Renewable Power Routing from a DC Microgrid to an Industrial Cluster

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***Abstract*—Nowadays, the exploitation of renewable energy sources is the most effective way to force a drastic abatement in greenhouse gas emissions. This consideration is even more strategic when envisaging the green supply of large power industrial loads, which are indeed responsible for an important quota of CO2 production. To foster the sustainability revolution in the industrial sector, an appealing option is to combine battery storage systems and photovoltaic power plant into a DC microgrid architecture. Such a power system is characterized by the presence of multiple power electronics converters, enabling its full controllability. The converters can be coordinated in order to direct the green energy towards the industrial factories. The paper wants to discuss about the smart DC power routing to support the energy demand of an industrial cluster.**

Keywords— DC microgrid, PV, storage, smart-coordination, power routing, industrial cluster.

I. INTRODUCTION

In the last years, the European Commission has set ambitious goals in terms of energy transition and emissions reduction, all summarized in the so called "European Green Deal". In this context, important actions are to be taken to reduce the environmental impact of human activities, ranging from the transportation sector to the industrial one. In other words, the activities where largest is the production of CO_2 emissions. Undoubtedly, the Renewable Energy Sources (RES) acquire a leading role to reach the EU sustainability goals. The renewables sources, especially photovoltaics (PV) and wind, can indeed guarantee remarkable benefits in terms of reduction in GHG emissions. Both for small scale users, like the newborn Energy Communities [1], as well as for high demanding ones, like industrial clusters [2]-[3], the RES can provide a sustainable contribution. In the expected scenario of green-digital transformation, the microgrids can be a powerful ally to integrate the RES and to boost their capabilities with the combination of energy storage [4]. In the design of such microgrids, one effective solution is the one based on DC power distribution. Indeed, this system architecture facilitates the connection of all the sources and loads [5], resulting in several advantages both on control and integration sides [6]. For example, it is possible to mention the full controllability and the capability to reallocate the available power, thanks to controllable power converters. When working on a complex system with multiple loads and sources, the single converters are controlled by standard algorithms, since the focus is more on the effective coordination between converters [7]. The coordination concept becomes even more crucial when pursuing the energy supply from renewable sources.

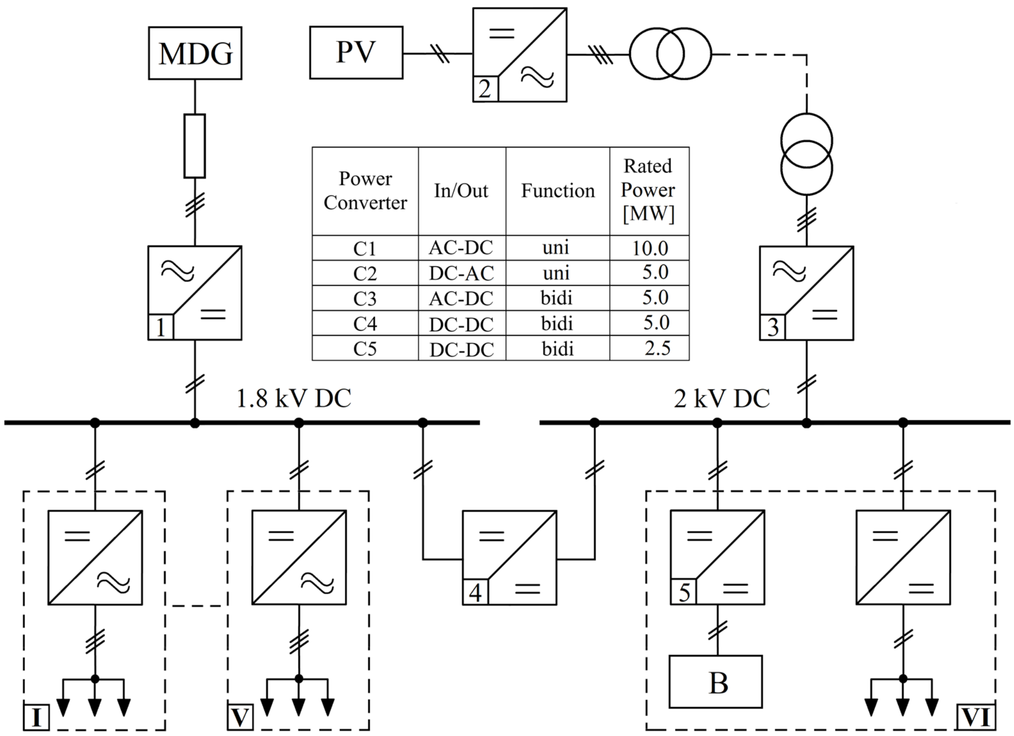
In this paper, an industrial cluster is the case study where maximize the green supply of factory loads. To support the energy sustainability, a 5 MW PV field is supposed to be installed on an available free surface in the industrial area. To this aim, a DC grid is conceived to proficiently exploit the RES. This controlled system is composed by two buses connected together through a DC-DC converter. The latter is in charge of the power sharing between the two DC systems. One bus includes a 10 MW set of factories, where the main AC distribution grid can provide the necessary energy quota. Differently, both PV-RES and a small industrial load are interfaced to a second DC bus, whose voltage is regulated by a Battery Energy Storage System (BESS). This BESS supports the voltage of the DC bus acting to compensate for the fluctuations of solar energy. Two loading scenarios are analyzed to evaluate the power routing during normal working and weekend days. The goal is to smartly manage the available green power to feed the industrial cluster.

II. DC MICROGRID FOR INDUSTRIAL CLUSTER POWERING

In the energy transition context, the paper wants to show how the smart coordination of power electronics converters can direct the renewable power to supply an industrial cluster's demand. To ensure this power routing, several converters are integrated into a controlled DC microgrid (MG). On one hand, the latter is designed to collect the green energy from a photovoltaic power plant. On the other, the DC microgrid is responsible to feed all the converter-fed industrial loads, while endorsing the sustainable exploitation. When the renewable quota is not sufficient to cover the industrial request, both storage and external input from AC grid are activated to ensure the essential power equilibrium.

A. *Green Powering of Industrial Facilities*

The renewable energy sources are a key element in the perspective of a less impacting energy production and a more rational energy usage. Indeed, their integration in the power grid of industrial facilities, representing one of the main sources of GHG emissions, can be beneficial, not only in terms of sustainability but also for their independency by the Main Distribution Grid (MDG) [8]-[9]. This paper case of study focuses on an industrial cluster supplied by the MDG and assisted by a PV source and battery storage. This combination of sources and storages guarantees uninterruptible power supply to the demanding industrial loads, while enabling economical benefits for the owner.



Power Converter	In/Out	Function	Rated Power [MW]
C1	AC-DC	uni	10.0
C2	DC-AC	uni	5.0
C3	AC-DC	bidi	5.0
C4	DC-DC	bidi	5.0
C5	DC-DC	bidi	2.5

Fig. 1. DC microgrid to supply the industrial cluster by sustainable photovoltaic power.

B. Photovoltaic Power Station

In the nearby (i.e. 10 km) of the industrial cluster, a free area is designated to host a PV field. This installation can reduce, even nullify, the power imported from MDG, resulting both in economic and environmental benefits for the factories. By assuming a quite standard PV efficiency, thus 147 W/m^2 as expected output from 1 kW/m^2 incoming radiation, a land rectangle having 3.4 hectares of surface (i.e. 170 m X 200 m as linear sizes) accommodates a 5 MW-PV plant [10]. Then two converters are installed as in Fig. 1 to get the no-emission power supply [11]. The C2 grid-following inverter operates at the output of PV field to convert the 1200 V DC string voltage into 600 V AC. Then, a transformer boosts this voltage value to 10 kV to reduce the losses on the 10 km-underground cables. Finally, a cascade of step-down voltage transformer (i.e. 10/0.6 kV the ratio) and C3 Grid-Forming (GFM) converter makes available the 2 kV on the DC microgrid bus. For simplicity, all these converters are no-losses elements, while their rated power is 5 MW (i.e. PV field peak-output power). Conversely, the line-losses are hypothesized as 5%. The PV field is modeled as a constant voltage source, whereas its power output is imposed by the C2 inverter's control loops.

C. Industrial Cluster Loads

The 2-1.8 kV DC MG is designed to green supply the industrial cluster, which is constituted by six factories as in Fig. 1. The first five factories (from I to V) adopt an internal AC distribution, therefore each single input converter provides the DC to AC interface. Conversely, in the last factory IV, an innovative DC-DC input is preferred as its industrial production exhibits a square-wave power request, eventually provided by the boost converter 4 as redirecting unit in absence of sun (i.e. power flow from 1.8 kV system to 2 kV system). The rated load power of each factory is approximately of 2 MW, therefore 12 MW is the total power value for the industrial cluster. Evidently, this request is not constant over the time. By hypothesizing a seasonal stop of production in factory VI, a realistic profile [12] for the entire

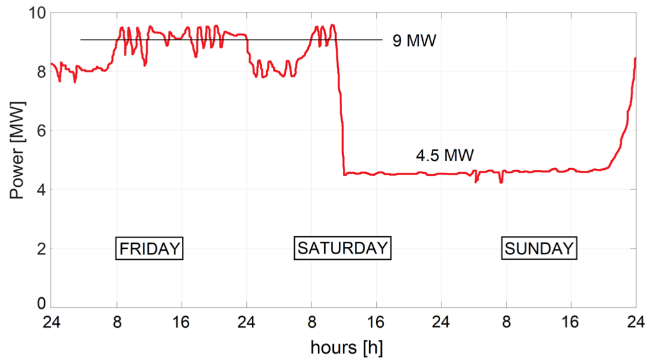


Fig. 2. Working cycle in the week/weekend transition.

cluster (thus factories I-V) is given in Fig. 2. Particularly, the time-scale considers the transition from working to festive days. For the entire cluster, Friday is the last day when the mean power request is near 9 MW. This power characterizes the so-called high-demanding scenario. Differently, in the low-demanding scenario from the 10 of Saturday till the 22 of Sunday the power demand decreases to 4.5 MW. The paper analyzes these two scenarios to understand the cluster powering during a classical working cycle. From one scenario to the other, the controlled DC microgrid leads the transition of PV plant from supporting to main source. Smaller the power to be bought from the MDG, better the sustainability performance for the industrial cluster.

D. Battery Energy Storage System

In Fig. 1, the DC microgrid operation is supported by a BESS, where the battery (B) is interfaced to the DC bus by the C5 bidirectional converter. By providing a buck-boost functionality, this DC-DC converter controls the 2 kV bus while assuring the continuity of power supply if the PV power output falls down [13]-[14]. This storage is primarily designed to support large power fluctuations on the bus, rather than supplying for longer period the loads. For this reason, the battery capacity is 1 MWh and the C-rate results equal to 3C.

E. Control architecture

In a complex power system like the one in Fig. 1, only an advanced coordination can ensure the renewable supply of industrial loads. To this aim, the DC MG is operated by implementing a hierarchical control architecture in order to properly manage the power flow between sources (i.e. MDG and PV field), BESS and factory loads. As conventionally adopted in the classical structure of microgrids [15], also in this case a Microgrid Central Controller (MGCC) is responsible to send the control references to be set on the primary control loops of power converters. Particularly, these setpoints are the outputs of secondary controls, which are in charge of implementing energy management strategies to maximize the RES adoption. As already expressed before, five converters (from C1 to C5) are coordinated to assure the green power flow. By starting from the left-up of Fig. 1, it is possible to notice the C1 converter, which is an unidirectional diode rectifier to make available the 1.8 kV on the left-DC bus (i.e. the line-line voltage from MDG is thus 1.33 kV). On the right, the C2-C3 couple to interface the PV plant to the right-DC bus having 2 kV as voltage value. Beyond this, it is remarkable to observe the MVAC cable between C2-C3 converters. This configuration is quite unique, since the missing connection to the main grid makes this MVAC line an isolated AC power system. Therefore, the Grid-forming (GFM) capability on C3 converter appears consequent [16]. This converter is thus controlled to impose the grid voltage/frequency on the MVAC isolated system. Its importance is crucial in the global coordination of power converters for the final sustainable aim. On the other hand, the C2 unit is controlled , at the output of PV as Grid-following (GFL) converter. This means that the C2 converter is synchronized to the isolated-internal AC grid by adopting a Phase-Locked Loop (PLL) [17]. The C3 converter is an AFE rectifier, redirecting all the available PV power to the left DC system. To close the entire path towards the I-V industrial factories, the C4 operates as isolated DC-DC bidirectional converter [18]-[19]. It actually enables the power flow between the two DC sides of the MG by receiving a power setpoint from the MGCC. When this setpoint orders a power flow from the 2 kV DC bus to the 1.8 kV DC bus, the C4 works as step-down buck converter. Differently, with an inverted control command, the C4 behaves as step-up boost converter. This particular operation is activated when the external source from MDG is necessary to feed the VI load demand, thus compensating for an insufficient power quota from PV. Finally, the bidirectional C5 converter to enable the buffer functionality of BESS. The latter has a fundamental function as it is in charge of controlling the voltage on the 2 kV DC bus. On the structure described so far, an efficient power routing can be envisaged by taking into account the lessons learned in [20].

III. Coordinated Green Power Routing

The DC microgrid operation is tested in order to highlight a sustainable power routing [18]-[19]. The following PSCAD simulations are conceived to show how the coordinated management on power converters is effective in redirecting the green energy towards the industrial cluster. To this aim, a high-demanding test (9 MW) demonstrates the cooperation of PV and external AC grid in powering the I-V factories. In this case, the PV can only offer a support. Conversely, in the low-demanding test (4.5 MW) the entire power demand is satisfied by the sustainable PV source. Particular attention is spent on the storage, whose function is essential for the convenient exploitation of photovoltaic energy.

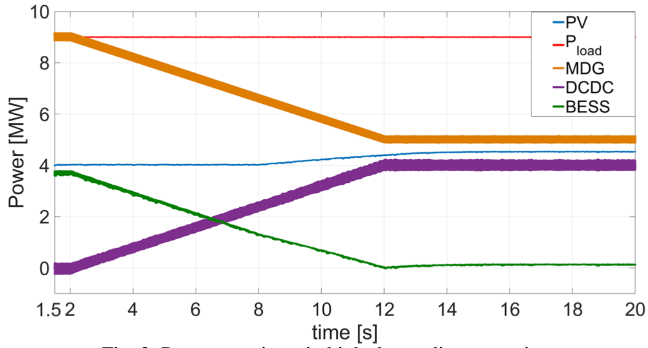


Fig. 2. Power transients in high-demanding scenario.

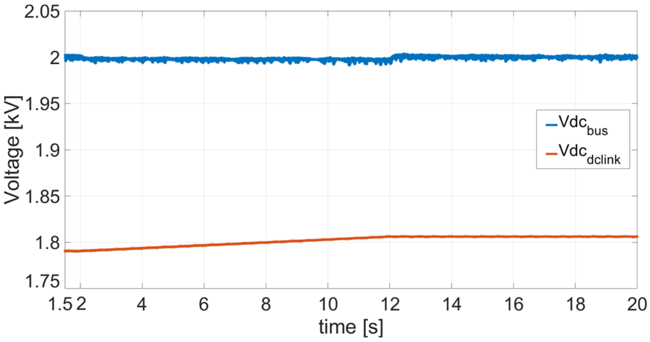


Fig. 3. Bus voltage transients in high-demanding scenario.

A. Green Power Support in High-demanding Scenario

The first scenario regards the high-demanding operation during working days, when the cluster load mean value is 9 MW (Fig. 2). As the PV peak-output power is 5 MW, this RES can only support the MDG in supplying the industrial cluster. The test assumes that PV plant initially only feeds the VI factory. When a seasonal stop is ordered for this factory, the C4 converter in buck mode can transfer the green power to the I-V factories as in Figs. 2-3. Particularly, Fig. 2 shows the PSCAD power transients, while the voltage ones are in Fig. 3. At the beginning of the test (i.e. t=1.5 s), the system is operating in steady-state. The I-V factories (9 MW, red line) are fully supplied by the MDG (orange line), whereas the 4 MW PV power output (cyan line) is directed to the 2 kV DC system. The available PV power (slightly less than 4 MW for the losses on AC lines) is equally shared between BESS and VI factory. At 2 s, the 2 MW load on VI factory is gradually turned off for operative reasons while the sufficiently charged BESS behaves as a buffer. Basing on this, the whole 4 MW of renewable power can be shifted through the DC-DC interfacing converter 4 (purple line) to feed the I-V factories. By increasing the output power of C4 with a ramp, this converter starts to contribute in powering the I-V factories. The load demand is now shared between C4 and MDG, whose contribution starts to consequently decrease (orange line) as C4 power grows. As the parallel of VI factory and BESS gradually reduces its power request (green line), C4 increases its power transfer reaching the 4 MW at 12 s. When the VI factory is switched-off at 12 s, the BESS is in charging mode. Indeed, the PV power output is 4.5 MW (sunny condition) and the 4 MW-setting on C4 power control is unmodifiable. Finally, the BESS converter plays its role in Fig. 3, when controlling/supporting the 2 kV DC bus voltage (blue line). Conversely, the red line voltage (i.e. 1.8 kV DC bus) only can remain within an acceptable range, being imposed by the C1 non-controlled diode rectifier. During the entire test, the power balance between the two DC buses is always guaranteed by a proper control strategy, and especially thanks to the bus voltage regulation capability of BESS converter.

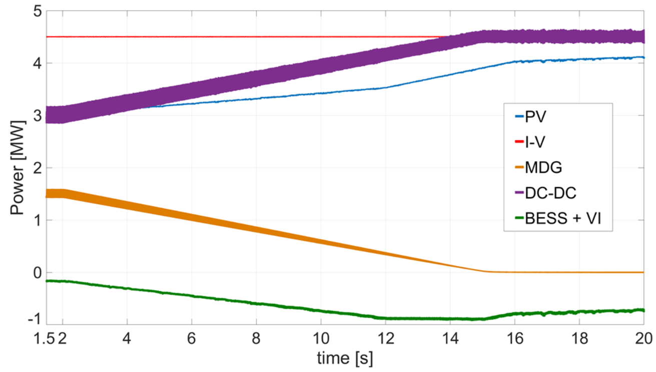


Fig. 4. Power transients in low-demanding scenario.

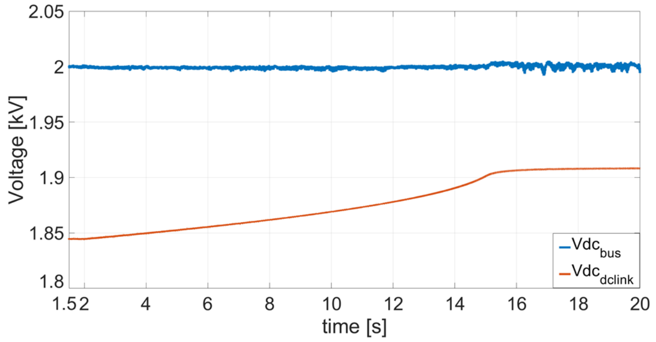


Fig. 5. Bus voltage transients in low-demanding scenario.

B. *Green Power Supply in Low-demanding Scenario*

In this second case, the coordination of DC microgrid converters is analyzed during the weekend, when the industrial cluster load is almost constant and lower, about 4.5 MW as in Fig. 1. In this low-demanding scenario, there is the possibility to achieve a full-renewable power supply also thanks to contribution of battery storage. For such a reason, this test acquires a notable importance when pursuing the sustainability target. To better discuss about this green power supply, some tests are run on PSCAD to obtain both power and voltage transients (Figs. 4-5). The test starts by assuming the system in steady-state. The 2 MW industrial load on VI factory is still disconnected (as in the end of previous test), while the voltage regulation role is still assigned to the BESS. In Fig. 4, the PV power output is initially equal to 3 MW (blue line), then constituting a power contribution through the C4 buck converter (purple line). Evidently, the residual demand is provided by the MDG, as in the orange line. To compensate for this external power supply, the essential function of battery storage B and an increase in solar radiation appear to be mandatory. This lucky eventuality is treated in the test, when the solar radiation slowly goes up (blue line) and the BESS supports the PV in providing power to the I-V factories (green line). At approximately 15 s, the power output from MDG is zero (orange line) and the industrial cluster (red line) is fully powered by PV and BESS. As the PV power quota then keeps a slow increase, thus the power output required from BESS consequently diminishes. For the entire test duration, the bus voltages are offered in Fig. 5. The blue line is the 2 kV bus, which is regulated by the battery converter. While the orange line refers to the 1.8 kV bus supplied by the MDG. Again, this bus voltage is not regulated but imposed through the diode rectifier. Nonetheless, the voltage stays inside the acceptable limits. This test shows how the controlled DC microgrid can provide the green supply of industrial cluster in specific conditions. This important result is made possible thanks to the coordination of different converters and the important contribution from the integrated energy storage device.

IV. Conclusions

The paper has discussed about the coordinated power routing to supply an industrial cluster with green energy. The energy storage system and the renewable PV source are the main elements to achieve this important result. Of no less importance, the power architecture to integrate battery and photovoltaic plant. In this regard, a controlled DC grid is the power architecture on which coordinate the electronics converters in reaching the sustainability goals. In this task, important is the role of control to smartly manage both grid-following and grid-forming inverters as well as DC-DC interfaces. In a realist working cycle, two load requests are studied to highlight the green power contribution, in standard working days and during the weekend. Thanks to the buffer functionality of battery storage system, the available PV power can entirely supply the industrial cluster of loads in low-demanding scenario. This result is noteworthy as it demonstrates how the green energy can even support the power demand of an industrial cluster.

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