

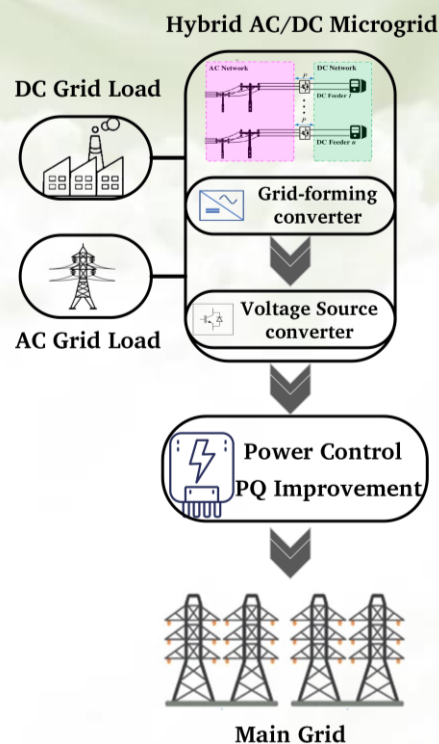
Control and Improvement of Power Quality in Hybrid Three-Terminal AC/DC Microgrids

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Highlight

- ❖ Presenting a synchronized power control technique for power sharing between power electronic converters
- ❖ Presenting a distributed cooperative control method for voltage and frequency control in AC MGs
- ❖ Providing voltage and current control in a DC MG for hybrid AC/DC MGs
- ❖ Performing both power control and power quality improvement of the AC/DC MG system

Graphical Abstract



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Citation

M. Shiravand, and A. Nakabandi, "Control and Improvement of Power Quality in Hybrid Three-Terminal AC/DC Microgrids," *Journal of Green Energy Research and Innovation*, vol. 1, no. 2, pp. 31-45, 2024.

 <https://doi.org/10.61186/jgeri.1.2.31>





Control and Improvement of Power Quality in Hybrid Three-Terminal AC/DC Microgrids

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ARTICLE INFO

Keywords:

Renewable energy sources,
Power control,
Hybrid AC/DC microgrid,
Power quality.

Article history:

Received: 27 January 2024;
Revised: 27 February 2024;
Accepted: 02 March 2024;

Article type:

Research Article

ABSTRACT

Nowadays, the use of renewable energy sources has gained more attention due to their lower pollution and cost compared to traditional fossil fuel generators. Microgrid (MG) structures are used for better management of these resources. This article focuses on power control in three-terminal AC/DC hybrid MGs. For this purpose, a network backup converter is used to improve power sharing and reduce power quality disturbances. The components of the MG include distributed generation units, AC loads, DC loads, energy storage system (battery), and parallel connecting converters. In the studied topology of AC/DC hybrid MG in this article, there are two main converters: a grid-forming converter that acts as an intermediary converter and is used to control the MG voltage, and a VSC converter that is located between the DC link (including the DC MG and battery) and the AC MG. In this article, a control system is implemented for a hybrid MG and simulations are performed in MATLAB software for four different scenarios related to active and reactive power of the MG and loads. Simulation results show that the energy management system and power control in the AC/DC hybrid MG have reduced harmonics and improved system reliability in the MG.

1. Introduction

The utilization of distributed generation (DG), frequently employing renewable energies, is experiencing a significant surge in recent years, mostly driven by growing environmental and economic concerns. The introduction of the MG concept aims to maximize the utilization of DGs and address the issues arising from their integration into power systems. At first, MGs were classified into two categories: AC MG and DC MG. Each of these structures possesses distinct benefits and drawbacks. In AC MGs, AC sources like wind turbines can be directly linked to the MG [1]. However, it is more cost-effective and energy-efficient to link most renewable energy sources, such as photovoltaic (PV) sources and electrical energy storage sources, to the DC MG due to their DC output voltage. Furthermore, with DC MGs, concerns of frequency management and reactive power

control have been eradicated. To leverage the benefits of both forms of MGs, hybrid AC-DC MGs were established. These MGs allow for the simultaneous utilization of the advantages offered by both types. The use of hybrid AC-DC MGs is experiencing a remarkable growth in the present day due to their numerous advantages over other types of MGs [2]. The hybrid AC-DC MG involves the interconnection of AC and DC MGs through bidirectional AC/DC converters, also known as interface converters. Hence, the primary converter holds significant importance in hybrid AC-DC MGs. The primary function of this converter is to facilitate the exchange of power between AC and DC MGs in both directions. Additionally, it is responsible for stabilizing the voltage in the DC MG and controlling the voltage and frequency in the AC MG to maintain them close to their desired values. In conventional configurations, AC MGs are directly linked to the AC grid transformer, while DC MGs are connected to AC MGs via one or more parallel inverters [3]. The prevailing configuration of the interface converter is the three-phase, two-level, common inverter. In this structure, several converters are usually used in parallel to improve control capability, increase power transfer capacity, and enhance reliability. In these conditions, the issues of circulating current and power sharing among parallel converters arise, leading to reduced stability, decreased power transfer capacity, and increased energy losses [4]. Alternative configurations for interface converters exist; but, the majority of these configurations exhibit significant drawbacks, as outlined in [5] and described below. AC MGs are directly connected to the AC grid and voltage and frequency fluctuations in the grid affect the power quality of the AC MG. In addition, harmonics generated by nonlinear loads in the AC MG are injected directly into the main grid [6]. The growing trend of consolidating DGs in MGs [7], along with the rising need for medium-voltage and low-voltage DC MGs, has led to increased focus on hybrid multi-terminal MGs. The aim of this paper is to propose a structure for hybrid AC-DC MGs that can isolate MGs from the main grid, provide complete power control between MGs and the main grid, prevent harmful harmonics from being injected into the main grid, increase control flexibility between MGs and the main grid, and enable operation in both grid-connected and islanded modes. Furthermore, a well-suited control configuration is devised for the new MG to guarantee its stable functioning in diverse settings [8]. A back-to-back converter is employed in [9] to regulate the power exchange among many interconnected AC-DC MGs. A back-to-back converter is a configuration where the DC sections of two inverters are interconnected. The same research employs hierarchical distributed coordinated control to regulate both AC and DC MGs. Additionally, a proposed internal control approach is offered for the utilization of back-to-back converters and power sharing among MGs. The suggested control mechanism is specifically developed to enhance the power quality in MGs. Telecommunication lines are incorporated to establish connections between MGs in this context. The benefits of this effort include the consistent online availability of these links, while the drawbacks encompass the potential for delays and disruptions. The solution in [10] aims to minimize power conversion steps and deliver DC energy at various voltage levels. It introduces a four-terminal configuration for hybrid AC-DC MGs. The proposed structure includes a modular multilevel converter as the main intermediate

converter between the medium-voltage AC terminal and the medium-voltage DC terminal, and a DAB (Dual-Active Bridge) between the low-voltage DC terminals. The advantages of this work include improved energy control and reduced switches. However, a drawback is the omission of any discussion on the AC MG. In reference [11], an integrated and switchable design for hybrid AC-DC MG and a hierarchical control method is suggested for it. A new structure for interface converter is presented, which is called smart connection unit, and it can provide multiple AC/DC connection. In the following, a hierarchical control structure is designed for the smart connection unit. In [12], a simpler and more flexible structure for hybrid MGs is proposed, which includes an interface converter with several output ports. By using this structure, the number of power converters required in hybrid MGs with different DC voltage levels is reduced, and at the same time, the control flexibility of the MG does not decrease. Reference [13] discusses the improvement of power quality in hybrid AC/DC MG. In this article, by using the control of the converter between the two AC and DC sides, in addition to the power transfer between the two MGs, the harmonics due to the nonlinear load on the AC side are also reduced. In fact, the DC converter and MG act as filters, which improves power quality by removing nonlinear load harmonics. In reference [14], the hierarchical control structure, including internal, primary and secondary control levels, is introduced for hybrid MG control. The internal control is used to adjust the output voltage of the inverter. The primary control is based on the droop control. The secondary control compensates the voltage difference of the MG which is caused by the primary control so that the voltage between the MG and the main grid are completely synchronous and consistent. The MG can work well with the same control schematic that is proposed in two grid-connected and islanded modes. In reference [15], a modified structure is presented for interface converter of the hybrid AC-DC MG. In the proposed structure, energy storage is used in the interface converter. Also, in this article, an energy management strategy is presented that improves the quality of MG power. The interface converter suggested in this work includes two parallel three phase inverters, one of which is connected to the AC grid through a transformer and directly to the DC grid. The second inverter is directly connected to the AC grid, but its DC side is connected to a storage device and is linked to the DC grid via a bridge converter. Reference [16] discusses the establishment and management of a hybrid MG in the context of fluctuating renewables. The decentralized control of converters enables the independent operation and coordination of all renewable sources without the need for communication between them. The suggested control allows it to function as an active power filter besides its power sharing operation. A harmonic compensation approach suitable for hybrid AC-DC ILCs operating at lower switching frequency is being planned [17]. The text covers the proposed approach, methods for modeling, study of stability, and a comprehensive design of virtual impedance. A unique control technique is introduced in [18] to enhance the power quality of renewables, including PV, wind turbine (WT), fuel cell (FC), and battery. The primary objective is to improve power quality by considering variations in both active and reactive power. Literature [19] suggest a transformation method that combines AC and DC MGs and electric car operation. This technique aims to

improve power quality and power reliability operation. The objective of [20] is to analyze the harmonic characteristics of hybrid MGs. In order to attain the intended objective, a customized active power filter and a power filter compensator kit modules have been employed to enhance the harmonics of the AC component of the system. In accordance with reference [21], a solitary MG is constructed utilizing PVs, WTs, and FCs as distributed energy resources. An investigation has been conducted on a controller in this MG to ensure that power quality issues are kept within the specified standard range. The controller's performance is evaluated by comparing it to PID and fuzzy-PID controllers.

2. The structure of the hybrid AC/DC MG and converters

The present study examines a hybrid AC/DC MG configuration that includes DGs, electrical loads, energy storage, and the main grid. Figure 1 depicts the arrangement of the hybrid AC/DC MG, including all the mentioned components.

As can be seen, in one side of the MG, DC sources and DC loads are placed, while AC sources and AC loads are located on the other side. Furthermore, the part on AC loads includes the modeling of nonlinear and harmonic loads. The main grid is interconnected with the MG, and the system also incorporates electric energy storage. The benefit of this configuration lies in the isolation of vulnerable AC MG loads in the grid-connected mode. This research examines a hybrid AC/DC microgrid topology where DGs utilize grid-fed converters functioning as maximum power point tracking (MPPT)-controlled current sources. The grid forming converter is an interlinking converter (ILC), which is used for regulating the voltage of the MG. Two network backup converters are used to enhance power sharing and minimize power quality disruptions. The ILC model is represented in the dq reference frame and is characterized as follows.

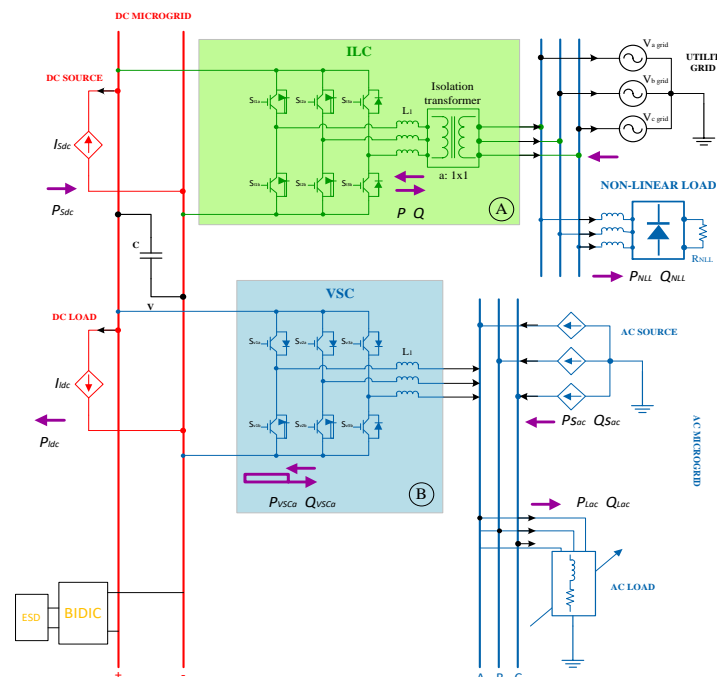


Figure 1. Structure of the hybrid MG under study.

A. ILC interface converter: The converter depicted in Figure 1 is a VSC that is linked to the main grid and a harmonic nonlinear load via a series inductor. The DC-link voltage is controlled, enabling the interconnection of DC sources and loads. Thus, the responsibility for power control between AC and DC MGs lies with ILC [15]. The ILC model is defined in the dq reference frame and is represented by Equations (1)-(2).

$$\begin{cases} L_i \frac{d}{dt} i_{id} = v_{id} - R_i i_{id} + L_i \omega_i i_{iq} - v_{sd} \\ L_i \frac{d}{dt} i_{iq} = v_{iq} - R_i i_{iq} + L_i \omega_i i_{id} - v_{sq} \end{cases} \quad (1)$$

$$\frac{C_{DCMG}}{2} \frac{dV_{DC}^2}{dt} = P_{ilcin} - P_{losses} - P_{ilcout} \quad (2)$$

where i_{id} and i_{iq} are d- and q-axes currents of the converter, and v_{id} and v_{iq} are voltages of the d- and q-axes. L_i and R_i are inductance and resistance of the filter L . Also, ω_i is the angular frequency of the ICL, and v_{sd} and v_{sq} are voltages of the d- and q-axes. C_{DCMG} represents the DC-link capacitor, V_{DC} is voltage of the DC link, P_{ilcin} and P_{ilcout} are the input and output power of the converter, and P_{losses} expresses the power loss in the converter. By applying the Laplace transform to Equations (1)-(2), and by considering only state variables, Equations (3)-(4) are established:

$$G_{cile}(s) = \frac{I_{id}}{m_{id}} = \frac{I_{iq}}{m_{iq}} = \frac{1}{L_i s + R_i} \quad (3)$$

$$G_{vile}(s) = \frac{V_{dc}^2}{P_{REF_{ile}}} = \frac{2}{C_{DCMG} s_i} \quad (4)$$

m_{id} and m_{iq} are modulation indices of the ILC in the dq reference frame, and P_{refile} is the reference power of the ICL.

B. VSC: Figure 1 illustrates the placement of this converter, which is positioned between the DC link (comprising the DC MG and battery) and the AC MG. The VSC modeling shares similarities with ILC, as both include VSCs equipped with L-filters [15].

3. Control block of the ILC converter

The ILC facilitates the two-way flow of electrical current between a DC MG and an AC grid. The ILC is driven by two control loops. The internal loop controls the electric current flowing through the L filter, whilst the external loop has control on the voltage across the DC-link capacitors. Figure 2 depicts the control design for the ILC. Part A in Figure 2 illustrates the Park transform alongside the use of a PLL to synchronize the ILC with the grid. To do this, the Park transform utilizes the three-phase voltages and currents obtained from the point of common connection (PCC) as its input. However, it is crucial that the synchronous angle created by the synchronous reference frame phase-locked loop (SRF-PLL) is also provided.

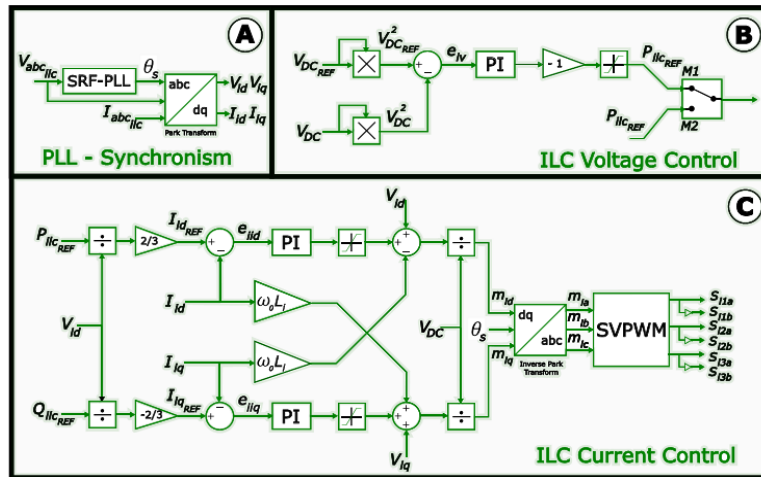


Figure 2. Control block of the ILC.

The voltage controller, seen in detail B of Figure 2, calculates the discrepancy between the squared reference voltage and the measured voltage in the DC link. This discrepancy is then utilized as the input for the proportional-integral (PI) controller. During operation in M₁ mode, the reference voltage loop is responsible for generating the reference power for the current loop. However, in M₂ mode, the reference power is obtained directly without any voltage control. The reference current for the dq axis is produced based on the relationships between the reference active and reactive power as given in Equations (5)-(6):

$$I_{dREF} = \frac{2}{3} \frac{P_{REF}}{V_d} \quad (5)$$

$$I_{qREF} = -\frac{2}{3} \frac{Q_{REF}}{V_d} \quad (6)$$

I_{dREF} and I_{qREF} represent the reference dq currents, while P_{REF} and Q_{REF} represent the reference active and reactive power, respectively. The formulae are same for both ILC and VSC converters. The current controller for the ILC is depicted in part C of Figure 2. The reference currents in the dq frame are determined by using the calculated reference active and reactive powers. The modulation indices are then generated through the use of PI controllers. Subsequently, the modulation indices in the dq reference frame yield the modulation indices in the abc frame, which serve as the inputs for the SVPWM and generate the ILC switching pulses. The primary objective of the ILC control strategy is to compensate the reactive power of the grid and share the active power using the droop control technique.

4. Control block of the VSC

The VSC is a power converter that links the AC MG to the energy storage device (ESD) and the DC MG, thus acting as a grid backup unit. VSC directly controls the voltage and frequency of the AC MG. Figure 3 shows the block diagram of the control section of the VSC converter.

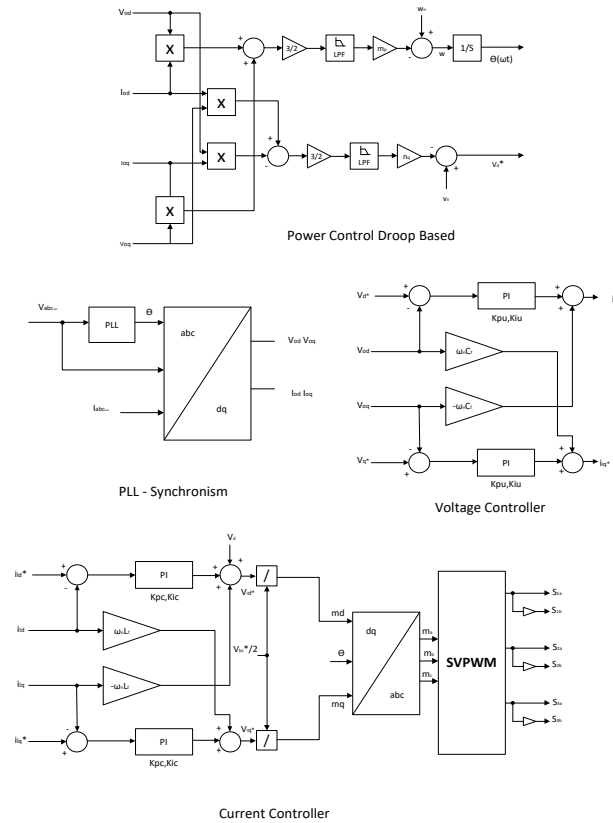


Figure 3. Control block of the VSC.

According to [Figure 3](#), this converter, which is of grid-forming type, is used to regulate voltage and frequency to meet the voltage and frequency distribution requirements. W is obtained using the equation $W=W_n-M_p(P_{avr}-P_n)$, and the reference voltage is obtained using the equation $V=V_n-N_q(Q_{avr}-Q_n)$. To make the output voltage follow the reference value, first, the reference current must be obtained in the voltage control block. After obtaining the reference voltage, it is fed into the current control block, and the reference output voltage is obtained, and then switching is performed.

5. Simulation results

In this section, the structure presented in [Figure 1](#) is implemented in MATLAB software, which includes AC and DC loads, AC and DC sources, an electrical energy storage device, and intermediate converters. The simulation system parameters in this study are listed in [Table 1](#).

To examine the simulation results of the proposed AC/DC hybrid MG, scenarios presented in [Table 2](#) are applied to the system. In [Table 2](#) the P_{ACMG} is power of AC microgrid and P_{DCMG} is power of DC microgrid that each one can have positive value or negative value. If P_{ACMG} is positive value, the AC microgrid will deliver active power to grid and if the P_{ACMG} is negative, the AC microgrid will consume active power. Also, there will be similar condition for DC microgrid. [Figure 4](#) illustrates the power curves of the AC MG, DC MG, grid, and storage for different scenarios.

During the time interval $t=0$ to $t=1$ s, the entire power of the grid is transmitted to the AC MG through the VSC associated with the AC MG. Here, the AC MG has a power consumption of -2 kW. Approximately 10% of the power is derived from the battery, while the other portion is supplied from the AC grid. The goal of droop control is to modify these ratios by either decreasing or increasing the droop control coefficient. DC and AC MGs rapidly produce electricity within a timeframe of 1 to 2 s and supply it to the main grid.

Table 1. Simulation parameters.

| Parameter | Value |
|---------------------------------|-------|
| Parameters of converters | |
| C_{DCMG} (μF) | 2250 |
| C_{BESS} (μF) | 1125 |
| L_i (mH) | 5 |
| L_v (mH) | 10 |
| L_b (mH) | 10 |
| R_{int} (Ω) | 0.1 |
| Rated values | |
| f_n (Hz) | 50 |
| $V_{dc_{ref}}$ (V) | 900 |
| $V_{n_{rms}}$ (V) | 220 |
| P_n (W) | 4500 |
| ESD | |
| E_{ob} (V) | 3.366 |
| R_{bat} (Ω) | 0.01 |
| SOC_0 | 0.5 |

Table 2. Performance conditions of sources and loads at different times.

| Scenario | 1 | 2 | 3 | 4 |
|-------------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|
| Time duration (s) | 1-2 | 2-3 | 3-4 | 4-5 |
| Conditions | $P_{ACMG} > 0$ $P_{DCMG} > 0$ | $P_{ACMG} > 0$ $P_{DCMG} < 0$ | $P_{ACMG} < 0$ $P_{DCMG} < 0$ | $P_{ACMG} < 0$ $P_{DCMG} > 0$ |

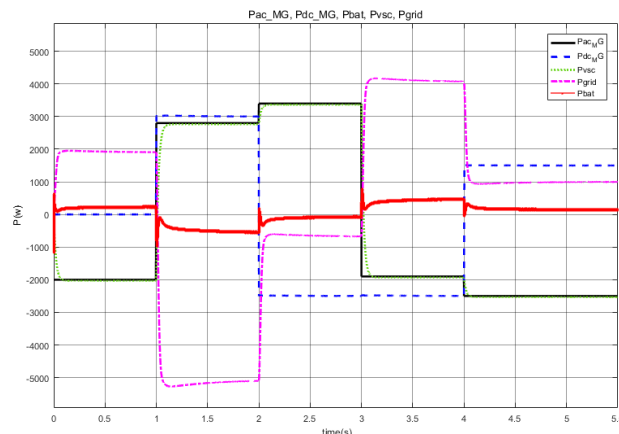


Figure 4. Active power curves of AC and DC MGs, the grid, and the storage.

In this case, excess power is stored in the storage. The AC MG transfers power to both the main grid and the DC MG within a time $t=2\text{s}$ to $t=3\text{s}$ using the VSC. In fact, in this case, the DC MG also has a power shortage. From $t=3\text{s}$ to $t=4\text{s}$, both DC and AC MGs have a power shortage, and this power is compensated through the main grid. It should be noted that some of this power is supplied by discharging the battery. During $t=4\text{s}$ to $t=5\text{s}$, the AC MG has a power shortage that is compensated through the main grid and the DC MG. In this case, the battery is in discharge mode.

To examine the performance of converters in this situation, it is necessary to study the system's reactive power curve. Figure 5 shows the reactive power curve of the main grid, VSC converter related to the AC MG, and ILC intermediate converter.

The presence of fixed capacitors in the grid results in a constant reactive power curve of 4500 Var. However, the reactive power curve of the ILC is zero, indicating that no reactive power is transferred through this converter. It means that just VSC is capable of grid transferring reactive power in various scenarios, depending on the MG's reactive power demand and the loads that are accessible. Figure 6 displays the voltage curve of the DC link and its association with droop control.

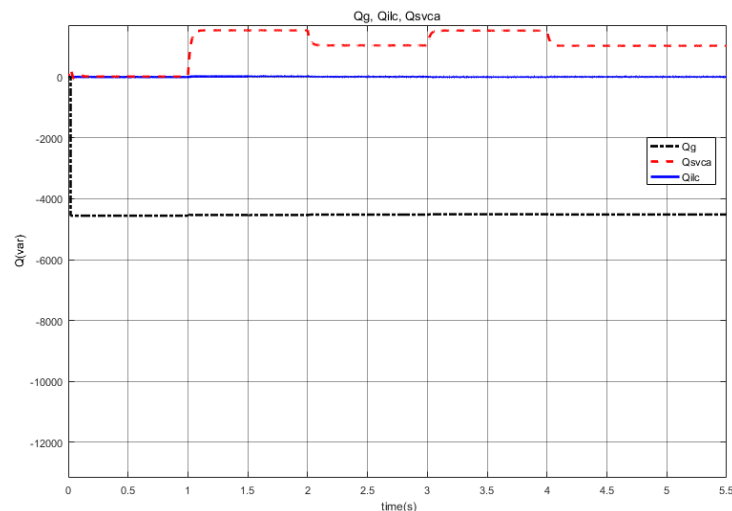


Figure 5. Reactive power curves of the main grid, the VSC of AC MG, and the ILC.

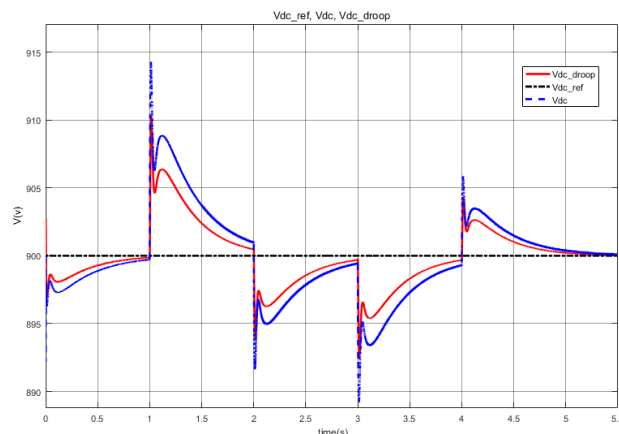


Figure 6. Voltage curve of the DC link and droop control DC-link.

Assuming proper functioning of the energy management system and controllers in the hybrid AC/DC MG system, the DC-link voltage is expected to consistently track the reference voltage value of 900 V across various conditions and scenarios. By altering the loads and system conditions at various instances, it is evident that the DC-link voltage deviates from its reference value. This deviation, whether a drop or a rise, remains within a margin of less than 2%. Furthermore, the voltage curves promptly align with the reference value. Figure 7 displays the current curve of the grid, the nonlinear load, and the ILC. The system's current fluctuates in various settings and conditions, corresponding to variations in both DC and AC demands.

The nonlinear load current curve in Figure 7 shows that the load enters the system at $t=1$ s and becomes harmonic from that moment on. Figure 8 displays the grid current curve, nonlinear load, and ILC converter at the time of the entry of the nonlinear load at $t=1$ s. As observed, before the entry of the nonlinear load into the system, the grid current curve is completely sinusoidal and without distortion, but with the entry of the nonlinear load, the curve becomes distorted.

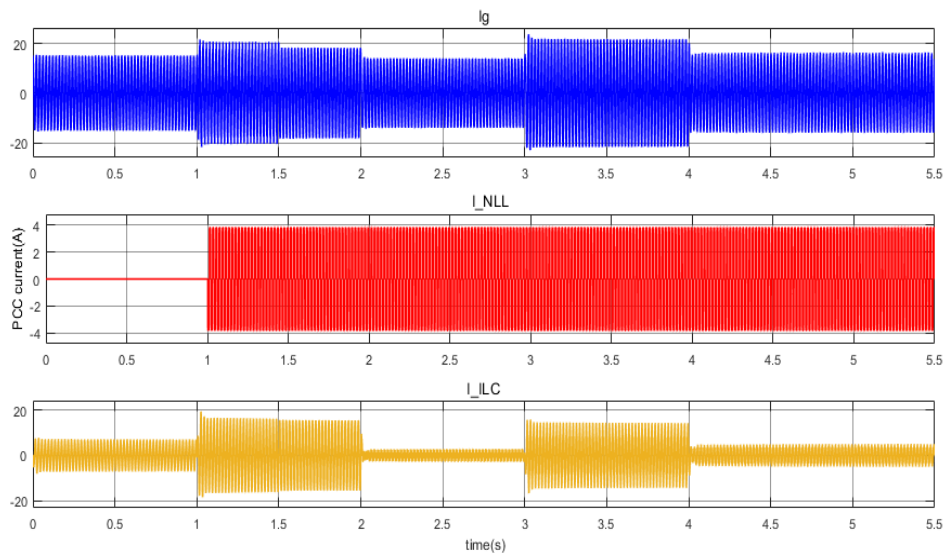


Figure 7. Current curves of the grid, the nonlinear load, and the ILC.

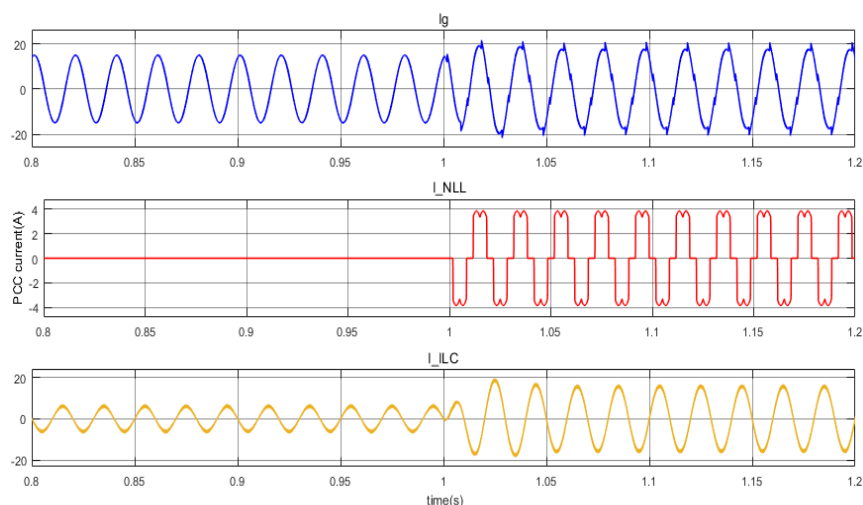


Figure 8. Current curves of the grid, the nonlinear load, and the ILC when the nonlinear load is introduced.

Figure 9 shows the grid current curve, nonlinear load, and ILC converter at the time of operation of the harmonic control section at $t = 1.5$ s. As observed, the control system operates well from 1.5s onwards and the grid current curve becomes undistorted.

It should be noted that harmonic compensation is done through the ILC converter, and for this reason, after 1.5 seconds, the current curve of the ILC intermediate converter is affected by harmonics to avoid having a harmonic grid current curve. To evaluate the level of distortion, FFT analysis available in Matlab is used to calculate the THD level. Figure 10 shows the level of harmonic and distortion in the grid current when there is no nonlinear load present in the grid, and the THD value is 1.91%, which is low and acceptable.

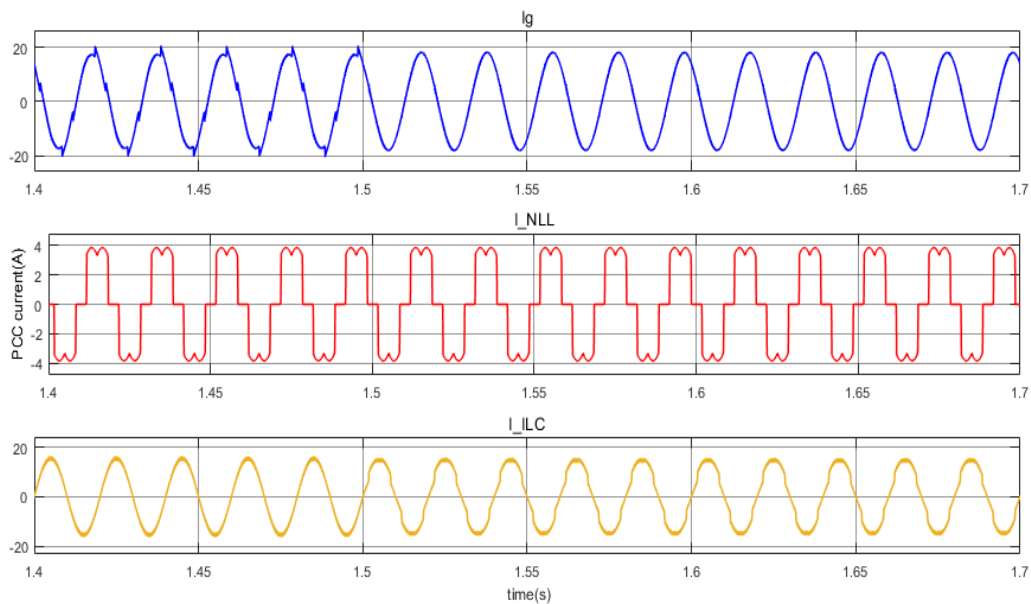


Figure 9. Current curves of the grid, the nonlinear load, and the ILC when the harmonic-generator control block operates.

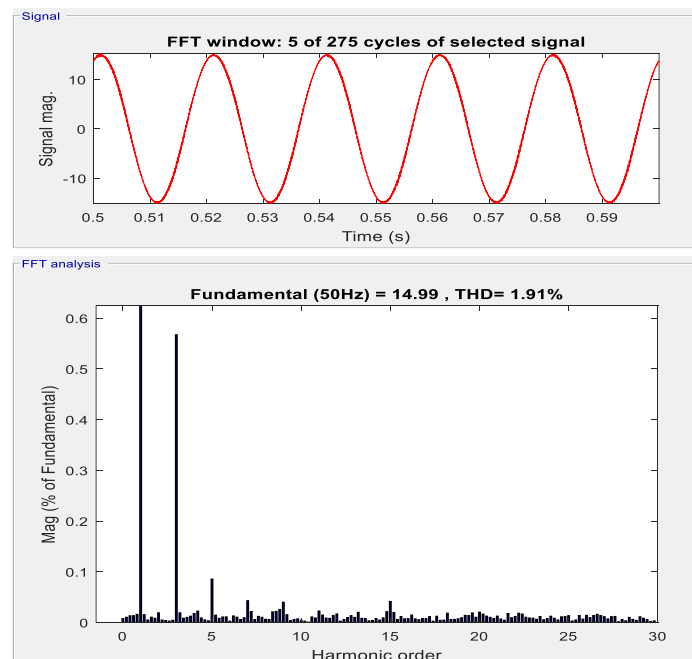


Figure 10. Harmonic and distortion levels of the grid current in the absence of the nonlinear load.

At $t = 1$ s, a load with both harmonic and nonlinear characteristics is introduced into the system. Figure 11 illustrates the level of harmonic and distortion in the grid current when the nonlinear and harmonic load is applied. In this case, the THD level of the grid current is 7%, which is higher than the standard value. Therefore, it is necessary to reduce the level of distortion. After the implementation of the control block related to harmonic compensation in the hybrid AC/DC MG, the THD level returns to its original value and even less than that. Figure 12 shows the level of harmonics and grid current distortion during the operation of the control and harmonic compensation section, with the THD level being about 1.87% and even less than the initial value.

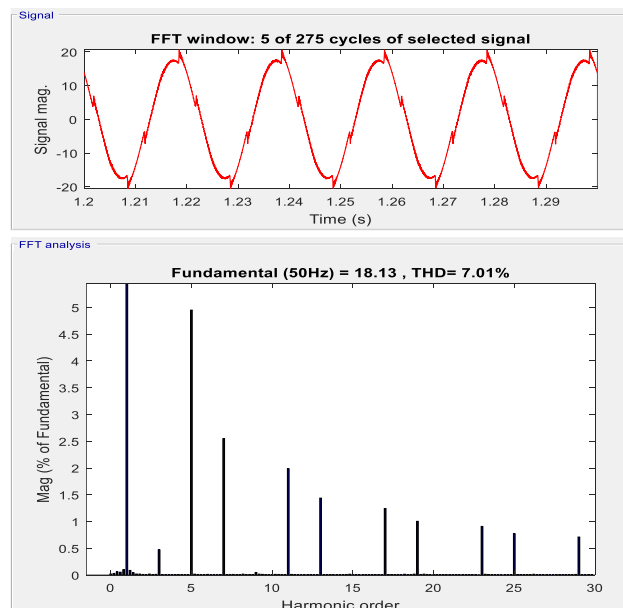


Figure 11. Harmonic and distortion levels of the grid current when the nonlinear, harmonic-generator load is introduced.

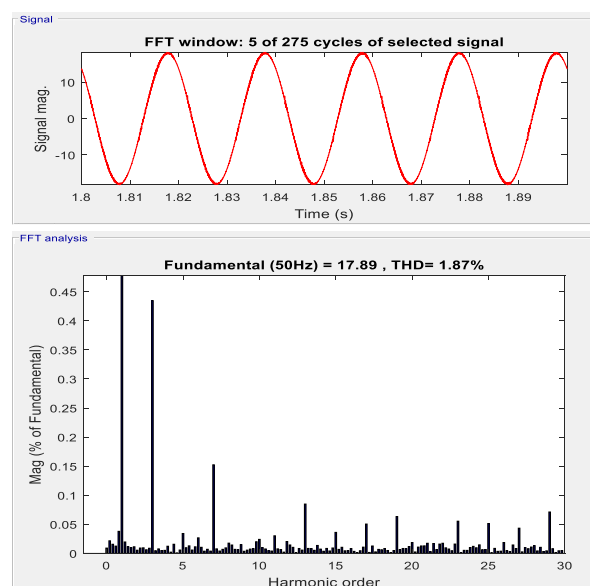


Figure 12. Harmonic and distortion levels of the grid current during the operation of the control block and harmonic compensator.

Therefore, the energy management system, power control, and the section aimed at improving power quality and reducing harmonics in the combined AC/DC MG have performed well under all conditions. Consequently, the proposed structure in this study has shown very good performance.

6. Conclusion

Hybrid AC/DC MGs have been designed for better integration of various DG resources with the power grid and to utilize the features of both AC and DC MGs. To establish the connection between these MGs, an interface converter equipped with a suitable power management and control scheme is required. To control frequency and voltage in the AC MG, the voltage in the DC MG must be adjusted and the power must be effectively managed and controlled based on the capacity of each MG. Therefore, it is essential to develop a suitable method for energy supervision in the hybrid AC/DC MG. In this paper, a novel architecture and a suitable control method for hybrid AC/DC MGs were presented. Also, a synchronized power control technique for power sharing between the power electronic converters is presented. In addition, a distributed cooperative control method for voltage and frequency control in AC MG and voltage and current control in DC MG for hybrid AC/DC MG was presented. The research investigated a hybrid AC/DC MG topology in which DGs utilize grid-forming converters. The grid-forming converter is an ILC used to control the MG voltage. Two grid-forming converters were used to boost the capability of power sharing and minimize power quality disturbances. Overall, the results indicate that both the power control and power quality improvement components of the AC/DC MG system work effectively under all conditions. Consequently, the structure described in this paper shows excellent performance. It should be noted that in this article, the AC MG is isolated from the main grid, and therefore sensitive loads are isolated from main grid faults and are not affected by them.

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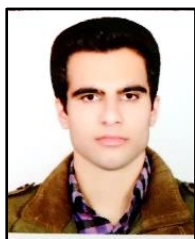
Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, have been completely observed by the authors.

Credit Authorship Contribution Statement

Mehdi Shiravand: Conceptualization, Data curation, Formal analysis, Methodology, Software, Roles/Writing - original draft. **Ali Nahavandi :** Conceptualization, Formal analysis, Methodology, Supervision, Validation Roles/Writing-original draft, Writing-review & editing.

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