Optimal Energy Management of A Cluster of Converters in Micro-grids

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RESUME - With the rapid growth in integration of renewable energy sources (RES) and the increasing interest in smart grids, the need for more efficient and modular converters has become a priority. In this work, a micro-grid with a cluster of converters is studied, trying to put forward an alternative for the current standard architecture with one converter per function concept. However, in order to study this solution, the stochastic nature of RES is also taken into consideration. In this work, a micro-grid equipped with RES, energy storage system (ESS) and a connection to the utility grid is modeled, based on real consumption and generation profiles. The cluster of converters is controlled by different power management strategies and the objective of this work is to assess the impact of different power flow optimization strategies on energy efficiency.

Mots-clés—'Energy Hub', 'Cluster Converter', 'Micro-grid', 'Distributed generation'.

1. INTRODUCTION

There are several generation and storage devices (called objects) with different characteristics in a smart grid. Some of these objects are bidirectional in terms of power (such as storage devices and utility grid) and others are unidirectional (such as photovoltaic panels and wind turbines). While storage devices are limited controllable sources and sinks of energy, utility grid can be regarded as a controllable infinite source and sink. Renewable resources, on the other hand, are uncontrollable source-only objects. Each object has a voltage levels that is different from the others, not to mention their dc and ac nature. Considering all the variability and differences, proposing a real time efficient system that can exchange energy between these objects is a challenging task. Due to their intrinsic characteristics, multi-port active-bridge (MAB) converters can exchange energy between several objects with different natures. Each port of a MAB converter is connected to a multi-winding transformer through an active bridge. Magnetic core of the transformer of the MAB converter is the link between the ports. Galvanic isolation between the ports, simultaneous power transfer between multiple objects, soft switching, small passive components and scalable structure are key properties of the MAB converter that make it an interesting candidate for application in a smart grid. Various application of MAB converters have been studied by researchers. In [1], application of a dual-active-bridge (DAB) converter in a more electric aircraft is studied. Through optimizing design and control, they were able to reach 2 kW/kg power density in a 3.75 kW prototype. Application of quad-active-bridge (QAB) converters as the interface between a three-phase and a DC network is studied and optimized in [2, 3]. Other works have analyzed application of MAB converters as an energy hub between several objects of a micro-grid [4, 5].

To further the advantages of MAB converters and address the shortcomings of standard architectures, this work proposes a cluster of MAB converters. In a classical architecture, there is one converter per function, which is design for maximum power requirement of that function, e.g., the converter that feeds the DC grid is designed for maximum demand on that grid. In a cluster of converters, on the other hand, multiple small converters are work in parallel for each function. Therefore, each converter is designed for a fraction of the maximum power. Higher efficiency and lower risk of load loss are the two main advantages of this architecture. Application of a cluster of converters in energy system of a micro-grid has been studied in [4]. The strategy to divide the power between parallel converters in [4] was simple and straightforward. This work develops on the same architecture and seeks to demonstrate how energy management in this cluster can be optimized. The impact of different strategies on energy efficiency and conversion losses in the system will be assessed by simulation of a test case.

The next section will present classical single-converter solution and discuss its shortcomings. Section 3 presents the proposed cluster of converters and the MAB converters, as building blocks. Different methods of optimizing power flow will be introduced in section 4. Simulation results of a real test case will be presented in section 5 and different management strategies will be compared. Section xxx includes conclusions.

2. CLASSICAL ENERGY CONVERSION SYSTEMS OF MICROGRIDS

The classical architecture of energy system of a microgrid involves multiple converters. One general solution is to use isolated DC/DC and DC/AC converters in order to connect each objects to the ac network. This solution provides good level of safety because all the resources are electrically isolated through the high frequency transformers. One major drawback of this solution is that it involves several energy conversions for each equipment. Moreover, there is one converter per function, and each converter has to be designed based on the maximum power of that function. The battery converter, as an example, will be

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designed regarding the maximum charge and discharge power. The actual charge and discharge power, however, will be smaller than the maximum power during a significant portion of its lifetime. Therefore, the converters usually operate at a fraction of their nominal power. Operation of power electronic converters at powers that are much smaller than their nominal power involves high losses and low efficiency. Fig. 1 illustrates a classic efficiency curve of power electronic converters, illustrating this fact. Consequently, the classical solution (one converter per function) is not an optimized one in terms of efficiency.

Fig. 2 shows another classic solution with reduced number of converters. Energy exchange from ac grid to dc consumers and batteries in this solution involves two and three conversion steps, respectively. Each conversion step involves losses, which means high losses. With low number of converters, this solution seems promising in terms of statistical reliability because it has low number of switches. However, in case of troubleshooting of one converter, a major system functions might be lost, i.e., reliability of the system is not optimal and load loss probability is high.

So far, the two main shortcomings of classical solutions with one converter per function architecture have been identified. The next section will introduce the clustering solution that can address these shortcomings.

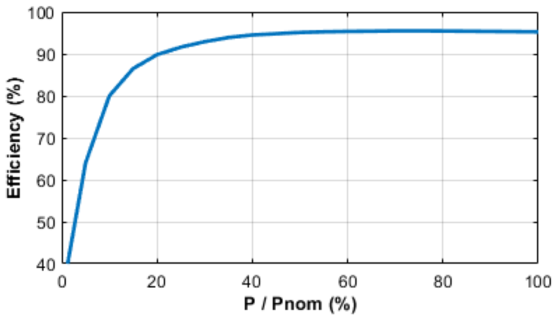

Fig. 1: Efficiency as a function of power; P is the transferred power and Pnom is the nominal power for which the converter is designed.

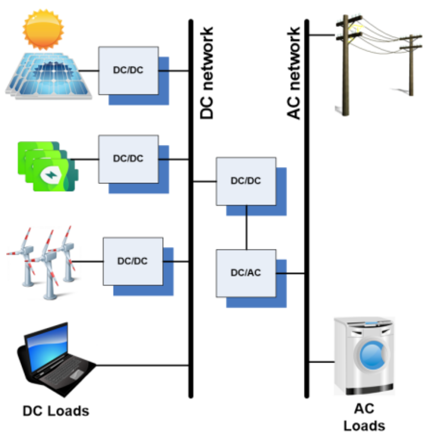

Fig. 2: Electrical network of a future smart building based on classic DC/DC and DC/AC converters.

3. THE PROPOSED SOLUTION

In order to solve the challenges of the classical solution that were presented in previous section, a cluster of converters can be employed. The clustering, its advantages and building blocks will be introduced in this section.

3.1. A cluster of converters

In an energy system with a cluster of converters, each function is performed by multiple converters, each one designed for a fraction of maximum power. Fig. 3 shows an example of the proposed cluster of converters. There are several functions displayed in Fig. 3, e.g., connecting wind turbines to storage and grids, or energy exchange between ac grid and dc grid. There are multiple converters in parallel for each function. The converters in Fig. 3 are quad-active-bridge (QAB) converters, which will be presented and studied in detail in section 3.2. QAB converters in the cluster can connect ac grid, dc grid, a storage device, and a renewable resource altogether in one place and simultaneously exchange energy between them. Each QAB converter is designed based on a fraction of the maximum power of its corresponding function.

The smart cluster controller (shown in Fig. 3) decides how to employ the converters at each moment. It is possible to change the overall nominal power of the cluster through changing the number of parallel converters that participate in power conversion. Whenever the power transfer is low, it will turn off some converters, which is equivalent to decreasing nominal power of the cluster, and let the rest operate closer to their nominal power to increase energy efficiency.

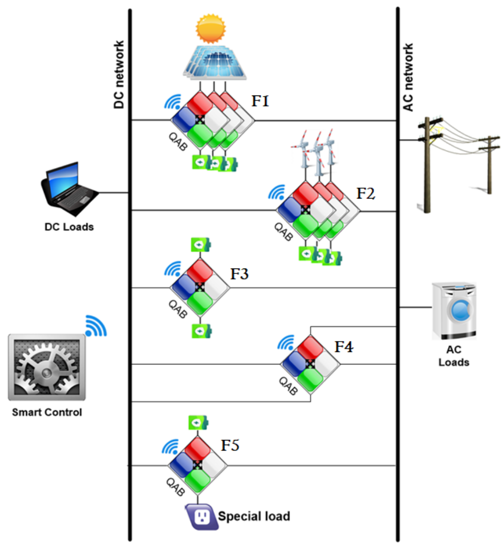

Fig. 3: A cluster of QAB converters with various possible functions (F1-F5), managed by a central controller

Compared to the classical single-converter architecture, a cluster of converters has many more active and passive components. Therefore, mean time to failure (MTTF) will be shorter than that of a single converter and the reliability will be lower on a statistical point of view. It is worth mentioning that single converters have to operate continuously, while cluster converters may spend long periods on standby. Ratio of standby period to operation period depends on the consumption and generation profiles. This means that the MTTF of a cluster of *n* converters is not exactly *n* times shorter than a single converter. The important factor here is the probability of load loss. While a classical single converter has to cease operation after the first failure, a cluster of converters will be able to continue providing services but at a reduced level even after a few failures. After a failure in one of the cluster converters, the cluster will not be able to provide the load when the demand passes a certain amount, which is usually a small portion of the day. Moreover, overdesigning and overloading are the possible options that help reducing the risk of load loss after the first couple of failures in cluster converters.

3.2. MAB converters

There are multiple reasons why MAB converter topology is a good candidate for application in the proposed cluster. The topology is scalable, i.e. it is possible to add any number of ports by adding an active bridge (the green box in Fig. 4-a) connected to a winding on the core of the multi-winding transformer (the red box in Fig. 4-a) through an inductor (the blue box in Fig. 4-a). Considering the application, a four-port MAB converter, QAB converter, has been chosen in this study. Each QAB is able to connect a renewable resource, a storage device, ac grid and dc grid altogether at one place, and simultaneously exchange power between them. Galvanic isolation between the ports, provided by the transformer, is an intrinsic property of MAB converters. It is essential for maximizing safety cautions, and usually comes with additional costs and complexities in other topologies [2].

Energy storage requirements of MAB converters is very small, meaning that the storage elements that are inductors are small. MAB converters can operate in soft switching mode over a wide range of power and voltage variations. Soft switching involves negligible switching losses, allowing high switching frequency. Increasing switching frequency leads to reduction in size of magnetic cores, hence, a small transformer core and further reduction in dimensions of inductors.

Fig. 4-b shows an example of voltage and current waveforms in a MAB converter. The 2-level and 3-level voltages waveforms are generated by switching signals from internal controller of each QAB converter. The flow of power between ports of a MAB converter is controlled through applying phase shifts between voltages of different ports, and controlling their duty cycle (in case 3-level voltage modulation). On control aspect, different sets of phase shifts and duty cycle can lead to any desired power flow inside the QAB converters. Some methods of finding these phase shifts and duty cycles are studied in [6] and [7].

Another advantage of MAB converters is voltage compatibility. It can connect several DC sources with different voltage levels together, through adjusting winding turn ratios. There are different options for interfacing this DC/DC topology with single-phase and three-phase AC networks. In this work, an intermediate dc link, controlled by and additional AC/DC converter, is assumed between the QAB converter and the AC grid. Direct and indirect connection of single-phase and three-phase networks is possible and studied in different works [2-3, 8].

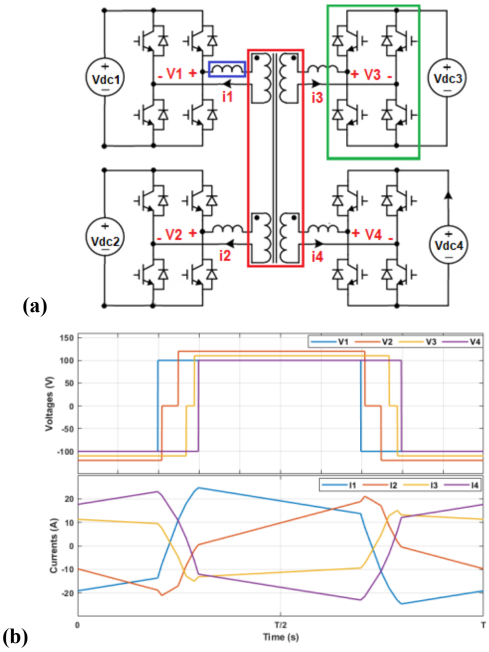

Fig. 4: QAB: (a) structure; (b) an example of voltages and currents of active-bridges for one cycle (T).

4. ENERGY MANAGEMENT STRATEGIES

The proposed architecture of clustered converters that has been introduced and studied in the previous section brings about certain challenges, mostly in design and control areas. One of the challenges is to find the best way to distribute the power among the converters of the cluster. Based on the demand on DC grid, the generation of renewable resources, and the energy stored in the batteries at each moment, there can be many different ways to employ the cluster converters to provide the demand, i.e. clustering brings redundancy and flexibility. In order to take advantage of redundancy and flexibility, an energy management strategy is required to find the optimal flow of power among the converters. The optimization goal in this work is to minimize conversion losses.

The energy management strategy that was used in [4] was a straightforward strategy. The strategy was to employ as few converters as possible to perform the task of power transfer. This work seeks to propose different ones and to assess the level of their impact on global loss reduction in the cluster.

4.1. The domain of optimization

The goal is to find optimal power distribution in a cluster of parallel converters, similar to what is illustrated in Fig. 3. It is assumed that only converters of function F1 in Fig. 3 are present in the cluster. The goal here is to find optimal the number of converters to participate in power transfer. It should be noted that usually all photovoltaic panels generate power during the day, therefore, all converters that have a generating photovoltaic panel on them should be turned on and operate. Therefore choosing optimal number of converters is not a case in this situation. During the nights, however, the power is totally provided by the AC grid (it is assumed that the storage devices are small batteries installed close to each QAB converter for maintaining the grid during short blackouts). In this case, it is possible to choose the number of converters that participate in power transfer. An example situation is a cluster of 20 converters, each designed for 1 kW nominal power, when the demand on DC grid is 15 kW. It is possible to employ 15 converters, each transferring 1 kW, employ 20 converters, each transferring 0.75 kW, or any number of converters between 15 and 20.

4.2. Approximate model of losses

The main losses of MAB converters are: 1) conduction losses in the windings of transformers, inductors and switches; and 2) magnetic core losses in transformers and inductors. Employing more converters in power conversion leads to reduction of sum of current squares, hence, lower conduction losses. On the other hand, In order to minimize core losses, it is better to employ as few converters as possible. The tradeoff between these two losses can give the optimal power flow. An approximate model of losses will be used in this section to find the optimal power flow.

The conduction losses in a single QAB converter can be determined as $\sum_{ports} RI^2$, where R and I are overall equivalent resistance of windings and switches, and effective current, respectively. Current can be approximated as power (P) divided by voltage (V), therefore

$$Loss_{cond} = \sum\nolimits_{ports} RI^2 = \sum R(\frac{P}{V})^2 \tag{1}$$

Core losses can be predicted using different methods. The iGSE method [9] is commonly used for predicting core losses when the voltage across the windings are non-sinusoidal, as in case of QAB converters. The core losses in iGSE method depend on core geometry and material, and the voltage waveform. Although the voltage waveform changes with the power, it can be approximated as a constant value in order to simplify calculations. The core losses are assumed to be a constant value, P_{core}, in each QAB converter. Therefore, total losses of a cluster that employs n converter to transfer P kilowatts from AC grid to DC grid would be

$$\begin{aligned} Loss_{tot} &= nLoss_{cond} + nP_{core} \\ &= n\sum R(\frac{P}{nV})^2 + nP_{core} \end{aligned} \tag{2}$$

It is assumed that the power is equally divided between the converters, therefor the current in each converter would be $\frac{P}{nV}$. In order to find the minimum losses, $\frac{dLoss_{tot}}{dn} = 0$ should be solved, which gives

$$n = \sqrt{\frac{R\sum\left(\frac{P}{V}\right)^2}{Loss_{core}}} \tag{3}$$

4.3. Maximum efficiency point

As explained in the previous section, the optimization is only possible when there is not power exchange with renewable resource and storage devices. Under this condition, only two ports of each converter (the ports connected to AC and DC grids) will be transferring power, hence, the QAB can be regarded as a DAB. An efficiency curve for a DAB can be determined theoretically, through an accurate model of losses, or experimentally, through measurements.

A simple method of finding optimal number of converters is to try to operate the converters at their maximum efficiency point. In case of a converter with a non-flat efficiency curve, the number of converters can be determined based on

$$n = \frac{P}{P_{max-eff}} \tag{4}$$

where $P_{max-eff}$ is the power at which maximum efficiency occurs.

5. SIMULATIONS AND RESUMTS

Two methods were introduced for finding optimal number of converters for performing power conversion task. Simulation results can help comparing global efficiency of these methods, with the method that was used in [4]. The extent of efficiency increase is expected to be dependent on load profile and converter design. A test case based on real data will be used in the simulations. In order to better assess performance of the proposed methods, two different converter designs (called A and B) will be studied. Fig. 5 shows efficiency curves of these converters. Peak efficiencies of converter designs A and B are 94.8% and 91.6%, which occur at 100% and 50% nominal power, respectively.

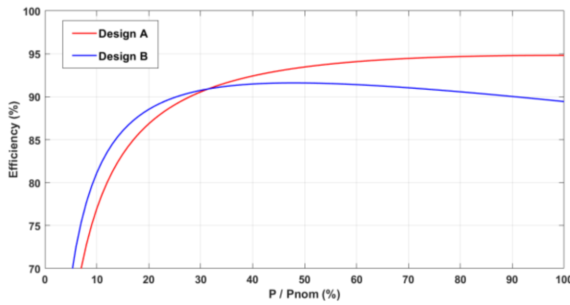

Fig. 5: Efficiency curves of the two converters used for simulations

5.1. Efficiency over the whole range of power

The first step is to compare efficiency of the cluster while the power rises linearly from zero to 100% nominal power. Fig. 6 shows the simulation results of a cluster of 20 parallel converters. The horizontal axis represents the power flowing from AC grid to DC grid, normalized based on nominal power of the cluster.

As discussed in the beginning of section 4.2, the optimal point is the balance between conduction losses and core losses. The converter design A has small resistances, therefore, conduction losses are small and core losses are the dominant losses. In this case, the optimal solution is to use as few converters as possible, which was the strategy used in [4]. This fact is verified in the simulation results of Fig. 6-a, where performance of the method in [4] is similar to the optimized solutions.

In case of converter design B, however, resistances are higher and conduction losses are the dominant losses. As discussed in section 4.2, it is better to employ as many converters as possible in this case. This is the reason why performance of the method in [4] is relatively lower than the optimized methods introduced in this paper. The results illustrated in Fig. 6 show that the two proposed methods are equivalent in almost all the operating points.

5.2. The test case

The consumption and generation profiles of the smart building where the authors of this article work is used for simulation. GreEn-ER is a smart building that houses G2ELab, Grenoble INP ENSE3, PREDIS, MEE Lab, and several startup companies, in Grenoble, southeast of France. Fig. 7 shows the average consumption profile of GreEn-ER over a period of three years. Total consumption over a year is around 1.7 GWh. The currently installed renewable generation, which is 90 photovoltaic panels, however, sums up to 24 MWh and is not comparable to the consumption. In order to be able to better study the test case, two assumptions were made:

1. 50% of rooftop of the building is covered by photovoltaic panels, adding another 14 arrays of 90 panels. Yearly renewable production reaches 360 MWh in this case. Fig. 7-b shows the generation profile.

2. A DC grid exists in the building, and lighting and wall plugs are fed through this grid. As the lights are LED and a significant portion of the consumers on wall plugs are DC consumers (such as PCs, LCDs, VOIP phones), this assumption will probably come true in future smart buildings. Total consumption of the two categories is 310MWh over a year.

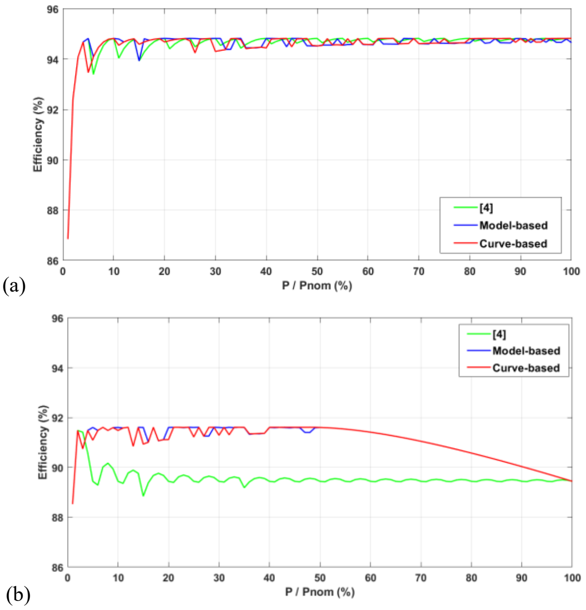

Fig. 6: Comparing efficieny of different methods over full power range for: (a) converter design A, and (b) for converter design B.

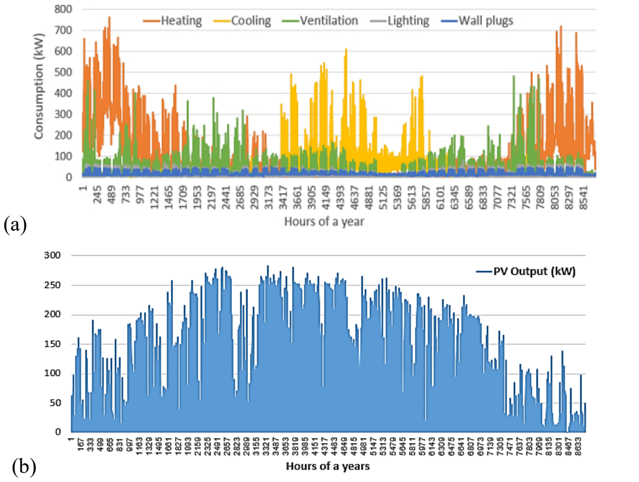

Fig. 7: (a) Consumption profile of the study case, divided into five categories of heating, cooling, ventilation, lighting and wall plugs; (b) Generation profile of 15 arrayes of 90 photovoltaic panels.

5.3. Simulation results of the test case

Results of simulation of the test case confirmed the conclusions that were made in section 5.1. Fig. 8 shows efficiency of the energy conversion system for three consecutive days of November. It shows that different strategies change the system efficiency during the nights.

Similar to what was illustrated in Fig. 6, in case of converter design A, different strategies have almost the same performance. In case of the converter design B, however, the proposed strategies lead to 1-2% higher efficiency during the nights. The strategy proposed in [4] employs the converters at 100% nominal power, while maximum efficiency of converter design B is at 50% nominal power. The strategies proposed in this work, on the other hand, are able to employ the converters as close as possible to their maximum efficiency point. In case of design A,

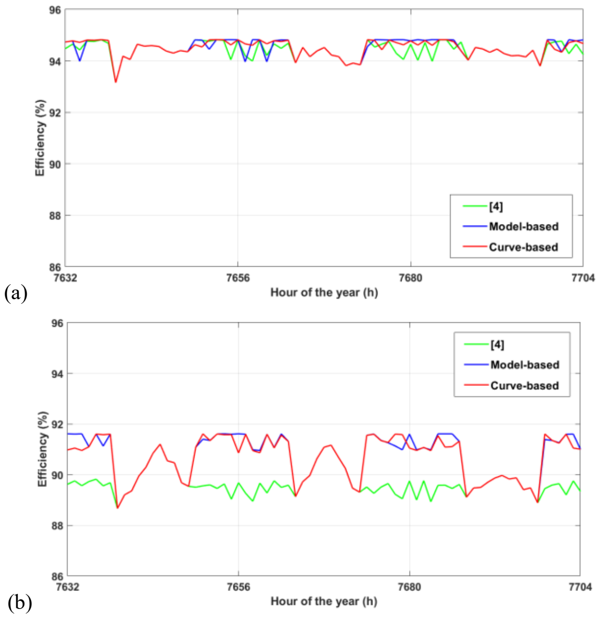

Fig. 8: Efficiency of energy conversion system over three consecutive days (15-17 November) for (a) converter design A; and (b) converter design B.

Table 1. Comparing yearly losses of different strategies on the test case for converter design B

Strategy	Total yearly losses (MWh)
Proposed in [4]	37.9
Model-based	36 (5% reduction)
Curve-based	36.3 (4.3% reduction)

total yearly losses of the system is almost equal for all strategies. The proposed strategies were able to reduce the total losses by around 5% in case of design B. It is worth mentioning that clustering itself had already reduced the losses around 40%, compared to the classical single-converter solution [4].

6. Conclusions

The microgrids have several different types of generation and storage resources and they will likely include DC grids in the near future in addition to the common existing AC grid. Exchanging energy between all the resources, loads and grids in a real-time and efficient manner requires novel converters and architectures. A cluster of converters is a good solution because of its ability to provide energy with high efficiency over a wide range of power, and reduce probability of load loss. Multi-port active-bridge converters have characteristics such as intrinsic galvanic isolation, small passive components and modular topology, which make them good candidates for building blocks of the cluster. Along with all the benefits, clustering brings with itself certain challenges, including the call for optimal control. This work proposed methods of finding optimal power flow between the converters of a cluster. Simulations of a test case based on consumption and generation profiles of a real smart building were performed to assess performance of the proposed methods. The results showed that the proposed methods were capable of identifying the optimal power flow in the cluster, regardless of the converter design.

7. References

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