

An Effective Controllable Grid Interface for Microgrids

Behnam Tamimi, *Senior Member, IEEE*, Hanwen Gu, and Claudio A. Cañizares, *Fellow, IEEE*

Abstract—The interest in the integration of distributed power generation and microgrids into power grids has significantly increased. In this context, interfacing microgrids with a host grid is of significant relevance, and therefore, in this paper, a cost-effective controllable grid interface for microgrids is proposed, modeled, and studied under various conditions, including smooth and abrupt power fluctuations, faults, and interface tripping. The proposed interface, named Microgrid Connector Controller (MGC), is an adequate and affordable alternative to the existing Back-to-Back (B2B) microgrid-grid interface, at a fraction of its capital costs. Thus, the proposed MGC's performance is compared a B2B interface through detailed time-domain simulations in a realistic benchmark test system to demonstrate the controller's capabilities. Compared with B2B, MGC's direct frequency synchronization and power and voltage control capabilities makes it easier for microgrid operators to satisfy required standards and reduce wear and tear in grid equipment and customer loads. Finally, the MGC's lower voltage ratings may translate into significantly smaller size and thus easier logistics and lower costs.

Index Terms—Active Distribution Network (ADN), Back-to-back (B2B), Distributed Energy Resource (DER), grid interface, microgrid.

I. INTRODUCTION

MICROGRIDS (MGs) are local clusters of loads and generators for reliable and economic integration of Distributed Energy Resources (DERs), Energy Storage Systems (ESS), and controllable loads [1]. Microgrids disconnected from the main grid are referred to as isolated or stand-alone microgrids, which are typically found in remote communities or mining sites, where a grid connection is not feasible because of technical or economical constraints. Microgrids are also expected to operate connected to a host grid; thus, flexible, economic, and reliable connection of microgrids to the main grid or other microgrids is of significant relevance in modern grids.

A controllable and effective grid interface should mitigate potential detrimental impacts of DERs on distribution systems; this impact depends on the characteristics and location of the DERs among other factors [2]. Moreover, as the proliferation of power Converter-Based Resources (CBRs) and transmission controllers increases, there is a greater likelihood of adverse interactions between these devices [3]–[5]. Grid interconnection standards, such as IEEE Std. 1547 [6], define and

recommend conservative limits and operation requirements for DER connection in Active Distribution Networks (ADNs). Thus, a flexible and well-controlled interface at the Point of Common Coupling (PCC) of a microgrid would benefit DERs and microgrid owners and operators. This interface should be able to satisfy the following requirements: bidirectional and controllable power flow operation, compliance with grid standards for interconnection, high reliability and easy maintenance, and be economically attractive.

The connection of two different networks, or parts of a grid, with controlled power transfer capability can be achieved by different means, for example: phase-shifting transformers, Variable Frequency Transformers (VFT), or Back-to-Back (B2B) links [7], [8]. The latter is currently the “standard” for microgrid-grid interfacing [9], as it is able to asynchronously connect two power networks and control the power flowing between them. The technical literature on B2B and its applications in the context of ADNs/microgrids is extensive. For example, a B2B connection between two different parts of ADNs, which are normally isolated, may improve voltage and reactive power control across the network [10]. Similarly, multiple B2B connections in an ADN could independently route and manage power flows in the system [11]. Single-phase B2B connections could also be used on individual phases to help with microgrid controls and regulation [12]. Another interesting application is that B2B can emulate different DERs such as wind, ESS, or PV in laboratory microgrid setups [13].

On another front, a converter interface based on a hybrid ac/dc topology referred to the Hybrid Power Flow Controller (HPFC) is introduced in [14], and in [15], an interesting geometrical representation of the device's operating region is presented. An Electromagnetic Transient Program (EMTP) model of the HPFC is briefly studied in [16], and the performance of the HPFC for improving the power transfer capability of a system is compared with that of the Unified Power Flow Controller (UPFC) in [17], based on time domain simulations using PSCAD-EMTDC. The authors in [18] implemented and studied the HPFC as a stabilizer in Simulink by connecting two Static Synchronous Series Compensators (SSSCs) and a Static VAR Compensator (SVC), without discussing in detail the control procedure and the device's capability limits. The modeling of the HPFC and its operating limits for power system studies, which typically require power flow, OPF, and dynamic analyses is presented in [19], and applications of the controller to transmission and distributions systems are presented in [20] and [21], respectively. Although the HPFC is capable of controlling the flow and voltage at its terminals, the topology and applications are different than those of the MGC proposed here, since the former requires a parallel ac

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path and thus cannot be used as a grid-microgrid interface.

Grid synchronization of a microgrid can be challenging due to controllers operating under different conditions. This notion is important in modern microgrids, as industry standards require a seamless grid synchronization and re-connection upon request [5], [22]. Furthermore, current trends in Essential Reliability Services (ERS), such as frequency and voltage regulation in the face of changes in the resource mix, require prioritizing efficient approaches and tools that could address the challenges and risks in a holistic way, including economic considerations [23]. These requirements have been addressed through multiple microgrid control strategies, which enable smooth transitions between grid-connected and islanded modes [24]–[28]. Thus, [24] proposes a centralized control-based hierarchical architecture combining the primary converter controller with secondary control loops for microgrid-grid seamless synchronization. However, this scheme suffers from single-point failure issues, making the system less reliable [25]. Distributed control schemes proposed in [26]–[28] can address this issue, presenting advanced features such as attenuating constant disturbances [28]. However, these existing control strategies only adjust the microgrid's power sources and not the microgrid-grid interface, making them less flexible than having a connector that can control the transferred power. Thus, in this paper, a flexible and economic alternative for microgrid connection is proposed, showing that this cost effective controller offers similar performance compared to B2B.

Based on the aforementioned discussion, the main contributions of the presented work are:

- Develop and propose a novel microgrid interface, microgrid-connector controller (MGC), including its detailed modeling and controls.
- Demonstrate the effective performance of the new interface compared with B2B in a realistic benchmark test system, based on detailed simulations of four interface-related microgrid conditions, including power fluctuations and severe disturbances.

The rest of paper is organized as follows: Section II describes microgrid and B2B technologies, as a background review for the proposed microgrid-grid interface solution. The proposed MGC interface with its modeling and controls for the intended microgrid application are described in Section III. Results and discussions of the application of the proposed technology in a benchmark test system are presented in Section IV. Finally, Section V highlights the main contributions and conclusions of the paper.

II. BACKGROUND

In this section, the general desired characteristics of an interface to connect a microgrid with the main grid or other microgrids are discussed, thus highlighting the challenges faced to meet high reliability requirements in the presence of significant DER penetration. In this context, the technology relevant to this paper for grid interfacing, namely, B2B, is briefly reviewed and its basic architecture is explained.

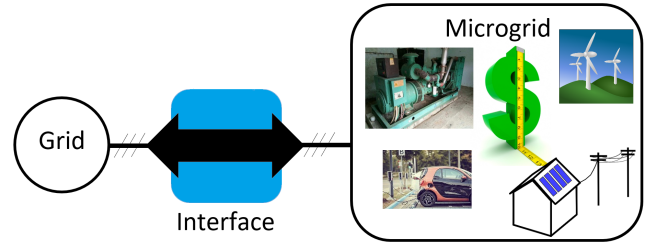


Fig. 1. Microgrid as a local cluster of loads and DERs interfaced with the grid.

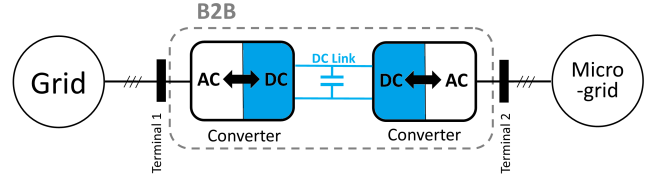


Fig. 2. Architecture of B2B as a microgrid interface.

A. Microgrid-grid Connection

A microgrid is a cluster of loads and DER operating as a single controllable system that provides power locally to its customers. To the utility, the microgrid may represent a single controllable load/generator that can respond quickly to control signals, connected to the grid through an appropriate interface, as depicted in Fig. 1. To the customer, the microgrid is an infrastructure that potentially meets their needs, including enhanced reliability, improved power quality, increased efficiency, to name a few. The interconnection of microgrids to the utility/grid should comply with well-established standards such as IEEE 1547 [6], which defines technical requirements for the interconnection. In this context, a proper microgrid interface should provide a bidirectional and readily controllable connection with the rest of the system.

Reliability and cost-effectiveness of the chosen interface should be in line with the requirements of the target system, ensuring a dependable solution based on customers' needs and economic aspects of the microgrid operation. Thus, an adequate design for the interface is desirable, which can be accomplished through the power-electronic technology reviewed next.

B. Back-to-Back (B2B) Interface

Fig. 2 shows the common circuit topology of a B2B interface used to connect a microgrid to the main grid or other microgrids. The interface generally consists of an ac/dc converter (including transformer, filters, and a commutation reactor) on each side, plus a dc capacitor linking the dc sides of the converters [29]. This technology can also control the reactive-power set point of the converter to obtain a desired power factor on each side. In other words, it can absorb or inject active and reactive power independently on both sides. However, it requires a sizable capital investment [30].

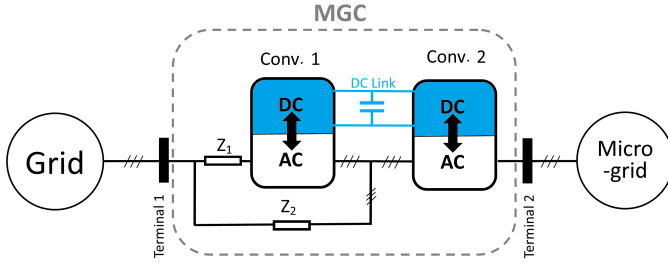


Fig. 3. Architecture of MGC as a microgrid interface.

III. INTERFACE MODEL AND CONTROLS

This section provides the modeling and control of the proposed MGC. Thus, first, the building components of this interface are presented, followed by a description of its different control blocks and their interaction in the time and frequency domains. It is important to note that, in the proposed microgrid-grid connection application, frequency deviations are commonplace, and thus both sides need to be constantly monitored and synchronized. Hence, in the proposed application, frequency synchronization has to be realized through proper controls.

A. MGC Architecture

The architecture of an MGC is shown in Fig. 3, which provides two paths for power flow between its terminals, namely, ac and dc links. It offers frequency control in addition to dc-link voltage control, to effectively eliminate frequency deviations in microgrid connection applications, and provide a synchronous connection between the two sides, so that its performance is comparable to a B2B interface. The flow division between a high-value Z_1 branch and a low-value Z_2 branch around Conv. 1 allows reducing its size and that of the dc link, whose voltage is controlled by this converter. On the other hand, the Conv. 2 controls the power flow of the MGC interface and guarantees the required frequency synchronization. Note that due to the series nature of the MGC, the voltage ratings of the converters and dc link are approximately 10 to 20% of the line voltage, which roughly determines the converter ratings for a B2B. The reduced ratings decrease the costs and physical size of the MGC, thus potentially resulting in 80 to 90% savings compared to the B2B.

The active power flow between the grid and the microgrid through the MGC is shown in Fig. 4; the reactive power control is discussed later under voltage regulation. Thus, a given P_2 value can be supplied from the main grid through both ac and dc links. Note that P_2 can be zero, implying a synchronous grid connection where the microgrid is supplying its load. The losses ΔP incurred in the MGC are supplied from the main grid to guarantee a stable and reliable dc voltage at the dc link, required for smooth operation of the converters.

The converters comprise a bidirectional-switch-based Voltage Source Converter (VSC), a transformer, filters, and other required passive elements as shown in Fig. 5. The transformer

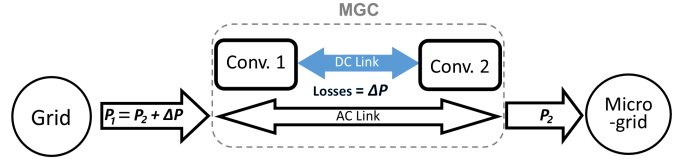


Fig. 4. Active power flow in the MGC.

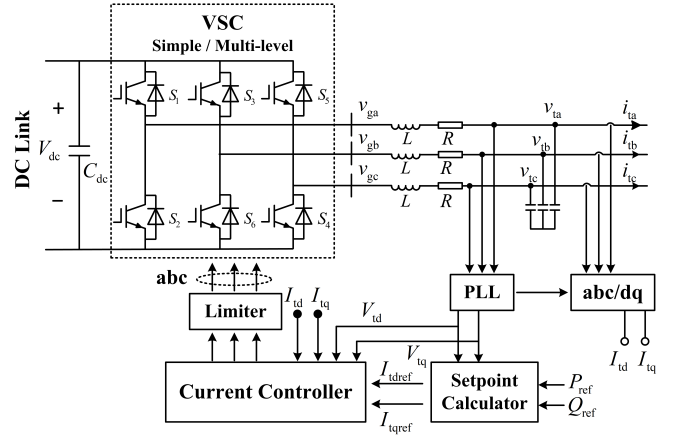


Fig. 5. Three-phase VSC with filter and controls.

and switch commutation inductance are lumped with the harmonic filter impedance. It is important to note that, although the main purpose of the filter is to remove harmonic content, it affects the fundamental frequency component as well, and thus its impact on the output voltage and current should be considered in the model [21]. Multi-level and other advanced forms of VSCs may also be used in this application.

Fig. 6 integrates Figs. 2 to 5 to show the detailed physical and control structure of the MGC highlighting the relationship between the different components of the device and their inputs/outputs. The PLL synchronizes the microgrid to the grid based on the voltage measured at the grid terminal, using power and voltage adjustments to compensate for the microgrid generators' phase deviations and their slow response to the changes in the system.

B. MGC Power Flow Analyses and Limitations

Fig. 7 shows the equivalent circuit of the MGC. Two series voltage sources represent the two VSCs of the interface, and the high-value Z_1 and low-value Z_2 (resistances) for Conv. 1 allow power division. The value of Z_2 is small representing a low-impedance connection, and the value of Z_1 is 2 or 3 orders of magnitude larger than Z_2 based on the converters' current ratings and the MGC losses as design parameters. V_{t1} and V_{t2} are the voltages of the connection terminals of the utility and microgrid systems, respectively; P_1 , Q_1 , and P_2 , Q_2 are the power flowing in and out of the MGC; P_x and Q_x are the active and reactive power flowing out of the VSC1 from the dc link; and P_y and Q_y are the power injecting into the Conv. 2.

Since the value of Z_2 is small, V_{t1} is nearly equal to V_m . Thus, V_x is basically V_{Z1} , and the power of Z_1 is mainly covered by the active power flowing out of Conv. 1. Considering

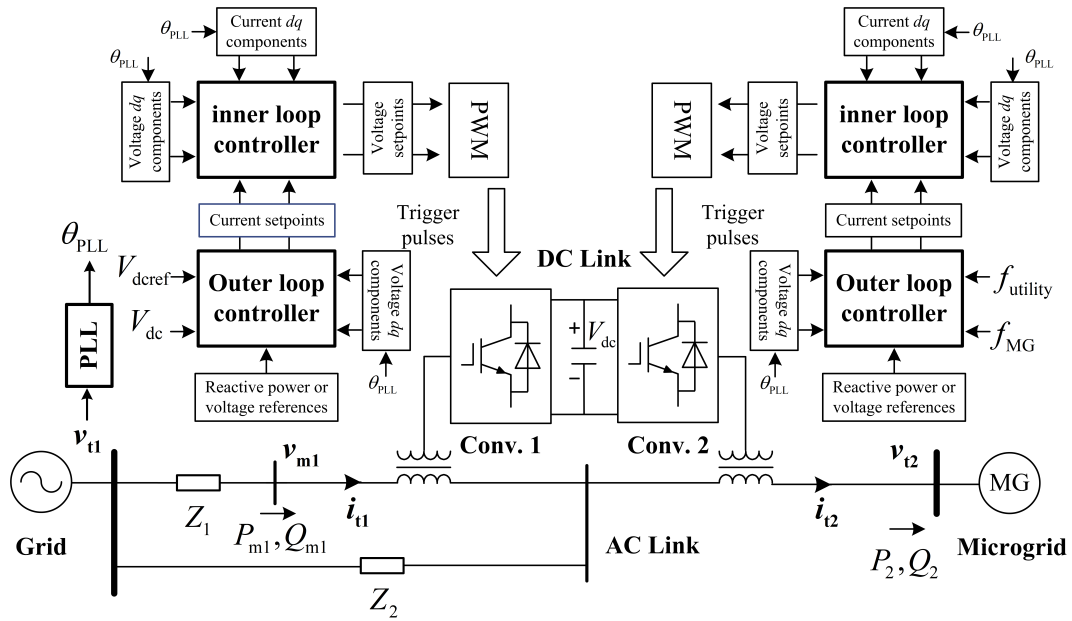


Fig. 6. Detailed physical and control structure of the MGC.

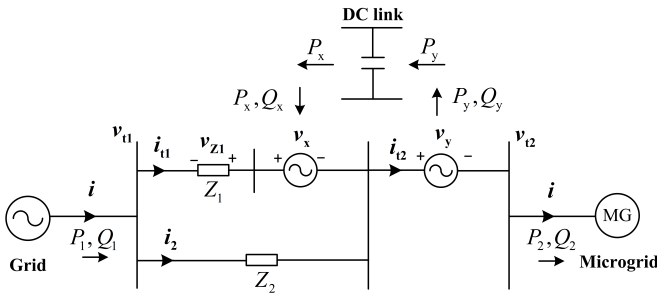


Fig. 7. Equivalent circuit of the MGC.

the power loss of the converters, the power balances of the MGC can be shown to be:

$$P_y = \Delta P + P_x \quad (1)$$

$$P_x = P_{Z1} \quad (2)$$

Based on these power flows, it can be concluded that $P_y > \Delta P$. Hence, the setpoints of the MGC should be chosen properly based on the power flow calculations to guarantee proper operation.

C. MGC Current Control

The current reference is obtained based on the system measurements and power flow setpoints provided by the operator, as illustrated in Fig. 8. The effect of the transformer turn-ratio as well as its phase shift, based on the connection type, should be included in the calculations. Limiter blocks at the output remove any unreasonably large values or spikes. An auxiliary signal is added to the active power reference point to account for internal losses and the dc link voltage regulation.

The control of the converters is realized using proportional-integral (PI) current controllers in the dq-reference frame [29];

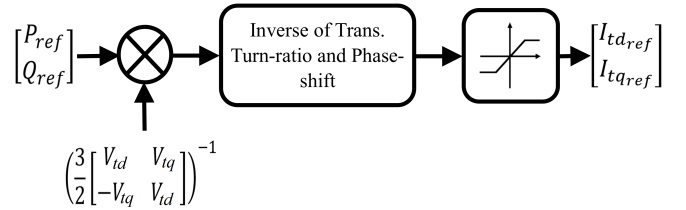


Fig. 8. Current setpoint calculation based on the power references.

this scheme allows independent active and reactive power regulation. The switching frequency ω_s is significantly larger than R/L if the filter parameters are chosen properly, and thus the high-frequency components of the input do not affect significantly the output, resulting in small ripples. Under this assumption, the relationship between the input and output voltages and currents in the dq-reference frame can be written as follows:

$$V_{gd} = V_{td} + \omega L I_{tq} + R I_{td} - \omega^2 L C V_{td} + R C \omega V_{tq} \quad (3)$$

$$V_{gq} = V_{tq} - \omega L I_{td} + R I_{tq} - \omega^2 L C V_{tq} - R C \omega V_{td} \quad (4)$$

These equations can be considered as an open-loop system with the currents I_{tdq} as the output, and voltages V_{gdq} as the input; the control objective is to regulate I_{tdq} . This can be achieved via the closed loop system shown in Fig. 9, in which the reference command is compared with the measured value, and the error signal is processed by a PI controller to generate the desired output. The outputs of the PI controller and the control loop must be properly limited.

The parameters K_p and K_i of the PI controllers can be chosen to cancel the pole created due to the presence of L at the output of the converter. Therefore, the equivalent control path from the current reference to the output value becomes a first-order lag with a time constant τ . Thus, based on the values

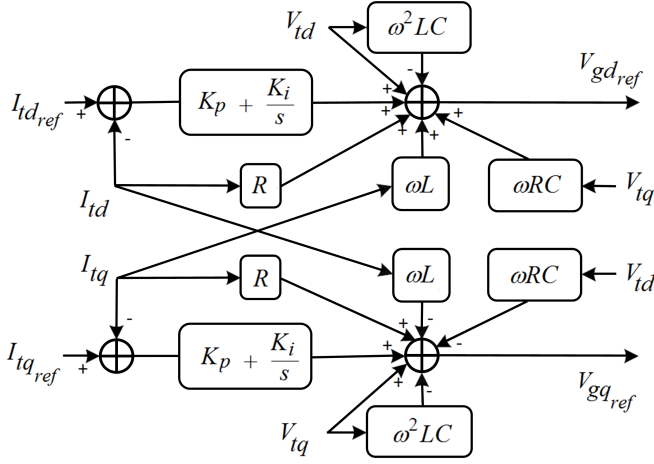


Fig. 9. VSC closed-loop current control in the dq-reference frame.

of the circuit elements R and L , and the design parameter τ , the gains can be defined as follows:

$$K_p = \frac{L}{\tau} \quad K_i = \frac{R}{\tau} \quad (5)$$

It is important to note that the time constant τ should be small to provide a fast current-control response; however, it should be large enough so that $1/\tau$ is considerably smaller than the switching frequency ω_s [29]. The latter constraint is required to be able to neglect high order harmonics, so that the output follows the fundamental-frequency component of the reference signal.

D. MGC Frequency Control

The MGC provides a synchronous connection to a microgrid; however, due to the nature of microgrid and intermittent resources, the frequency might deviate from the nominal value due to an imbalance between local load and supply. Therefore, the frequency at both sides should be constantly monitored and, if needed, proper control signals should change the active power setpoint P_{Cref} of the microgrid interface and of the local generators P_{Gref} , as shown in Fig. 10. Note that the local frequency regulators are slower than the PI controller in the f-control loop of the MGC. Thus, in the case of any frequency deviations in the microgrid, the MGC first responds quickly and balances the supply-demand from the main grid. However, the frequency regulators on the local generators sense the frequency deviation as well, and thus react to it. Therefore, after a delay, local generators respond and relax the interface f-control requirements, with the nominal frequency being supported by local units.

The described control approach requires a nested control structure in the MGC. Thus, the closed loop bandwidth of the outer frequency control loop should be adequately lower than the inner current control loop of the MGC, and higher than that of local generators. In other words, the PI-controller parameters are chosen so that the time constant of the f-control loop is considerably larger than the current-control loop time constant τ , while being faster than the local DER controls.

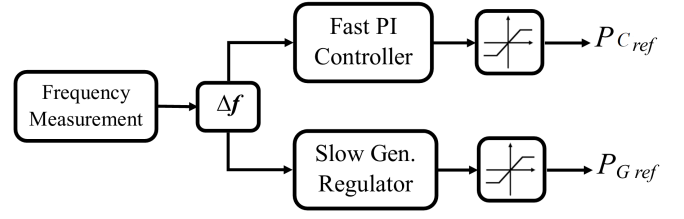


Fig. 10. Active power setpoint calculation for the MGC and local frequency regulators based on frequency deviation in the microgrid.

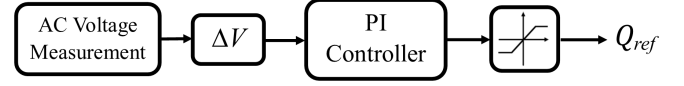


Fig. 11. Reactive power reference calculation for ac voltage regulation.

In the application at hand, Conv. 2 in Fig. 4, which is closer to the microgrid, is mainly responsible for frequency regulation. However, the roles can be switched between the converters due to the modular design of the controller.

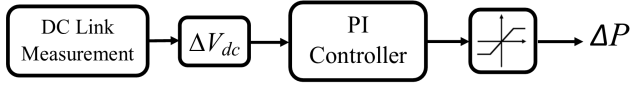
E. MGC Voltage Control

In the previous section, it was assumed that reference values were provided for active and reactive power flows at the device terminals. However, the voltage magnitude at a given controller terminal can equivalently be controlled instead of controlling the reactive power supplied/absorbed. In this case, a control loop for regulating the voltage magnitude at the device terminal is required, as shown in Fig. 11, where the reference voltage is compared with the measured value, and the error signal is passed through a PI controller to generate the required reactive power reference in Fig. 8.

Similarly to the frequency control, the described voltage control approach requires a nested control structure. Thus, the closed loop bandwidth of the outer voltage control loop should be adequately lower than the inner current control loop [21]. Moreover, coordination with local voltage regulators, if any, should be considered in the design phase.

F. MGC DC-link Voltage Control

The converters need a smooth and stable dc voltage to function properly. The dc link, in its basic form, is modeled as a dc capacitor connected in series with a resistive component to represent losses in the circuit. Its dc voltage fluctuates based on the instantaneous flow of energy in and out of the controller. Thus, a dedicated control loop is required to regulate the dc link voltage level, as shown in Fig. 12, which is used to compensate for the MGC losses ΔP , as mentioned in Section III-A. In the current control scheme, Conv. 1 in Fig. 4 is responsible for V_{dc} regulation, since it is assumed closer to the main grid; however, similarly to the frequency control loop, it can be switched to Conv. 2. In the next section, the results of applying the MGC with these controls for a microgrid-grid interface, compared with a B2B interface under similar conditions, are presented.

Fig. 12. Change in P reference for dc link voltage regulation.

IV. RESULTS

The results of applying the discussed MGC controls to interface a microgrid with a distribution system are presented in this section, comparing these with the results for a B2B interface, under the following relevant operating conditions:

- Case 1: Grid-microgrid connection, disconnection, and changes in the interface power setpoints.
- Case 2: Gradual load changes of the microgrid.
- Case 3: Large load shedding in the microgrid.
- Case 4: Three-phase fault conditions at the end of a microgrid feeder.
- Case 5: Abrupt power changes due to a sudden loss of local generation in the microgrid.
- Case 6: Unbalanced loading of the microgrid.

The studies were conducted based on detailed time-domain simulations in PSCAD [31].

A. Test System

The test system shown in Fig. 13 is a 12.47 kV and 60 Hz ADN based on the North American CIGRE distribution system from [32], and comprises two main parts, namely, the main distribution system and a microgrid connected via MGC or B2B interfaces, as illustrated in Fig. 13. The main distribution system includes three switches to introduce loops and allow to test various DERs and new controllers under different configurations, in the context of smart grids. The total load of the main system is about 3 MW, distributed among the buses connected via feeders modeled as coupled-pi sections.

The microgrid is assumed to represent an industrial site or a residential complex. It includes two diesel generators as DERs, 4 nodes, and 5 impedance loads. The generators and governors are modeled using PSCAD's models, which represent the generator as a voltage source behind an $R_s + jX_s$ impedance modeled with classical mechanical speed dynamics, and a governor for frequency regulation modeled with a first order transfer function with droop, which suffices for the purpose of the simulations and tests presented here. The microgrid accommodates a total of about 2 MVA local demand, with the main parameters presented in Tables I to IV. Switches S1 and S2 can connect or disconnect the MGC/B2B interface between the microgrid and the main distribution system, with the B2B being modeled similarly as the MGC dc interface VSCs and controls. Switches S3 and S4 are used for the case studies regarding load and generation changes in the microgrid; in the other cases, these are assumed to be open.

B. Simulations

1) *Case 1:* The microgrid should be able to transition from grid connected to isolated and vice versa without significant

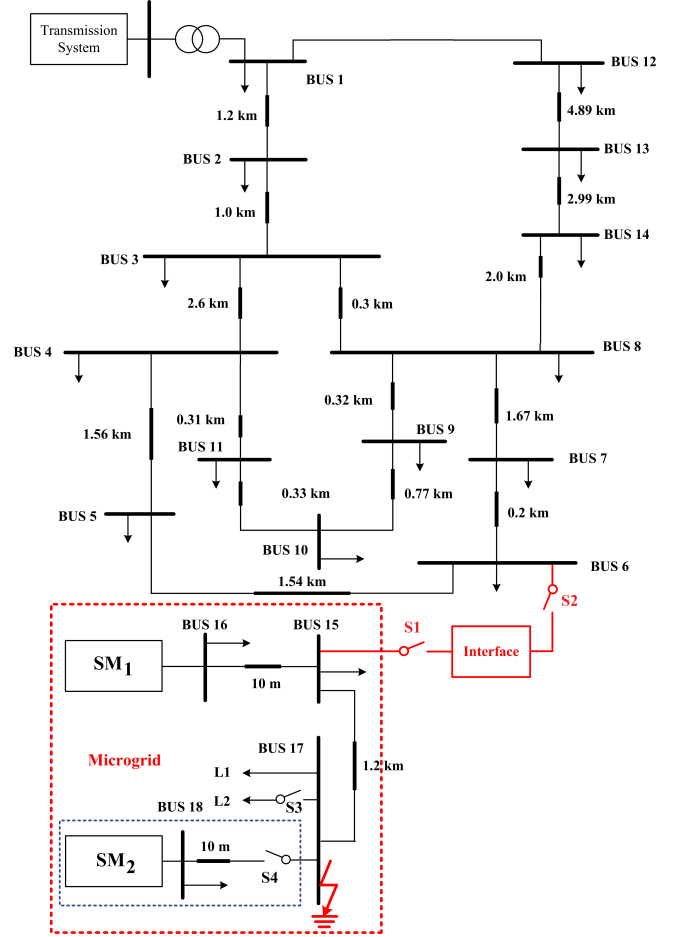


Fig. 13. Test system based on the North American CIGRE distribution benchmark system.

TABLE I
DER PARAMETERS

Parameter	SM_1	SM_2
S	4 MVA	1 MVA
V	12.47 kV	12.47 kV
f	60 Hz	60 Hz
R_s	0.02 pu	0.02 pu
X_s	0.005 pu	0.005 pu
Inertia	2 s	2 s
Gov. Droop	3.33%	2%
Gov. Time const.	0.2 s	0.1 s

TABLE II
MICROGRID LOAD

Node	P [kW]	Q [kvar]
15	10	10
16	300	300
17-L1	1085.4	685.9
17-L2	0–60	0–30
18	90	30

TABLE III
B2B CONVERTER/CONTROLLERS PARAMETERS

Parameter	Conv. 1	Conv. 2
R	0.1Ω	0.1Ω
L	40 mH	100 mH
C	10 μ F	10 μ F
PLL (K_p, K_i)	(50, 900)	(50, 900)
Active power controller (K_{p1}, K_{i1})	(5, 100)	(5, 100)
Reactive power controller (K_{p2}, K_{i2})	(5, 100)	(5, 100)
DC voltage controller (K_{p3}, K_{i3})	(10, 50)	-

TABLE IV
MGC CONVERTER/CONTROLLERS PARAMETERS

Parameter	Conv. 1	Conv. 2
R	0.1Ω	0.1Ω
L	40 mH	60 mH
C	10 μ F	10 μ F
PLL (K_p, K_i)	(50, 900)	(50, 900)
Active power controller (K_{p1}, K_{i1})	(5, 100)	(5, 100)
Reactive power controller (K_{p2}, K_{i2})	(5, 100)	(5, 100)
DC voltage controller (K_{p3}, K_{i3})	(10, 50)	-
Frequency controller (K_{p4}, K_{i4})	-	(5, 20)
Z_1, Z_2	10 $\Omega, 0.01 \Omega$	-

undesirable transients. Moreover, the transferred power between the two systems needs to be controlled precisely and flexibly based on the operators' dispatch signals. Therefore, the grid-microgrid connection, disconnection, and changes of power setpoints are studied in this section. The two systems operate separately in steady state before closing Switches S1 and S2 at 30 s. The setpoints of the active and reactive power injected into the microgrid are 0 MW and 0.8 Mvar (this is, approximately, the minimum reactive power needed for MGC stability). The dc-voltage level references for the MGC and B2B are 7 kV and 24 kV, respectively. To demonstrate the power control capabilities of the interface, the active power setpoint changes from 0 MW to 0.1 MW at 80 s. Finally, the switches S1 and S2 are opened to disconnect two systems at 160 s.

The simulation results of the connection are shown in Figs. 14 to 17. Note that the dc voltages shown in Fig. 14 are maintained at their desired values. Fig. 15 shows the microgrid frequency and the voltage of the microgrid connection terminal. Observe that the MGC offers a better frequency response with smaller deviations due to its additional frequency controller. Figs. 16 and 17 show the power of the microgrid interface and local generator, showing that the active and reactive power injected into the microgrid is controlled at the command values 0 MW and 0.8 Mvar, respectively.

The simulation results of the power setpoint change at 80 s are shown in Figs. 18 and 19, where the MGC shows a better frequency response due to the cooperation of the frequency regulators in Conv. 2 and the local generator. However, the active and reactive power needs a longer time to settle for the same reason.

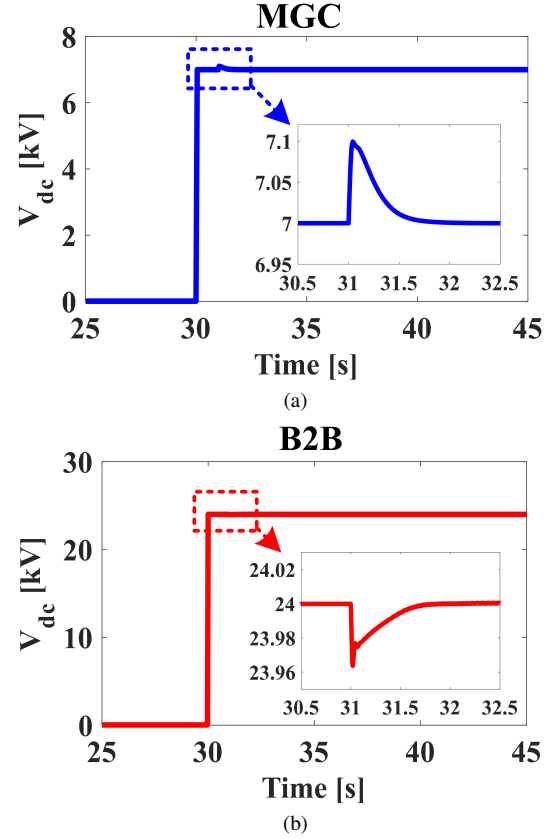


Fig. 14. (a) MGC and (b) B2B dc voltages at connection for Case 1.

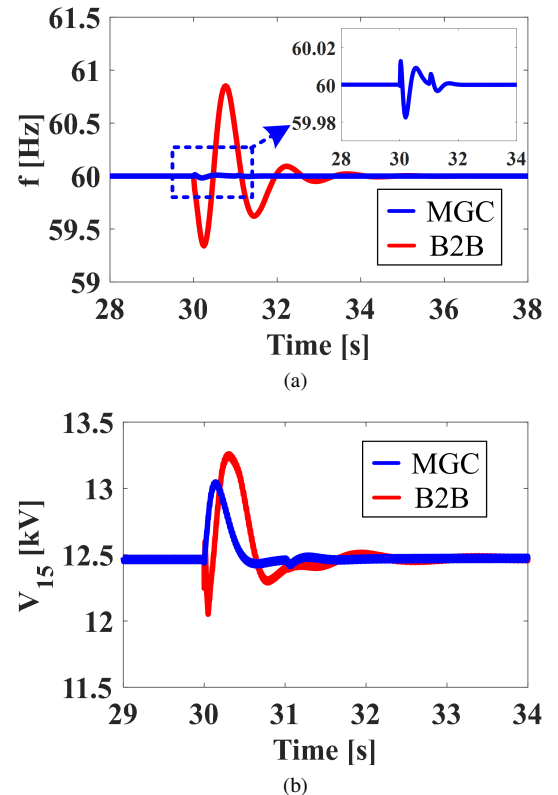
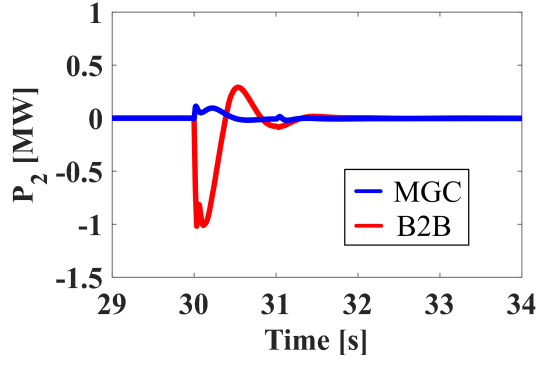
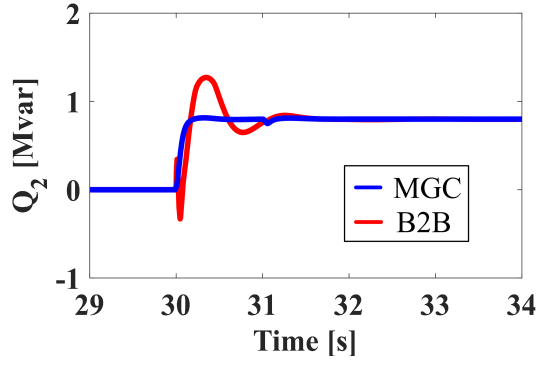


Fig. 15. Microgrid (a) frequency and (b) voltage at connection for Case 1.

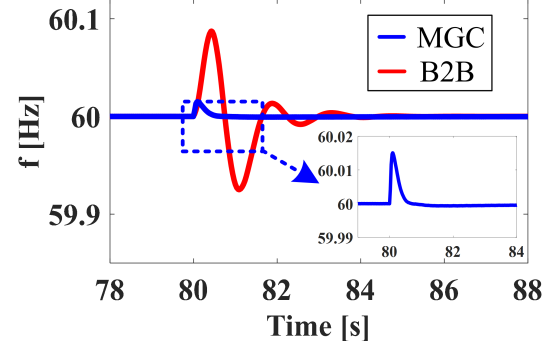


(a)

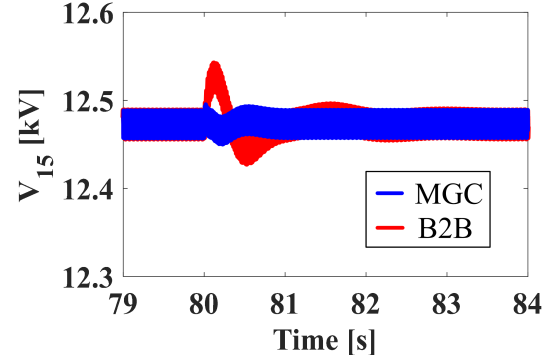


(b)

Fig. 16. (a) Active and (b) reactive power injected into the microgrid at connection for Case 1.

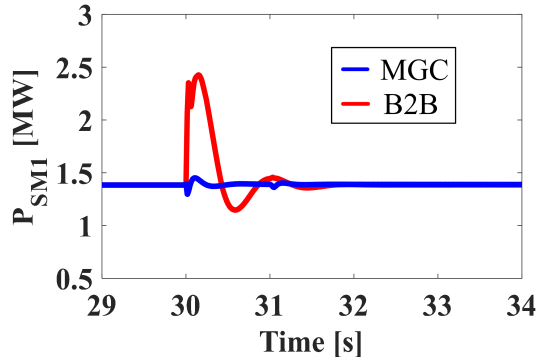


(a)

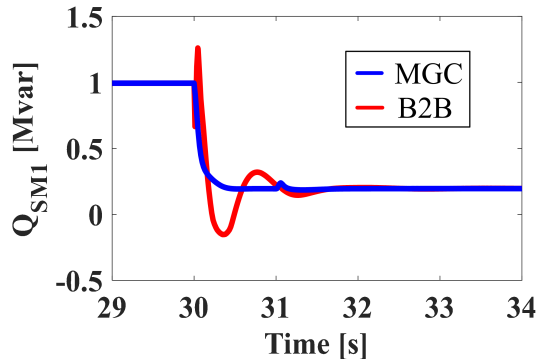


(b)

Fig. 18. Microgrid (a) frequency and (b) voltage at setpoint change for Case 1.

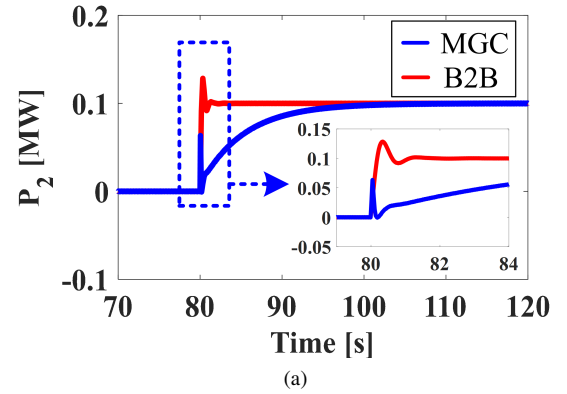


(a)

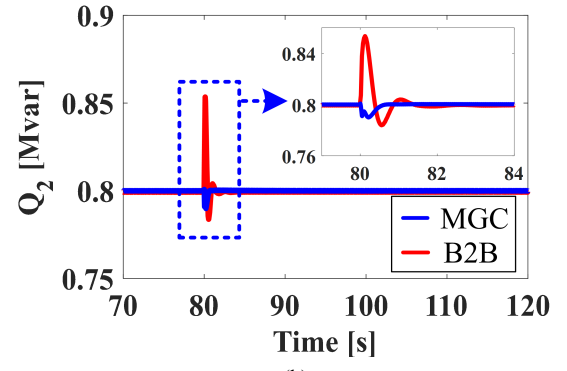


(b)

Fig. 17. (a) Active and (b) reactive power of the microgrid generator at connection for Case 1.

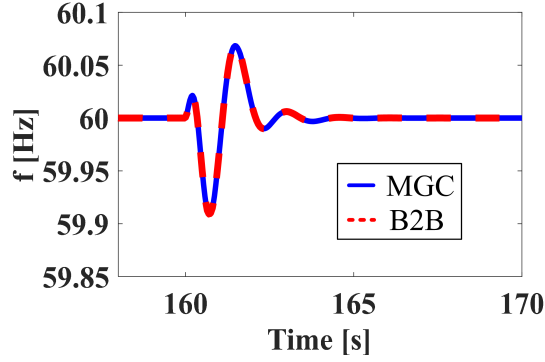


(a)

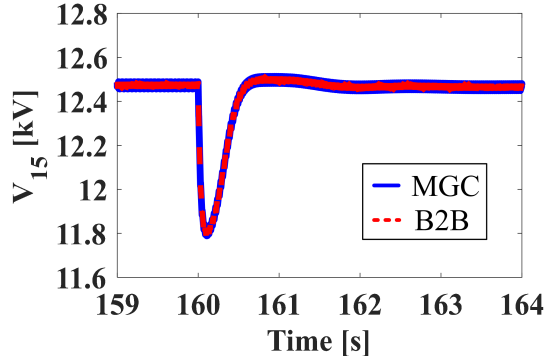


(b)

Fig. 19. (a) Active and (b) reactive power injected into the microgrid at setpoint change for Case 1.

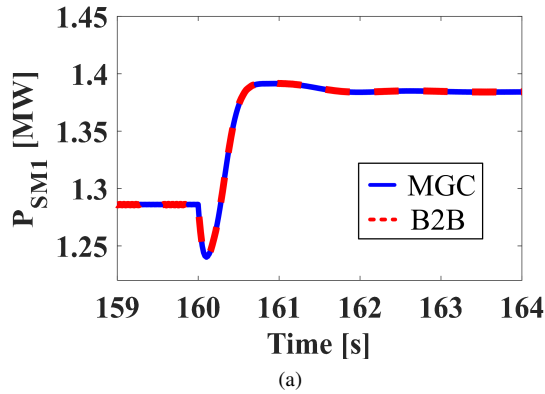


(a)

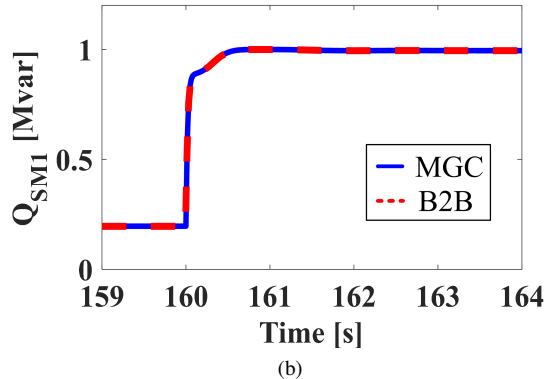


(b)

Fig. 20. Microgrid (a) frequency and (b) voltage at disconnection for Case 1.

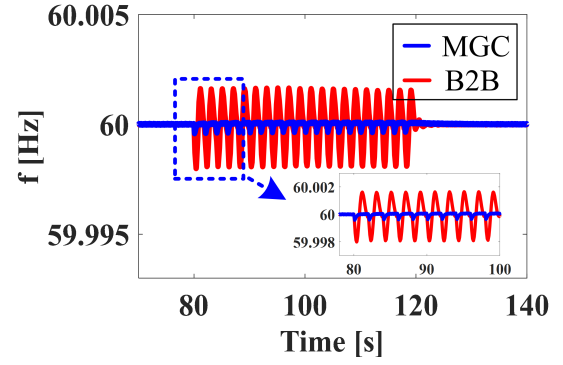


(a)

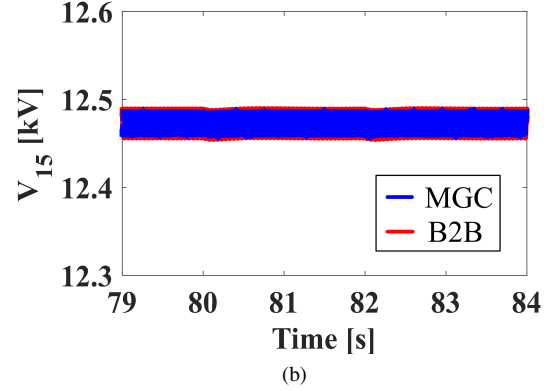


(b)

Fig. 21. (a) Active and (b) reactive power of the microgrid generator at disconnection for Case 1.



(a)



(b)

Fig. 22. Microgrid (a) frequency and (b) voltage for Case 2.

Figs. 20 and 21 show the simulation results of the interface disconnection at $t = 160$ s. Observe that the local generator picks up the flow that was being supplied by the utility system through the interface, isolating the microgrid. The responses of the microgrid with the B2B and MGC interfaces are identical, as both controllers respond quickly, with the system operating satisfactorily before and after disconnection.

2) *Case 2: Load Fluctuations* or changes in the microgrid are expected in practice. Thus, the microgrid interface coordinated with the local generator should be able to mitigate the impact of such events on the microgrid frequency and loads. To simulate these operating conditions, Switch S3 is closed at 80 s, and the load gradually increases from 0 to 60 kW and 30 kvar at a rate of 3 kW and 1.5 kvar every 2 s, respectively. The setpoints of dc-voltage, and active and reactive powers are identical to those of the previous study before 80 s.

Figs. 22 to 24 illustrate the simulation results for this case. Note that the ac voltages in the two types of interfaces experience a slight fluctuation. Compared with the B2B, the MGC covers first the power changes of the microgrid with its additional frequency controller, with the local generator then reacting to the frequency deviations slowly, thus relaxing the power requirements from the MGC. The load increase is eventually supplied by the local generator, and the power of the interface returns to its initial value. In this case, the MGC-based system shows a smaller frequency deviation than with the B2B, more significant active power fluctuations, and longer time for the active power to regain its initial value.

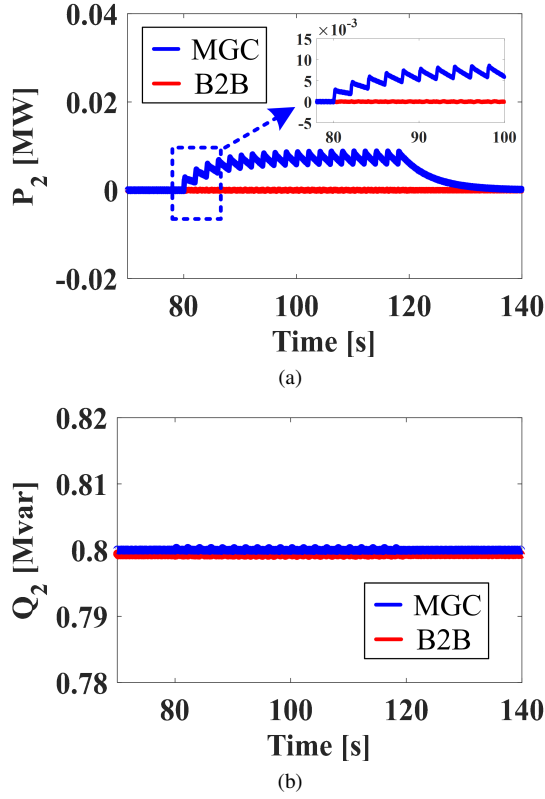


Fig. 23. (a) Active and (b) reactive power injected into the microgrid for Case 2.

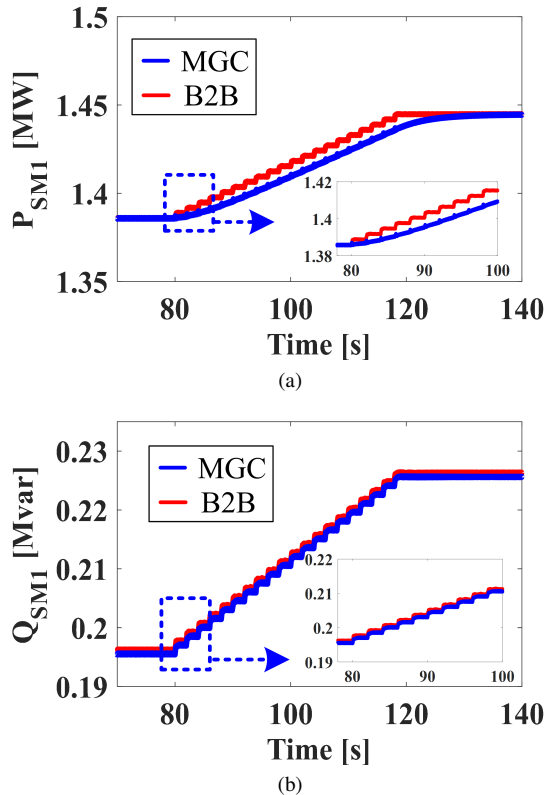


Fig. 24. (a) Active and (b) reactive power of the microgrid generator for Case 2.

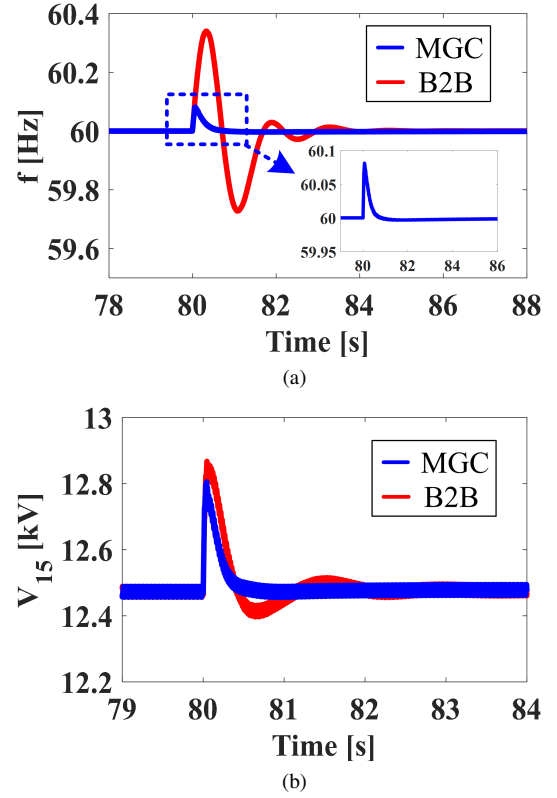


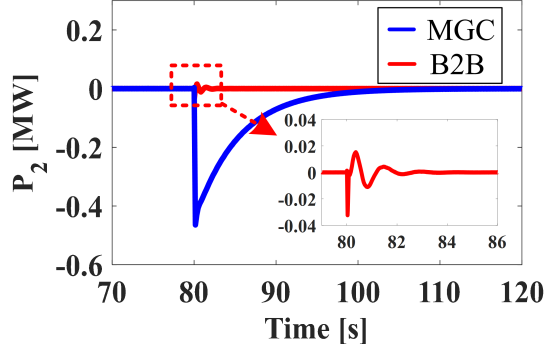
Fig. 25. Microgrid (a) frequency and (b) voltage for Case 3.

3) *Case 3*: Significant load shedding is studied in this section, which severely affects the system frequency response. To simulate this operating condition, the load at Bus 17 is abruptly decreased by 495.3 kW and 325.9 kvar, which is more than one-third of the total load. The setpoints of dc-voltage, and active and reactive powers are identical to those of the previous study before 80 s.

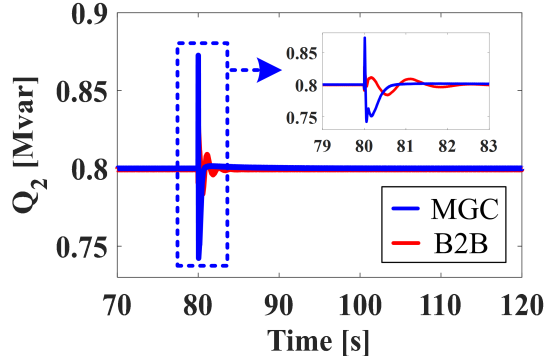
Figs. 25 to 27 illustrate the simulation results for this case. Observe that the MGC interface offers a better frequency response but more significant power fluctuations and longer adjustment time due to the cooperation of the two frequency regulators. The local generator eventually covers all of the load changes.

4) *Case 4*: The performance of controllers under fault conditions is studied here; thus, a three-phase resistive fault at Bus 17 at the end of the microgrid feeder is simulated in this case. The fault occurs at 80 s and clears after 3 cycles (50 ms). The setpoints of the interfaces are identical to those of the previous study before 80 s. In this case, the interface controllers respond to the event, as shown Figs. 28 and 29. Observe that the controllers perform similarly, with the MGC showing better response due to its frequency and voltage control capabilities, which are required for the interface to properly operate with a synchronous connection.

5) *Case 5*: An abrupt loss of local generation capacity is considered here, which directly impacts the system frequency and loads. To simulate this loss, Switch S4 is assumed to be closed at the start, thus connecting the second synchronous machine to the system, and the setpoints for the interfaces are

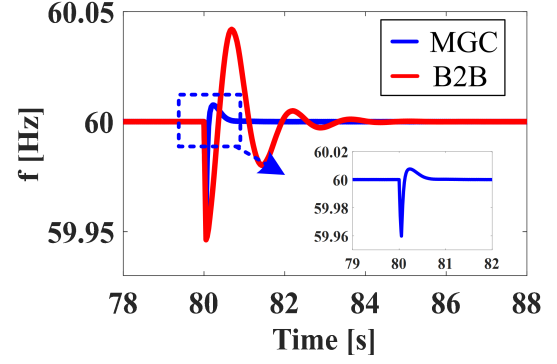


(a)

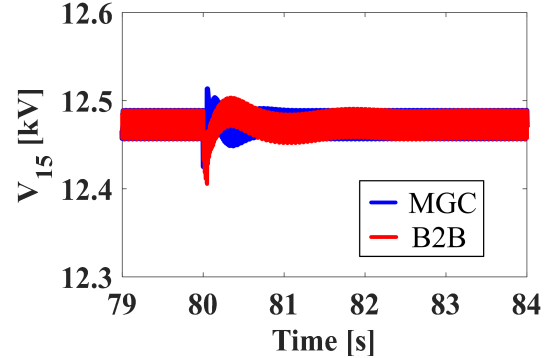


(b)

Fig. 26. (a) Active and (b) reactive power injected into the microgrid for Case 3.

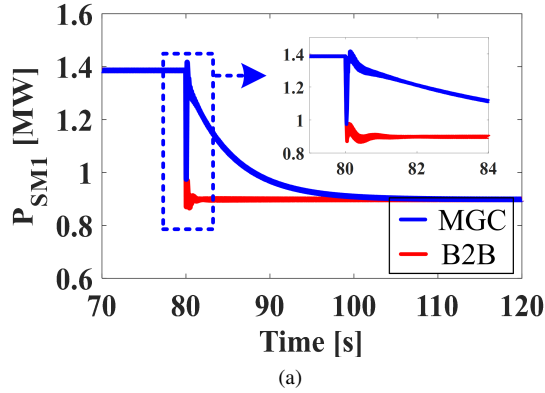


(a)

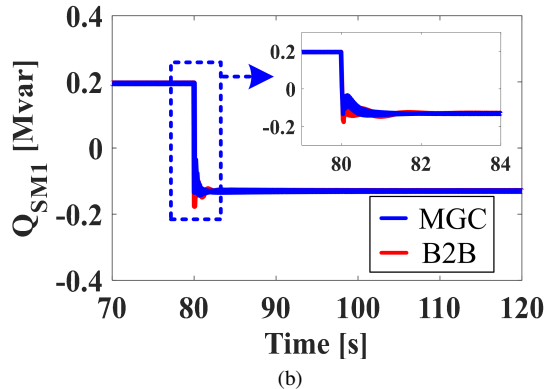


(b)

Fig. 28. Microgrid (a) frequency and (b) voltage for Case 4.

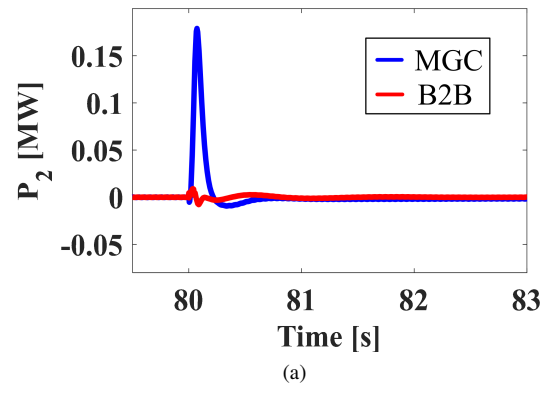


(a)

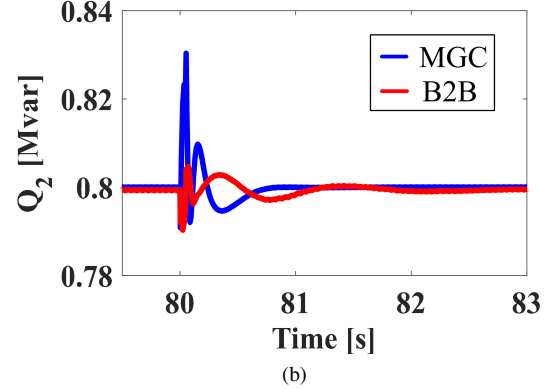


(b)

Fig. 27. (a) Active and (b) reactive power of the microgrid generator for Case 3.



(a)



(b)

Fig. 29. (a) Active and (b) reactive power injected into the microgrid for Case 4.

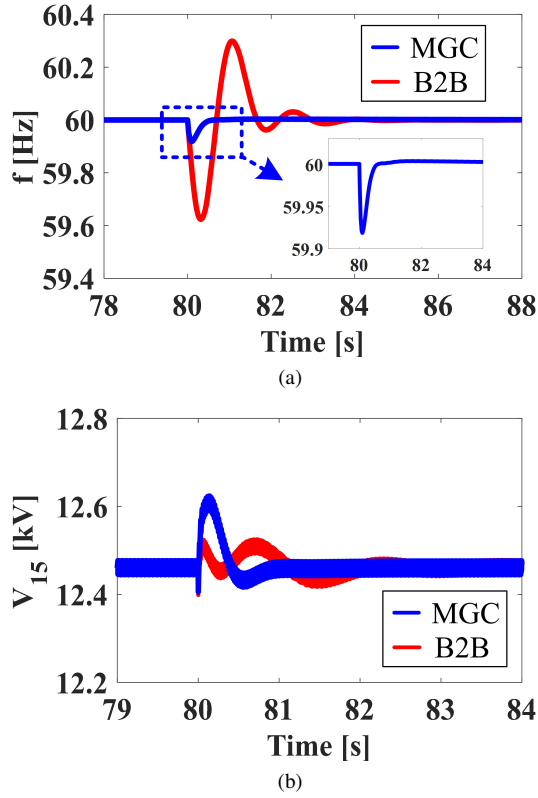


Fig. 30. Microgrid (a) frequency and (b) voltage for Case 5.

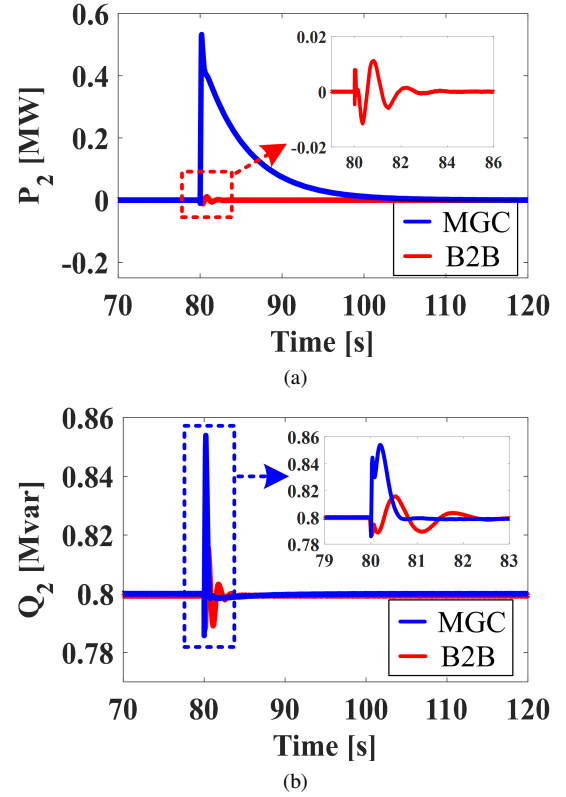


Fig. 31. (a) Active and (b) reactive power injected into the microgrid for Case 5.

assumed identical to the previous case before 80 s. The switch then opens at 80 s, abruptly reducing the local generation by 510 kW. As shown in Figs. 30 to 32, the microgrid interface controllers respond immediately, compensating the lost generator from the main grid, to give time to the other generator to bring the frequency back to its nominal value. Note that with both controllers the frequency recovers quickly to its nominal value, but the MGC performs slightly better due to better coordination with the DER and faster controls.

6) *Case 6:* The operation of the interfaces under unbalanced loading conditions in the microgrid is studied in this case, which is particularly relevant for microgrid operation. To simulate this scenario, some of the loads in the microgrid are made significantly unbalanced; thus, the 300 kW + 300 kvar balanced load connected at Bus 16 is changed to three different single-phase loads of 50 kW + 50 kvar for phase *a*, 100 kW + 100 kvar for phase *b*, and 150 kW + 150 kvar for phase *c*. Similarly, the 1085 kW + 686 kvar balanced load connected at Bus 17 is changed to 181 kW + 114 kvar for phase *a*, 362 kW + 229 kvar for phase *b*, and 543 kW + 343 kvar for phase *c*. The connection case in Section IV-B1 is studied again here for the same interface set points. As shown in Figs. Fig. 33 and 34, the performance of the controllers is nearly the same as the results for Case 1, with only minor double-frequency components occurring in the dc voltage and the transferred active and reactive power due to the negative-sequence components that appear during unbalance operation.

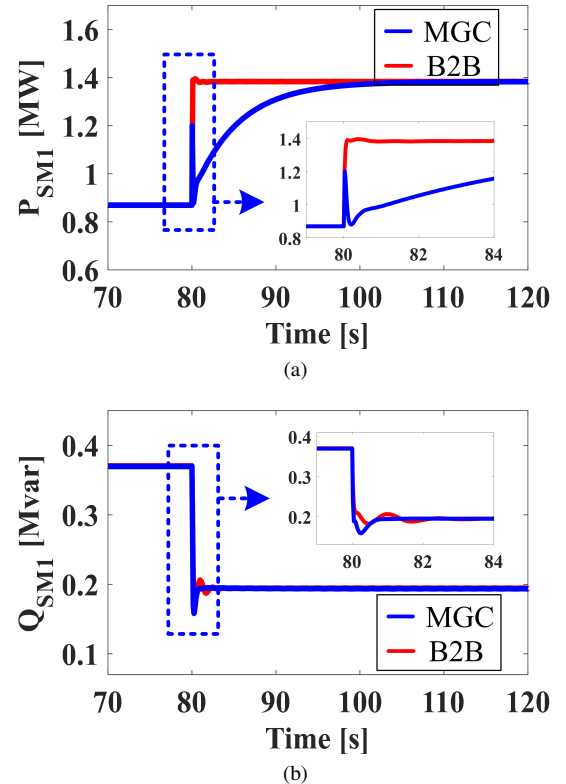
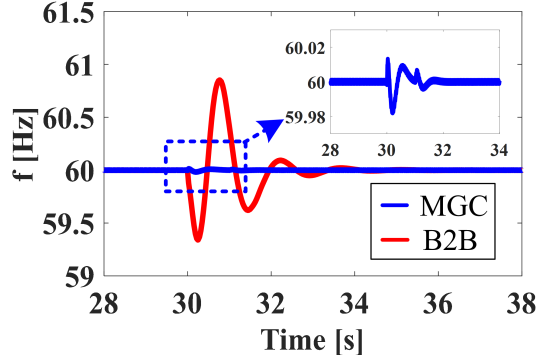
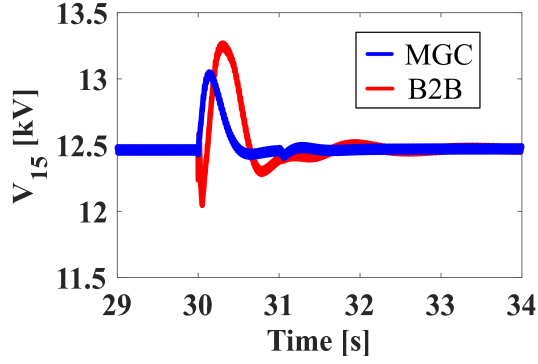


Fig. 32. (a) Active and (b) reactive power of the first microgrid generator for Case 5.

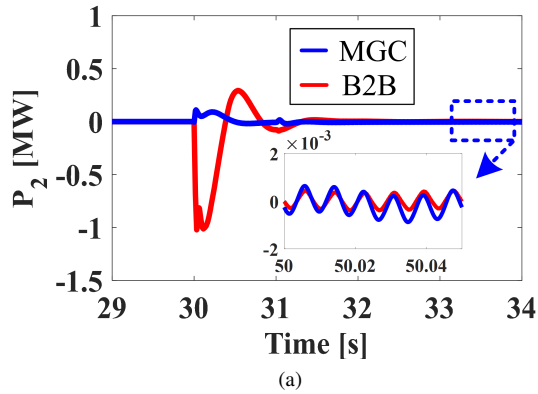


(a)

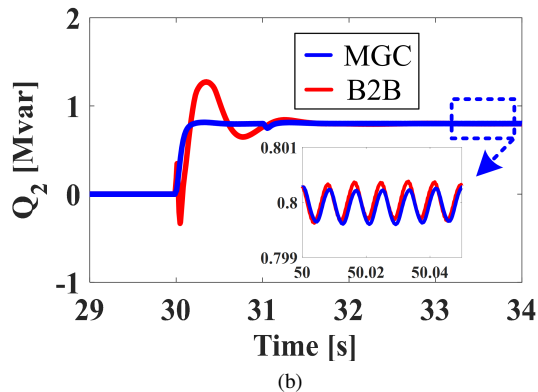


(b)

Fig. 33. Microgrid (a) frequency and (b) voltage for Case 6.

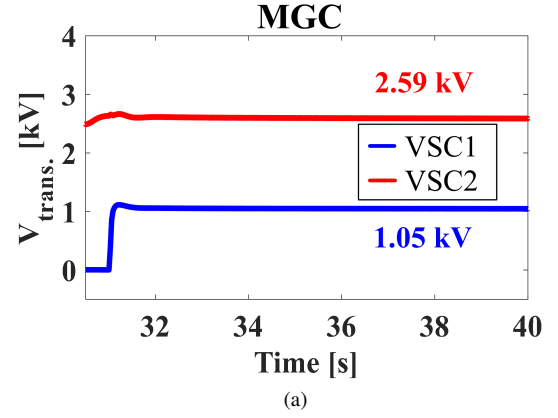


(a)

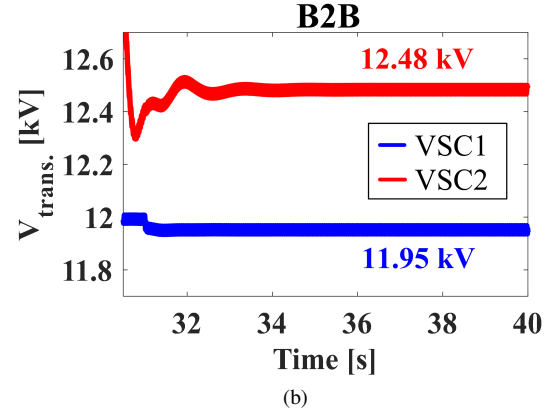


(b)

Fig. 34. (a) Active and (b) reactive power injected into the microgrid for Case 6.



(a)



(b)

Fig. 35. Voltage on the secondary sides of the converters transformers for (a) MGC and (b) B2B at connection for Case 1.

C. Economic Comparison

The voltage ratings of the two VSCs and the dc link in the MGC and B2B are compared here to analyze minimum hardware requirements that could directly affect the installation costs and logistics. The setpoints for active and reactive power are assumed to be 0 MW and 0.8 MVAR, respectively, as in Section IV-B1. Note that the dc voltage levels of the dc links for the MGC and B2B are significantly different, i.e., 7 kV and 24 kV, respectively. Fig. 35 shows the voltages on the secondary sides of the converter transformers for both interfaces. Observe that the voltage levels for the MGC (1.05 kV and 2.59 kV) are much lower than those for the B2B (11.95 kV and 12.48 kV), whereas that the current ratings of MGC and B2B are identical; thus, the ratio of their ratings are approximately the ratio of their converter voltage ratings, which in this case is about 20%. Similar argument can be made for the capacitor dc voltage. Therefore, for a given \$/kVA price for the converters, the MGC's smaller ratings would result in reduced hardware costs by about 80%.

The final installation costs including construction costs of the buildings housing the equipment are roughly double of the hardware costs [33] which again results in reduced costs for the MGC, given its smaller size and footprint. Finally, the smaller size and voltage ratings of the MGC simplify the installation and operational logistics including component delivery etc. resulting again in further cost reduction.

V. CONCLUSIONS

An economic synchronous microgrid-grid MGC interface has been proposed, designed, modeled, and analyzed in this paper. The architecture of the MGC provides two paths for power flow between its terminals, namely, ac and dc Links. It also offers frequency control in addition to voltage/flow control, to eliminate frequency deviations as a commonplace problem in microgrid connection applications. This architecture allows reducing the converter size of the interface and of the dc link, resulting in voltage ratings of a fraction of the system line voltage.

A test system based on the North American CIGRE distribution system was used to study the controller under several relevant conditions, i.e. microgrid-grid connection, disconnection, changes to the transferred power, gradual load increases in the microgrid, large load shedding on the microgrid side, three-phase fault conditions, abrupt partial loss of local generation, and unbalanced loading conditions in the microgrid. The performance of the proposed MGC controller was compared with a typical B2B controller interface, showing that it delivers similar performance compared to the B2B, proving its technical viability. Finally a brief economic analysis based on the controller power and voltage ratings was presented, showing that the presented MGC is a much cheaper alternative for connection of microgrids to power networks than a B2B interface, while delivering similar performance.

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