N data sets with different weather and load combinations, several statistical indicators will be calculated, as shown in (17)–(20), including the maximum, $r^1_{ECmax}$, average, $r^1_{ECmean}$, and minimum, $r^1_{ECmin}$, reduction rates it can bring to the systems. Those indicators will provide a range of the reduction rate the systems can obtain after implementing the MVB2B converter. The value at a certain percentile, $r^1_{ECX\%}$, can also be calculated to accommodate specific considerations. Equations (17)–(20) use the DER generation curtailment in System 1 as an example; the statistical indicator calculations apply to all other analysis metrics defined in (2)–(4).

$$
r^1_{ECmax} = \max\left(r^1_{EC1}, r^1_{EC2}, \ldots, r^1_{ECN}\right) \tag{17}
$$

$$
r^1_{ECmean} = \text{mean}\left(r^1_{EC1}, r^1_{EC2}, \ldots, r^1_{ECN}\right) \tag{18}
$$

$$
r^1_{ECmin} = \min\left(r^1_{EC1}, r^1_{EC2}, \ldots, r^1_{ECN}\right) \tag{19}
$$

$$
r^1_{ECX\%} = x \text{ percentile}\left(r^1_{EC1}, r^1_{EC2}, \ldots, r^1_{ECN}\right) \tag{20}
$$

Based on the mean value calculated in (18), the average marginal value, $\Delta r^1_{ECmean}$, through increasing the size of the MVB2B by $\Delta P$ will also be calculated, as shown in (21), to determine a minimum MVB2B size that can bring the maximum DER enhancement value and provide a range for the MVB2B size. This sets a foundation for the MVB2B capacity sizing for real-world system implementation. A comprehensive MVB2B capacity sizing that considers the price of the converter, the price of the energy storage, the existing DER penetration level, etc., will be discussed in our follow-up paper.

$$
\Delta r^1_{ECmean} = r^1_{ECmean}\left(P^{\text{limit}}_{B2BC} + \Delta P\right) - r^1_{ECmean}\left(P^{\text{limit}}_{B2BC}\right) \tag{21}
$$

The DER hosting capacity improvement can be quantified by leveraging the voltage load sensitivity matrix (VLSM) developed in our previous work [25]. The voltage change, $\Delta V_j$, that happens at bus $i$ caused by the real power load change, $\Delta P$, and the reactive power load change, $\Delta Q$, at bus $j$ can be quantified by the real power sensitivity factor, $p_{ij}$, and the reactive power sensitivity factor, $q_{ij}$. The real/reactive power sensitivity factors constitute the VLSM for the real power (VLSMP)/reactive power (VLSMQ), as shown in (22)–(24).

One common limit constraining the DER hosting capacity is the voltage limit. Large amounts of DER generation could cause a large voltage increase and cause the voltage to exceed the upper boundary.

Usually, the hosting capacity is capped by the worst scenario. Under that worst scenario, when there is an MVB2B converter connecting the two systems and connected to the bus, $\beta$, in System 1, the new voltage, $V^\beta_\alpha$, at a weak bus, $\alpha$, in this system can be calculated by (25) when the MVB2B converter can transfer power with an amount of $\Delta P_\beta$ to System 2, where $V_\alpha$ represents the original voltage at bus $\alpha$. Then the capacity improvement at this bus can be calculated by (26).

Equation (27) has been derived from (25) and (26) to simplify the calculation. The calculation in (27) can be applied to multiple representative weak buses in the system, and the suggested new hosting capacity can be defined as the original capacity plus the minimum/mean $\Delta C_{DER}$ among those buses. Here, $p_{\alpha\beta}$ is the sensitivity factor quantifying the voltage change at bus $\alpha$ if the load at bus $\beta$ changes by 1 unit, and $p_{\alpha\alpha}$ represents how much voltage will change at bus $\alpha$ if this bus has a power change itself.

$$
|\Delta V| = |\text{VLSMP}| |\Delta P| + |\text{VLSMQ}| |\Delta Q| \tag{22}
$$

i.e.:

$$
|\Delta V_1| = |p_{11} \ldots p_{1n}| |\Delta P_1| + |q_{11} \ldots q_{1n}| |\Delta Q_1| \tag{23}
$$

$$
|\Delta V_n| = |p_{n1} \ldots p_{nn}| |\Delta P_n| + |q_{n1} \ldots q_{nn}| |\Delta Q_n| \tag{24}
$$

derived from (2):

$$
\Delta V_i = \sum_{j=1}^{n} p_{ij} \Delta P_j + \sum_{j=1}^{n} q_{ij} \Delta Q_j \tag{25}
$$

$$
\Delta C_{DER} = - V_\alpha - V^\beta_\alpha \tag{26}
$$

$$
\Delta C_{DER} = p_{\alpha\beta} \Delta P_\beta \tag{27}
$$

A case study analysis on the metrics quantification methods is discussed in Section V.

IV. DATA PREPARATION

Ideally, a statistically meaningful grid value analysis and quantification of the MVB2B converter on the DER hosting enhancement needs years of load and DER generation profiles on the targeted two distribution systems, but data resources on distribution systems are usually limited. Moreover, the load types and compositions on a distribution system could change in the future as the population moves or new commercial technologies/industries develops.

Therefore, to create a comprehensive database that covers numerous combinations between the load and weather conditions for years, and that covers different distribution system load types and compositions to accommodate possible future changes, a Monte Carlo method is used to generate the inclusive database needed in the grid value analysis.

Based on the characteristics of the data that are accessible, first, the load profiles in the data pool need to be categorized into different types (e.g., residential, commercial, industrial). Then, different data sets that have different load type compositions can be generated from the categorized pool. As shown in Fig. 4, some data sets are dominated by commercial loads, whereas others are dominated by residential loads. For data sets fully comprising residential/commercial loads, the load patterns can also be different from each other.
Given the different load data sets generated, the DER generation profiles will be shuffled to create various load-DER profile combinations, as shown in Fig. 5. The DER generation profiles can be better categorized into groups of different seasons if the DER generation is largely influenced by the weather conditions and the targeted area has distinct seasons in a year. If there are no obvious seasons, the DER profiles can be freely shuffled around a year to create different load-DER combinations.

V. CASE STUDY

This section presents the case study performed on two utility-provided, realistic distribution systems and discusses the insights obtained from the results analysis. This case study focuses on the value that the MVB2B converter can bring to the solar PV hosting enhancement for the two distribution systems.

A. Scenario Design

The two realistic distribution system models used in this analysis are shown in Fig. 6. Both systems have more than 200 load nodes. As shown, the connection buses for the MVB2B converter on the two systems are designated in the middle area of the systems. When selecting the system connection buses for the MVB2B converter, several factors need to be considered, such as the power transfer impact on the connection bus, the impact on other buses caused by the power change at the connection bus, and the convenience of the connection in a real-world implementation. Because this paper focuses on the value analysis, the connection bus selection will be discussed in our follow-up paper. In this case, the two buses shown in Fig. 6 are selected because the voltage impact on the connection bus and the real-world connection convenience are weighted as the most important considerations, and the connection buses could change if other considerations are placed in a more important position.

A data pool has been built using the utility-provided 30-minute resolution data, including 3 years of load profile data of more than 600 commercial buildings and residential houses and 1 year of solar PV generation data. Fig. 7 shows samples of 1 week of load profiles and PV generation profiles. As shown, the profiles of the residential loads [Fig. 7(a)] and commercial loads [Fig. 7(b)] have obvious differences in patterns and characteristics. When combined with various PV generation profiles under different weather conditions [Fig. 7(e)], they will have various net load profiles that can create a comprehensive database for the MVB2B value analysis. Fig. 7(c)–(d) show the 1-day aggregated load profiles of 300 commercial and 300 residential loads, respectively. The aggregated commercial load has a lower peak/valley ratio during the daytime than the aggregated residential load.

By leveraging the Monte Carlo method, we built a database that includes 22 data sets, as shown in Table II (with detail in Table III) and Table IV.

The data sets shown in Table II are all developed under single-load scenarios, where the two systems are occupied by one load type. Take Set 1 as an example: The loads on System 1 are all set as residential loads, whereas the loads on System 2 are all commercial loads. Here, R represents residential, and C represents commercial.

The seven data sets are grouped into three clusters, where the two systems in one cluster have similar peak loads, and the systems in the other two clusters have different peak loads. Note that each data set has three subsets, as shown in Table III, and
TABLE II
SINGLE-LOAD SCENARIOS

| Set | System 1 | System 2 | Note |
|-----|----------|----------|------|
| 1   | 100% R   | 100% C   |      |
| 2   | 100% R   | 100% R   |      |
| 3   | 100% C   | 100% C   |      |
| 4   | 100% C   | 100% C   | One has a slightly higher peak load. |
| 5   | 100% R   | 100% R   |      |
| 6   | 100% C   | 100% C   | One has a much higher peak load. |
| 7   | 100% R   | 100% R   |      |

TABLE III
SCENARIO DETAIL IN EACH SET OF TABLE II

| Set 1 - System 1 - 100% R | 100% PV, 500 profiles | 80% PV, 500 profiles | 50% PV, 500 profiles |

TABLE IV
MIXED-LOAD SCENARIOS

| Set | System 1 | System 2 | Set | System 1 | System 2 |
|-----|----------|----------|-----|----------|----------|
| 8   | 20% C    | 20% C    | 15  | 40% C    | 80% C    |
| 9   | 40% C    | 60% C    | 16  | 60% C    | 50% C    |
| 10  | 60% C    | 80% C    | 17  | 80% C    | 50% C    |
| 11  | 80% C    | 50% C    | 18  | 50% C    |          |
| 12  | 50% C    | 40% C    | 19  |          | 50% C    |
| 13  | 40% C    | 80% C    | 20  |          | 80% C    |
| 14  | 60% C    | 50% C    | 21  |          | 50% C    |
| 15  | 50% C    |          | 22  |          |          |

each subset has a different PV penetration level. Inside each subset, there are 500 yearlong PV generation profiles, and each is paired with a yearlong load profile to create a net load profile. So, in each set shown in Table II, there are 1500 yearlong profiles. Here, the PV penetration is defined as $\frac{PV \text{ capacity}}{peak \text{ load}}$. All the profiles used in this paper are aggregated profiles at the distribution system substation, which are the summation of all the load node profiles selected from the data pool.

The 15 data sets in Table IV are developed under mixed-load scenarios. The load profiles of the systems comprise both residential and commercial loads. The percentage of the commercial load ($X%\text{C}$) is defined as $\frac{C \text{ load peak}}{(C \text{ load peak} + R \text{ load peak})}$. The PV penetration levels of these 15 data sets are all 100%, which means that there are 500 net load profiles in each data set instead of 1500, as in Table II.

B. Value Analysis

After performing the analysis methodology presented in Section III with these data sets, the value analysis results are presented via violin plots in Figs. 8–17.

Figs. 8–12 summarize the analysis results for the seven data sets described in Table III. The violin plots provide a vision of the data distribution and mark the mean and median of the data set. The left half of the violin plot is the data distribution
area plot, and the right half is duplicated from the left half to constitute a violin shape. For the x-axis labels, the one before the slash represents the scenario on System 1, and the one after the slash represents the scenario on System 2.

Each violin plot represents the results distribution of the 500 profile scenarios of a specific PV penetration level under each data set. From left to right, every three violin plots in the same color represent one set, with PV penetration from 100%, to 80%, to 50%. To demonstrate the different energy storage (shorted to “ES” in the figure titles) capacity reductions for System 1 and System 2 for the residential/commercial case (Set 1 in Table III), we show two figures for each system, respectively. For the other metrics, we show only the results for System 1 because the data distribution and the trend of the results for System 2 are similar to those of Feeder 1, with only some differences in the mean and median values.

In addition to the metrics in (2) and (3), which are listed in Section III, the number of deep cycles is also analyzed here for energy storage. One charge/discharge cycle is defined as a deep cycle if the charge/discharge rate is greater than 80% of the energy storage power rating.

Figs. 8–9 demonstrate the energy storage capacity reduction for System 1 and System 2, respectively, over the seven data sets. If the two systems all have commercial loads, the energy capacity reduction increases when the PV penetration reduces. But the trend is reversed for the scenarios where the two feeders all have residential loads. The figures also show that the reductions brought by the converter are similar for the two systems if they both have the same types of loads. But for the case where one system is modeled with only residential loads and the other system is modeled with only commercial loads, the reduction brought to the energy storage capacity for the two feeders is different. Figs. 8–9 show that the residential feeder can benefit more from the converter than from the commercial feeder.
Figs. 8–10 show that the average reductions for the energy storage capacity can be up to 50%, and even 100% for cases with both commercial loads and 50% PV penetration. But the reduction for the power rating is not that significant—the average reductions range from 5%–10%.

Figs. 11–12 show that the reduction in the number of deep cycles and the non-curtailed PV energy through the use of the converter are both significant—greater than 50% for most cases. Figs. 13–17 present the value analysis results for the 15 data sets described in Table V. Similar to Figs. 9–13, for the x-axis labels, the one before the slash represents the scenario on System 1, and the one after the slash represents the scenario on System 2.

Comparing the violins in the right part of Fig. 13 to Fig. 14(starting with the 6th violin from the left) shows that the system with fewer commercial loads can obtain more energy storage capacity reduction when the two connected systems have an obvious difference in their commercial/residential load ratios. Comparing the first four violins in Figs. 13–14 shows that if the two systems have similar commercial/residential load ratios, when there are fewer commercial loads in both systems, the MVB2B converter can better reduce energy storage capacity.

Fig. 15 shows that the power rating reduction is not very significant, ranging from 5%–10%, with some best cases achieving 20%. Many cases can achieve a reduction rate of more than 50% on the deep-cycle number, as shown in Fig. 16. The PV energy curtailment reduction is also significant—greater than 50% for most cases, as shown in Fig. 17.

The PV hosting capacity improvement needs to be evaluated based on a PV hosting capacity study. In this case study, the weakest bus and worst scenario are empirically selected to demonstrate the hosting improvement calculation method described in Section III. Taking the data in Table V and calculating the hosting improvement as shown in (28) shows that the hosting improvement is approximately 20% of the maximum power the converter can transfer to another system during the worst scenario.

For a selected weakest location, the converter is connected at two nodes, respectively. As shown, Case 2 has a better hosting capacity improvement than Case 3 according to the voltage criteria.

In addition to the voltage drop on the targeted buses, the voltage impact on other buses and the distance between the MVB2B converter location and the major DERs on the system will also have substantial impacts on both the system performance and the converter implementation; therefore, the location selection of the MVB2B converter is critical, and we will discuss this in detail in our follow-up paper.

\[
\Delta C_{DER} = \frac{P_{\alpha\beta} \Delta P_{\beta}}{P_{\alpha\alpha}} = 192.9551\text{KW} \quad (28)
\]

C. Marginal Value Analysis

To investigate the marginal value that the MVB2B converter can bring by increasing one unit, we performed an analysis of the non-curtailed PV energy improvement by using the converter for the 100% PV penetration subset of the seven data sets in Table II. The caption of each subfigure is corresponded to the x-axis label of Fig. 8 which represents the load scenario of the two feeders. The converter capacity is increased from 200 kva to 750 kva, with 50 kva as a step. The marginal value decreases as the converter size increases, so an optimal size can be selected for each scenario.

For the cases shown in Fig. 19(b), (e), and (f), the optimal converter sizes for the two feeders are very close, so the converter size can be easily designed. For the case shown in Fig. 19(d), continuing to increase the size of the converter should be able to lock down an optimal size. For some cases, however, such as the residential/commercial case shown in Fig. 19(a), the optimal sizes of the two feeders are not the same; therefore, a balance between the size of the converter and the benefit brought to the two feeders needs to be analyzed before determining the converter size. The selection of the optimal MVB2B converter size will be discussed in our follow-up paper.
D. Conductor Loading Analysis

To investigate the impact of the MVB2B converter on the connected line conductor loading, a snapshot power flow simulation has been performed to examine the loading condition of the connected lines during the MVB2B power transfer. The total load of the two feeders is 5.4 MW, and the converter is transferring 1.5 MW of power from Feeder 1 to Feeder 2 in this extreme case.

Compared with the case without the MVB2B converter transferring power between the two feeders, with only load and PV, the results show that the conductor loading increased, with percentage to both normal and emergency capacities. Note here the emergency capacity is usually around 150% of normal capacity, with room to tolerate some emergency conditions. But it is still significantly below the upper limit. The increase in the total system loss of the two feeders is not substantial.

Considering that this experiment is an extreme case where a significant amount of power is flowing out of and into the conductors, normal cases with the MVB2B converter transferring power should have less risk of overloading.

E. Insights Summary

From the case study, a couple of representative insights can be summarized:

1) The MVB2B converter can bring significant value to avoid PV curtailment in the system and to improve the PV utilization rate. If no energy storage system is installed with the PV, the MVB2B converter can save 40%–80% of the energy that might need to be curtailed if no MVB2B converter connects the two systems.

2) The MVB2B converter can reduce the energy storage capacity for the system with a higher portion of residential loads if the two connected systems are both mixed with residential and commercial loads. The energy storage power rating reduction is relatively small compared to the capacity reduction, whereas the deep-cycle number reduction is substantial (greater than 40% for most cases).

3) The connection location of the MVB2B converter would impact the PV hosting capacity improvement constrained by the voltage criteria.

4) The optimal size of the MVB2B converter might be different for the two connected systems if one is considering maximizing the value brought to one system. An ideal size needs to be determined by balancing the benefit brought to the two systems.

F. Real-World Implementation Considerations

As analyzed in this paper, the MVB2B converter has the potential to bring significant value to the grid. To fully reveal its value, it is critical to address three challenges in real-world implementation: the size of the converter, the feeder pair selection for connection, and the connection location selection. With these three challenges addressed, connected feeders can effectively benefit from the MVB2B converter.

In our follow-up paper, we will thoroughly discuss the methodology we developed for addressing these three challenges. We use cost-benefit analysis and time-of-return analysis to determine the optimal converter size. We use statistical metrics of the feeder aggregated load profile to select feeder pairs that can best benefit from the MVB2B converter connection. And we leverage the voltage load sensitivity matrix and consider the distance between the connection point and the major DERs to help find the optimal MVB2B converter location.

Fig. 20 is an example from our follow-up paper demonstrating the years of return and the value versus size brought by the MVB2B converter. As shown, the value decreases as the converter size exceeds the optimal point, and the years of return increase as the converter size increases. There is an optimal size that can provide the most value from the converter with less time needed to start realizing the benefit.
This work analyzed the value that the MVB2B converter can bring to the DER hosting enhancement of distribution systems as supported by the quantified power transfer function of the MVB2B converter. A systematic analysis methodology was proposed, and a case study on two utility-provided distribution systems was presented and discussed. The value analysis performed in the case study shows that the MVB2B converter can bring significant value to reducing PV curtailment and to reducing the number of deep cycles regardless of the load types the systems have. The energy storage size reduction is more sensitive to the load situations of the two connected systems. This also indicates that the load situations on the systems need to be considered when deciding which two systems are a better pair.

In future work, a methodology will be developed to address three problems: selecting systems which can benefit from the MVB2B converter, selecting the optimal locations of the connection buses on the two systems, and determining an optimal size of the MVB2B converter.

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