Interconnecting industrial multi-microgrids using bidirectional hybrid energy links

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ABSTRACT

Sharing and exchange energy among nearby industrial microgrids are crucial, especially with high energy requirements for their production targets and costly energy storage systems that may be oversized for their operations. Facilitating energy exchange can provide an economic advantage for industrial production by utilizing cheaper energy sources and reducing production costs. This manuscript presents an efficient approach for transferring large energy packets with minimal energy losses using high-voltage direct current (HVDC) energy transmission. The manuscript methodology focuses on implementing an industrial multi-microgrid using a modular multilevel converter. This converter utilizes two power link channels: a three-phase AC and an HVDC link, creating a hybrid energy transmission between microgrids. When a substantial amount of energy to transfer, the HVDC method enhances overall efficiency by reducing copper losses and mitigating issues associated with the AC link, such as harmonics and skin effects. The modular multilevel converter topology offers high flexibility and the use of fewer converters. Additionally, the HVDC link eliminates distance restrictions for energy transfer between industrial microgrids. A case study illustrates the functionality of this topology, demonstrating optimized power transfer and decreased energy losses. This methodology allows industrial microgrids to enhance energy efficiency and productivity while minimizing operational costs.

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1. INTRODUCTION

Industrial microgrids (MG) are becoming more common every day due to their capability to introduce new renewable energy resources, which reduces production cost, improves total energy efficiency, and quickly permits recovers of their investment. According to the US Department of Energy, an MG is a group of distributed generators (DGs) and electrically bounded energy storage systems that supply electricity to load in a localized area at the distribution level operating in isolation or interconnected to the grid [1], [2]. An industrial MG uses DG units such as wind turbines (WT), photovoltaic (PV), and combined heat and power (CHP), among other conventional or renewable sources, to provide electricity and thermal energy simultaneously to the production line. Frequently, clean energies are preferred over other contaminant technologies. Using MG technology has four comparative technical advantages, which are: i) transmission power loss can be greatly reduced in comparison to legacy power systems; ii) MGs can operate in both stand-alone and grid-connected modes; iii) energy control of MGs can bring needed energy from their various forms of storage to lower the $/kWh in peak demand hours, increasing profits; and iv) during emergencies on the main grid, case of connected MGs, MGs can isolate and operate in stand-alone mode, increasing the reliability of local power supply [3].

With the expansion of DGs, liberalization of the energy market, and the advent of information communication technology, distribution networks have evolved into a distributed structure with multiple multi-MGs (MMGs), which can be interconnected [4], as shown in Figure 1. These MMGs could exchange energy using AC or DC links without importing the distance between them. It must use a high voltage direct current (HVDC) transmission for long-distance cases due to its immunity to all AC phenomena (skin effect, eddy currents, harmonics, and others) over the wires. Additionally, power grid renewal costs are reduced because it is unnecessary to update the electrical connections. Recently some countries have invested in new HVDC networks. HVDC lines use thousands of volts to reduce the current over the conductor, permitting more energy transfer with high efficiency. So, transmission losses are reduced in a quadratic factor according to the model of power conductor losses.

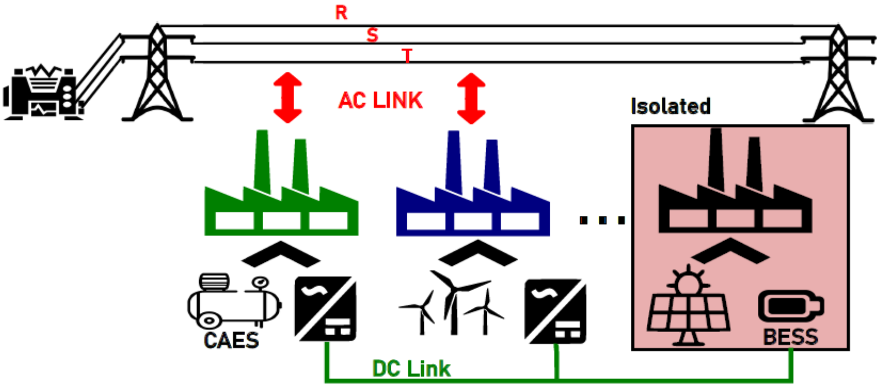

Figure 1. Distributed structure with multiple MMGs

Each industrial MG, associated with MMGs, uses different energy converters and storage devices to satisfy its energy requirements. Therefore, an MMGs structure must provide intelligence and flexibility to be more competitive inside the energy market (where the industrial consumers have lower prices than other providers, and generators can bid outside their location area). However, energy control is becoming more complex by accommodating different types of control, such as the multi-agent control in Figure 1. Thus, clarifying exits three types of control for an MG: i) Primary control, which controls the voltage and frequency, reduction of conversion losses, active and reactive power of the system, as well as power quality control (flickers, harmonic compensation, among others), as developed in [5]–[7], see Figure 2; ii) Secondary control, in charge of compensating voltage/frequency caused by the primary control, as developed in [8], [9]; and iii) Tertiary control, which manages the energy flow from distributed renewable energy sources between isolated and non-isolated MG [10]–[13].

For optimal energy control in MG, developing a multi objective optimal control algorithm at the tertiary level must satisfy the demand profiles and their corrections. The tertiary control determines the entry into the storage systems' operation to flatten the demand curve's peaks. At the same time, the primary and secondary control loops are responsible for providing stability to the DG by controlling its basic technical parameters.

In this manuscript, we develop a methodology where it will adapt a modular multilevel converter topology as a power bridge between AC and DC links of industrial multi-microgrids. Initially, on the next section we show how is possible interconnect microgrid to export energy using a HVDC method that improves the energy transfer and reduce the losses. After that, we will develop the control based on the modular multilevel converter (M2C) model. With this model, we can differentiate which variables are relevant for its control and to guarantee the stability of the converter. Finally, a study case is develop using computational simulations tools.

Reviewing the state of the art of Interconnecting MGs. Inside [14], a single-period energy-trading algorithm was proposed based on dual decomposition for multiple MG systems. Finally, in [15], the optimal scheduling problem for multiple MG interconnection systems was investigated by proposing a Nash bargaining utility sharing.

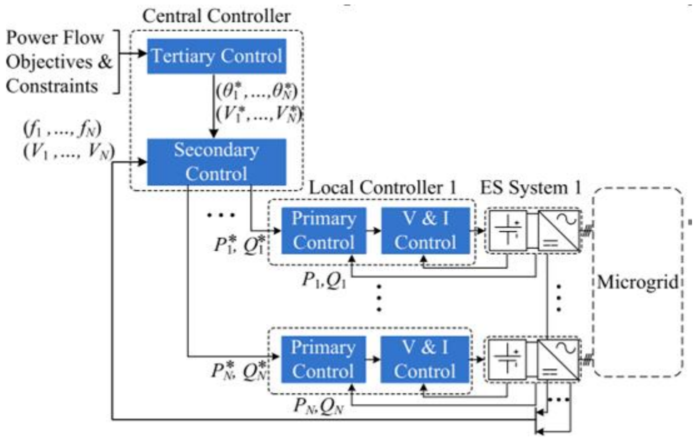

Figure 2. Classification of control types in MG extracted from [5]

Regarding the evaluation of control and energy management techniques, in [16]–[18] consider the uncertainties associated with the demand for the multi-MG system. For this purpose, an energy management system (EMS) [16] was established, considering the daily demand. Likewise, a daily dispatch strategy is proposed in [17], [18]. However, the previous works are limited to semi-distributed MG, which implies a single centralized unit to perform the EMS. In turn, another drawback lies in knowing in advance the probability of market uncertainty that is sometimes impossible to predict. As a solution to this drawback, a robust optimization is a good option because it optimizes the objective function without considering uncertainties. Such optimization has been used in several energy systems to respond to energy demand [19], energy sales [20], and the integration of electric vehicles (EV) to the MG [21], and ancillary services [22], among others.

The problem of semi-distributed systems is based on gathering information in a centralized way to make control decisions. Although the various MG operators may not provide this information and may need help finding it feasible to share their information with others, predicting demand behavior and associated MGs is possible without this information. In addition, any inconvenience in communication and erroneous information can limit the operation of the MG, even generating instability.

On the other hand, the predictive control model (PCM) has been implemented in studies [23], [24] for optimal power flow control. The study [25] proposes a multi objective optimization with high DG penetration using renewable energies. Various stochastic strategies for optimal energy management are shown in [26], [27]. A commonly used stochastic formulation is the two-stage problem. For example, in [28] suggests a stochastic formulat1ion for minimizing operating costs, including grid energy losses of a GM. Similar two-stage formulations are shown in [29]–[31]. A limitation of this formulation is the assumption that all uncertainty is revealed at once. For a multistage formulation, the uncertainty reveals in stages, and the system control is updated in stages as the uncertainty is revealed. This formulation is widely used in hydroelectric scheduling [32], and stochastic dual dynamic programming is an efficient technique for solving large-scale multistage stochastic problems [33].

According to the literature of MMG architecture, the M2C is one of the power converters most studied, see Figure 3. This topology has two bidirectional ports (one AC-on the left- and another configurable DC or AC depending on the modulation-on the right side), with which it is possible to extract flow from any of the buses and send it to the other. It is important to show that this converter is a converter that combines AC and DC behavior within the converter to achieve its goal. Furthermore, this converter can easily implement HVDC transmission as its output DC value limit-right side is virtually infinite. For this HVDC application, the M2C uses an array of floating capacitors inside each SM. This modular converter can add SM infinitely by cluster to reach higher voltages.

This growing interest is due to its flexibility and power scalability, especially when used inside microgrids. It is flexibility corresponds to how it redirects the energy flux between ports, with the only change in its control algorithm. Power scalability refers to M2C could have more submodules to increase its total power. Also, the M2C has six main technical advantages: i) M2C can integrate different sources taking or giving power to any port; ii) it is submodules (SMs) are bidirectional that easily redirect the power flow using a high-level algorithm; iii) M2C has a configurable port that can generate DC or AC monophase according to requirements; iv) improved energy efficiency due to utilizing a diminished number of converters; furthermore, v) fast modulation of DC transmission power can damp power oscillations in an AC grid, improving system stability.

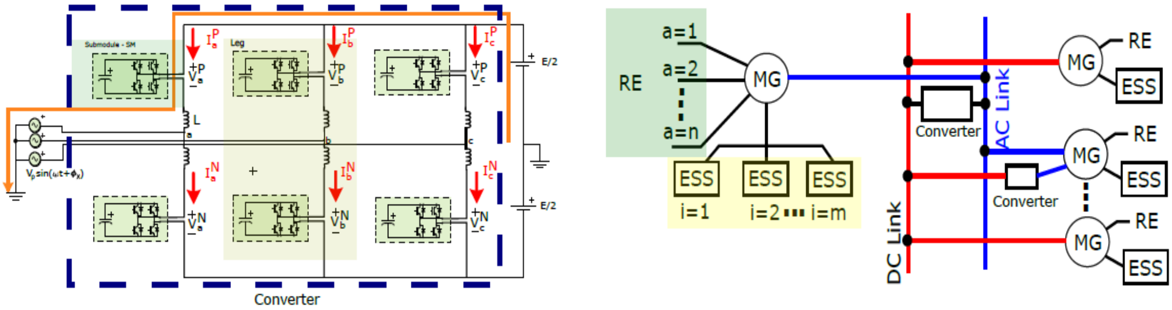

Figure 3. Conventional M2C topology

This manuscript proposes that each industry be a cell or SM of an M2C. Thus, when each SM has a synchronization problem can be insulated to become a stand-alone MG. With two energy links to share energy between industrial microgrids, AC and DC, it is possible to decrease the number of power converters. So, if an energy source is, DC can be connected directly over the DC bus. On the contrary, it will add an AC source (generator or others) to the AC bus. As a result, it improves the MMG's total energy efficiency.

As the main aims, this manuscript implements and validates an M2C topology with high energy efficiency for exchanging energy between MG through simulation. This analysis is done before its hardware implementation, trying to prevent any problem or instability that destroys the converter. Therefore, the analytical framework for the energy exchange between links is developed and detailed in this manuscript. Additionally, the proposed methodology is implemented in a SiL configuration to validate the energy management strategy. It is important to highlight that this manuscript is an extension of a paper titled "Hybrid energy transmission for industrial microgrids", which was exposed in ICEMS2021. Several control details are related here in this manuscript, such as the grid synchronization, the stability analyses, and others.

2. METHODOLOGY FOR IMPLEMENTING THE HYBRID ENERGY TRANSMISSION

The proposed method for interconnect industrial MMGs consists of fourth steps: determine the M2C power model to transfer energy between topology components. Define the technical requirements for each MG or submodule associated with M2C. Analyze the operation modes of an MG. Establish the high-level control algorithm that permits redirecting the power between MG according to demand.

2.1. M2C power model

Analyzing the M2C model of Figure 3, we can find the characteristic equation using Kirchoff voltage law (KVL). So, by applying KVL over a close loop, we could obtain the following:

$$\begin{bmatrix} V_a & V_b & V_c \\ -V_a & -V_b & -V_c \end{bmatrix} = -L\frac{d}{dt}\begin{bmatrix} i_a^P & i_b^P & i_c^P \\ i_a^N & i_a^N & i_a^N \end{bmatrix} - \begin{bmatrix} V_a^P & V_b^P & V_c^P \\ V_a^N & V_a^N & V_a^N \end{bmatrix} + \frac{E}{2}\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \tag{1}$$

where *a*, *b*, and *c* are the phases, *V* the SM voltage, *i* the arm current, and *E* the output voltage. This voltage-current model coupled the current with the difficult voltage signals is controlled. For this reason, this manuscript uses the $\Sigma\Delta\alpha\beta 0$ transform to uncouple all variables.

$$\Sigma\Delta\alpha\beta 0 = \begin{bmatrix} \Sigma \\ \Delta \end{bmatrix} X_{abc}[\alpha\beta 0]^T = \begin{bmatrix} X_a^P + X_a^N & X_b^P + X_b^N & X_c^P + X_c^N \\ X_a^P - X_a^N & X_b^P - X_b^N & X_c^P - X_c^N \end{bmatrix} X_{abc}[\alpha\beta 0]^T \tag{2}$$

where,

$$[\alpha\beta 0]^T = \begin{bmatrix} 2/3 & -1/3 & -1/3 \\ 0 & 1/\sqrt{3} & -1/\sqrt{3} \\ 1/3 & 1/3 & 1/3 \end{bmatrix}^T$$

The (2) represents the $\Sigma\Delta\alpha\beta 0$ transform. *X* is voltage or current indistinctly in *abc* reference, and $[\alpha\beta 0]$ is the classical bi-phase Clarke transformation. Once applied, the $\Sigma\Delta\alpha\beta 0$ transforms all currents and voltages, and neglecting any drop voltage on *L*, the model is decoupled for it is posterior control. Thus, the M2C model of (2) turns in:

$$\begin{bmatrix} 0 & 0 & 0 \\ -2V_\alpha & -2V_\beta & -2V_0 \end{bmatrix} = -L \begin{bmatrix} i_\alpha^\Sigma & i_\beta^\Sigma & i_0^\Sigma \\ i_\alpha^\Delta & i_\beta^\Delta & i_0^\Delta \end{bmatrix} - \begin{bmatrix} V_\alpha^\Sigma & V_\beta^\Sigma & V_0^\Sigma \\ V_\alpha^\Delta & V_\beta^\Delta & V_0^\Delta \end{bmatrix} + \begin{bmatrix} 0 & 0 & \frac{E}{2} \\ 0 & 0 & 0 \end{bmatrix} \tag{3}$$

All plants model is obtained when the instantaneous power model through a Hadamart product among voltage and current, shown in (4). The mean power is obtained by multiplying the capacitor current with its voltage. To ensure M2C stability, the mean power transfer from capacitors must be zero. So, with this comparison, it is possible to obtain all plants for its control.

$$P_{\alpha\beta_0}^{\Sigma\Delta} = V_{\alpha\beta_0}^{\Sigma\Delta} \odot I_{\alpha\beta_0}^{\Sigma\Delta} = \begin{bmatrix} V_\alpha^\Sigma I_\alpha^\Sigma & V_\beta^\Sigma I_\beta^\Sigma & V_0^\Sigma I_0^\Sigma \\ V_\alpha^\Delta I_\alpha^\Delta & V_\beta^\Delta I_\beta^\Delta & V_0^\Delta I_0^\Delta \end{bmatrix} \tag{4}$$

To obtain all plants, proportional-integral (PI) and proportional-resonant (PR) controllers in dq_0 or $\alpha\beta_0$ references are necessary for controlling these equations according to their nature. These controllers are developed and implemented similarly to [34]. In addition, the controllers triggered the insulated-gate bipolar transistors (IGBTs) and modified the voltages of the capacitors. The power model proposed permits to generate control about the circulating currents $I_{\alpha\beta}^\Sigma$, common voltage mode V_0^Δ and transfer power from and to the DC port P_0^Σ.

2.2. Submodule technical requirements for each MG

Each SM has some technical requirements that guarantee stability in the M2C operation. First, the primary control must determine a close-loop control for both links. In the AC link, the control must supervise the voltage and frequency. The control will determine the SM voltage required for the DC link according to the energy flux. That means when a DC MG gives energy to the link, the voltage must be slightly higher, as shown in (5) and (6). Thus, it prevents high circulating currents due to the disparity between voltages. On the other hand, the before requirements are also accomplished when we transfer energy to the AC port.

$$\begin{cases} V_{SM} > V_{DC}^{Link} & E_{SM} > 0 \qquad SM\ gives\ energy \\ V_{SM} < V_{DC}^{Link} & E_{SM} < 0 \qquad SM\ recieves\ energy \end{cases} \tag{6}$$

Additionally, if the M2C is used as a rectifier, the voltage of each cluster is (7). This variable voltage depends on the modulation and synthesis of the AC three-phase voltage. So, if we use a symmetric modulation in the N submodules, the SM voltage will be (8).

$$V_{Cluster} = \frac{V_{DC}}{2} + \sqrt{3} V_{rms}^{3\phi} \tag{7}$$

$$V_{SM} = V_{Cluster}/N_{SM} \tag{8}$$

2.3. Analyze operation modes of a submodule

We must establish the SM behavior according to its topology to analyze all operation modes. Each SM inside the M2C will be an individual industry with or without any renewable energy source (RES) as energy storage. The proposed topology for the SM is shown in Figure 4. In the Figure, any RES with DC voltage output can be connected to the H-bridge through a DC-link, where an uncoupled capacitor is present. This capacitor will permit isolated the MG when exists a problem between the M2C and the MG.

Switches 1 and 2 are disabled when the MG is isolated. However, the proposed configuration permits enabling each MG energy flux. So, when the S1 is closed, some energy units are exported from the MG to the M2C. On the contrary case, energy is imported to the MG. The industry would be connected directly to the M2C three-phase port in the AC microgrid case. That means that a phase control for energy injection is required.

To validate the performance and power quality of the proposed three-phase MMC, each cluster (2 per leg) must correct by the secondary level of reactive power. For the above, it is observed that the MMC converter proposed in Figure 3 must maintain the reactive power taken from the network at zero, i.e., only take active power from the network if required. The converter's bidirectional energy flow must consider the energy market to know when to occupy the grid at some power level. It is important to note that each SM in parallel can provide different powers to the leg.

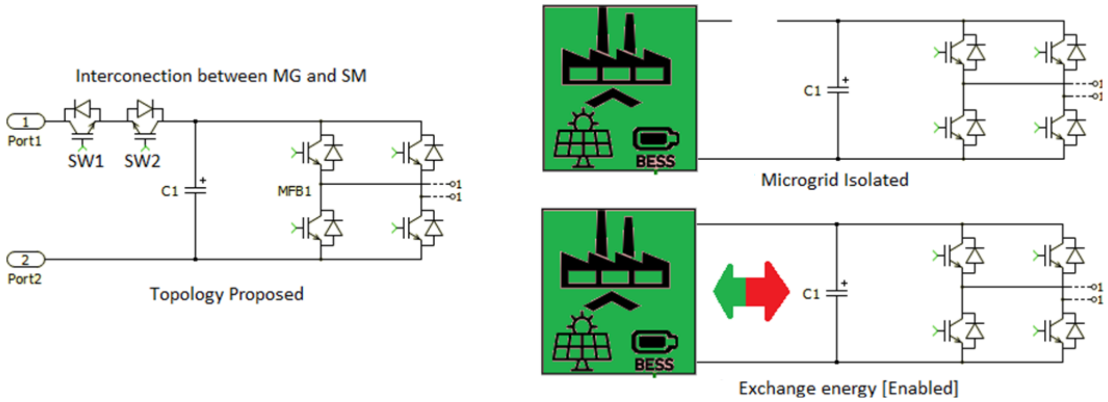

Figure 4. How interconnecting a DC microgrid to M2C industrial system

The power quality (voltage sag, voltage swell, voltage interruption, voltage harmonics, impulsive transient, and oscillatory transient) in the MMC converter must be analyzed according to the power input port. For this case, the sinusoidal current input coming from the mains must be evaluated so that the converter does not generate any of the faults, as mentioned earlier. Therefore, the frequency component in this signal should be 60 Hz for the Colombian case. As shown in Figure 5, one of the advantages of $\Sigma\Delta\alpha\beta0$ modulation, as opposed to other predictive control techniques such as model predictive control (MPC), lies in the non-deformation of the currents taken from the grid. For this reason, considering this and managing to control the power factor (phase difference between the current and the voltage of the network), it is possible to obtain different active powers from the network without injecting harmonics.

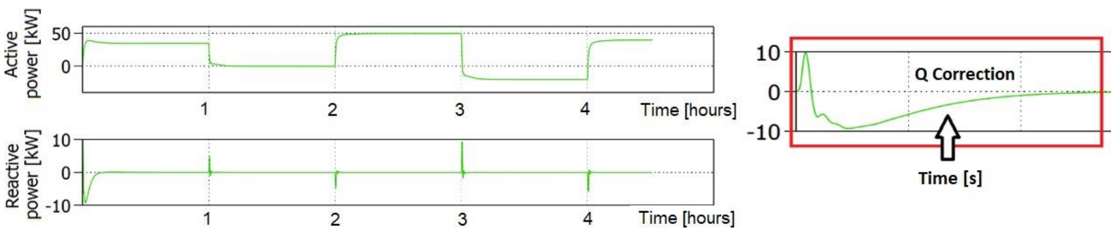

Figure 5. AC port reactive power correction

On the other hand, the proposed M2C consists of six clusters, which some energy generation or storage can form. In this case, full bridges will give flexibility to the converter, as shown in Figure 4, for AC generation from a renewable energy source. The topology is shown in Figure 4 allows giving total flexibility to the topology seen from the generation side since it must be considered that: i) the renewable energy source provides 100% of the power to the bridge rectifier as shown in Figure 4, so the capacitor suppresses all power peaks in this mode; ii) the plant factor of the different types of RES can render the submodule inoperative at some hours of the day, so it would not deliver any active power. To overcome this drawback, it uses the capacitor and full bridge to become a dummy cell (a cell that maintains the voltage, but its active power delivered is zero); iii) the source can also parallel the capacitor to provide a higher peak current than the renewable energy source or the battery system.

3. RESULT AND DISCUSSION

A study case takes three industries where energy requirements are different over time. Two cases exist; the first is when the M2C is a converter between both links. The last case exists when an MG is connected through an SM inside the M2C. Thus, each SM indicates if it gives or needs to receive energy from the M2C. Always guaranteeing full converter stability through a high-level supervisory algorithm is important.

For the first case, the M2C works with all its SM as a half-bridge capacitor, which means it is just a converter that links the AC and DC ports. So, the power balance is always guaranteed due to the compensation that performs one port over another when the primary control sees a deviation over the basic technical parameters such as voltage, current, and frequency in any port. This case is the simplest application of this M2C converter for sharing power between links.

On the second case, the Figure 6 shows the power exchange from the AC and DC ports of the M2C using energy from SMs. Different operation conditions are simulated to establish the entire functionality of the bidirectionality of the energy flow. For simplicity of the simulation, each hour represents an operational condition. First hour, $0 < t < 1$, it performs a transfer of 50 kW is given in the DC port using a linear combination of 40 kW of the three-phase port and 10 kW used to charge the battery energy storage system located inside a SM. On $1 < t < 2$, the active power taken for the AC port is 0 kW, meaning that 50 kW is obtained from batteries or energy storage supercapacitor (ESS) inside the M2C legs. In other time slots, $2 < t < 3, 3 < t < 4$, and $4 < t < 5$, the active power is changed to test the different sources controlling how much battery power or other ESS is used and its origins and validate that the reactive power is regulated to 0 VA. Thus, it is possible to extract energy from any SM or leg of the M2C.

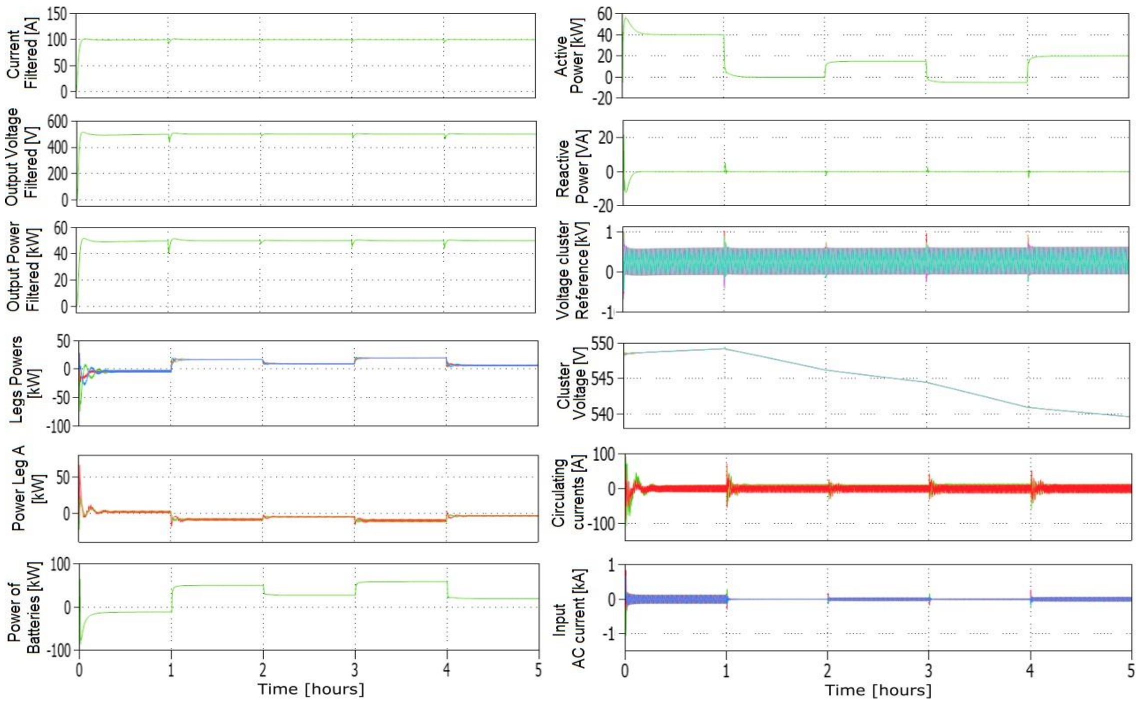

Figure 6. Results of moving energy between M2C ports

As a general consideration, the output power by the DC port is always constant at 50 kW. That means that the energy is always exported to the DC link. it is important to highlight that each cluster's full bridge or submodule can connect MG. For this reason and data testing, we designed a 50 kW converter that allows drawing power from the SM with ESS attached to the clusters. On the other hand, the control allows us to verify that SM dummies are regulated at 0 kW. So, each cell regulates its voltage cluster during all simulation time. The circulating currents that depend on inter-cluster and intra-cluster energy balancing must remain as low as possible.

The circulating currents can be altered when different powers are extracted from each SM. These current disbalances occur when a leg gives power to the DC port. From the above, it is possible to determine that the power balance control is feasible, as well as the power control of the input and output ports of the M2C. As a conclusion of the simulations developed in PLECS and MATLAB, it is possible to assure that tertiary control or power flow control is possible within an MG and between MGs of industrial character.

As section conclusions, it is shown in Figure 6 a successful energy exchange between the two ports (AC and DC). This energy interchange is defined at intervals of 1 hour, starting with $0 < t \leq 1$ and finalizing with $4 < t \leq 5$. However, according to the P_{Legs} graph, all legs give the same power. On the right side of Figure 6, we can find all parameters that guarantee the M2C stability. These parameters are active and reactive powers, cluster voltage, and circulating currents. On the other hand, if it observes intervals 1 to 2 and 3 to 4, it does not take power from this port when there are no phase currents.

4. CONCLUSION

An M2C topology is a good option when required to implement a bridge between AC and DC links. This converter can perform two basic works: first, it may work stand-alone with any MG inside, just monitoring (primary level) parameters. These parameters are the current, voltage, and frequency of the AC link to decide on importing energy from the DC link when required. Moreover, as a second work, it is possible to include several MG inside the M2C, taking advantage of this modularity.

In the second work, it is important to highlight the possibility that the MG be isolated from the M2C. For this, the SM topology allows will to determine when it is necessary to work stand-alone. This characteristic stabilizes to an MG when the M2C lacks adequate technical parameters. All results in this manuscript are a brief example of M2C potentiality when used as a power bridge. Normally, this DC link can be an HVDC link to reduce losses at the moment of transport energy.

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