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## USING LOCAL RENEWABLE ENERGY TO ENERGISE A MICROGRID: IMPACT OF THE SHARE OF GRID FORMING INVERTERS

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### ABSTRACT

*When a portion of the low-voltage distribution grid, typically a village, is disconnected from the upstream network due to a fault or for maintenance, the Distribution System Operator (DSO) can temporarily re-energize it. Usually, the black-start capabilities in such a scenario are provided by a diesel generator which is conveyed to the islanded grid portion. However, less direct carbon emissions and higher resilience could be achieved if the islanded grid could be re-energized by using the available local renewable power generation. This requires changing the controllers of some of the currently grid-following residential photovoltaic inverters to grid-forming control mode, so that they can provide black-start capabilities and impose frequency and voltage. This paper studies the minimal ratio of grid-forming over grid-following inverters. It shows that for the case of the chosen grid, a stability limit exists as a function of the number of grid-following inverters and for a given capacity of grid-forming inverters. Other parameters such as the repartition of grid-forming capacity over several devices are studied.*

### I- INTRODUCTION

With the urgent need to reduce emissions due to electricity generation, increasing attention is given to grids fully based on renewable energy sources (RES), especially at the microgrid scale. RES in microgrids are mainly decentralized and connected via power electronic converters, requiring control strategies that are fundamentally different from the ones used with synchronous generators. Some demonstrators, listed in [1], are already up and running to confront the newly developed inverter controllers with real-life conditions. Many of those demonstrators have the vocation to be used to temporarily supply a portion of the distribution network in case of upstream fault, as this is the case for the DEMOCRAT and AusNet GESS demonstrators [1].

However, this paper intends to go a step further by considering the particular case of a grid that would not have been originally designed to be operated in islanded mode, and without allowing the addition of any external source. This applies to portions of the low-voltage (LV) distribution grid that a distribution system operator (DSO) would like to temporarily operate in islanded mode following a fault or maintenance on the upstream grid, but without bringing the traditional diesel generator. The two

major challenges when considering this particular case are the robustness of the procedure, which must remain valid for different LV grid topologies and without a communication network, and its simplicity, which can be reflected by the minimization of changes required to maintain the stability of the grid when switching to an emergency mode of operation.

Today, in the distribution grid, inverters are connected in grid-following (GFL) mode (cf. Section II). However, GFL inverters are not able to create and maintain the grid voltage. Consequently, for re-energization, grid-forming (GFM) inverters need to be used instead, as they can create and stabilize the grid voltage. In [2], GFM units first black-start the microgrid, and only then loads can be reconnected, followed by GFL inverters. The reconnection of loads and GFL inverters is conducted with the help of smart meters, which manage the switching times of the grid elements. In [3], a similar procedure is employed, but using only two GFM inverters and no GFL inverter. In [4], the black start procedure relies mainly on the possibility to sectionalize the microgrid at several points, which is not possible in a portion of the LV distribution grid.

The above-mentioned papers both consider small grids containing few inverters (GFM and GFL). In such small-size scenarios, interactions between inverters are limited, and the study of the proportion of GFM versus GFL inverters is not meaningful. However, with respect to the aim of minimizing changes in the distribution grid, one of the major objectives is to minimize the number of inverter (currently operating in GFL) to be switched to GFM control. Therefore, it becomes necessary to study the interactions and minimal ratio of GFM over GFL inverters required for the stable operation of the microgrid.

This topic is cited in [5] as an area of research that needs to be investigated, both regarding the number and power rating of the GFM sources required and their spatial location. Indeed, few studies have tackled this issue at the level of the LV distribution grids. Among them, the authors of [6] have determined the minimal share of GFM inverters as a function of the grid inverter. In the case of 100% inverter penetration (i.e. 100 % inverter-based grid), the minimal share of GFM required to maintain stability was found to be 12.1 %. However, the study was based on a distribution and transmission grid with more than 10,000 inverter-based resources, therefore having different characteristics than the considered small-size LV grid.

In [7], a metric called System Grid-Forming Capacity (SGFC) has been developed, which is the ratio of the GFM inverter capacity over the total (GFM+GFL) inverter capacity. A lower bound of 37,5% to ensure system

stability has been determined by the authors. Again, the simulations in this work are based on a transmission grid, but the results are highly different from the ones in [6]. Moreover, the authors of [7] suggest that the results can vary a lot depending on the spatial location of the inverters in the grid (close or far from the major load centres), and they assume that all their converters are “large in size”. In [5], the authors claim that in a given network, small grid-forming units are unable to maintain stability, and that the stability can be threatened if the ratio of the capacities of two grid-forming units is too large (in a 2-GFM-unit grid). They also state that a grid with a few large GFM units is more favourable in terms of stability than a grid with many small GFM units. Finally, they assert that GFM units far away from each other will synchronize more easily than units that are close together.

Consequently, it appears that the topic of the ratio of GFM/GFL inverters required in an inverter-based microgrid needs to be further investigated, especially for the LV distribution grids. In this paper, a portion of an LV, inverter-based distribution grid is simulated in islanded conditions with a focus on the impact of the ratio of GFM/GFL inverters on the success of the black start of this microgrid. This constitutes a preliminary study of the establishment of a re-energization procedure for a portion of the LV distribution grid from local renewable sources, which will be addressed in future work.

The remainder of the paper is organised as follows: in section II, the GFM and GFL models and controllers are presented, along with the load and grid models. In section III, the methodology used in the paper is described. The results are exposed in section IV.

## II- MODELS AND CONTROL SCHEMES

Traditionally, inverters connected to the main grid are controlled in GFL mode. However, the GFM type of control is given more and more attention today. These two types of control are presented in this section. Both types of control have been implemented in the dq0 rotating frame.

### Grid-following controller

Inverters controlled in GFL mode can be modelled as a current source [8]. In the implemented model, the upstream PV source + boost converter is also modelled as a controllable current source. The GFL controller is presented in Fig. 1. GFL inverters are given a DC voltage set-point, which is then converted into a current set-point by the DC bus controller. A phase lock loop (PLL) is used to retrieve the frequency of the grid voltage. The reference signal is then converted into a pulse width modulation (PWM) signal and fed to the inverter switches.

In this paper, the DC bus is modelled by a controllable DC source. The low-pass filter is made of a series RL-filter and a shunt C filter. Those two considerations apply to the GFM inverter as well.

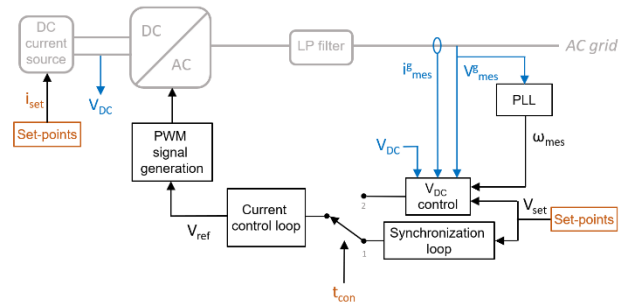


Fig. 1: Grid-following controller

### Grid-forming controller

The GFM model is based on the model developed in the MIGRATE project [9]. The control scheme is presented in Fig. 2. GFM inverters can be modelled as voltage sources. They are given frequency and voltage set-points which are used to generate the PWM signals via a cascaded voltage and current loop, both using PI controllers. A droop controller is also implemented to ensure power sharing with the other inverters, and a virtual impedance bloc is implemented to ensure better stability performances [9].

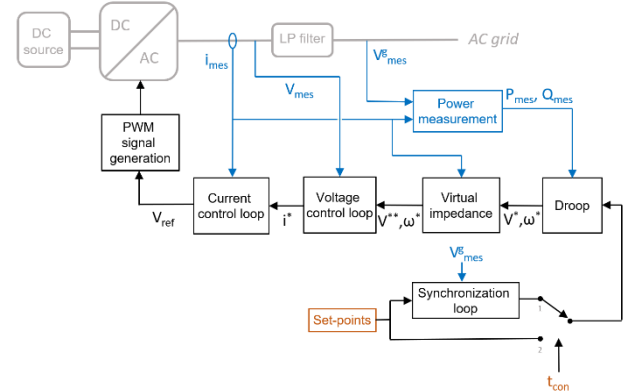


Fig. 2: Grid-forming controller. Note: The Master GFM does not have a synchronization loop.

### Load

A residential load model has been built, based on an exponential load model expressed in (1).

$$P = P_0 \left( \frac{V}{V_0} \right)^\alpha \quad \text{and} \quad Q = P_0 \tan(\varphi) \left( \frac{V}{V_0} \right)^\beta \quad (1)$$

The following parameters have been selected to represent a residential load in summer:  $\alpha=1.2$ ,  $\beta=2.9$  and  $\cos(\varphi)=0.995$ . The model is built as a 3-phase current source with a low-pass filter, which has a time constant of 3.3 ms. A current set-point is sent to the source based on the above equation. The parameter  $P_0$  is varied during the simulation with a step function. Due to the short line distances in the grid, only one aggregated load is considered. Simulations have shown that the location of its point of coupling does not impact the following results. This residential load model has been chosen because it is more representative of a real load than a simple resistive one for example, with which the following results would be greatly affected.

## Grid

The microgrid scheme is pictured in Fig. 3. It is assumed to be a 3-phase AC balanced grid, constituted of 7 buses, each separated by a 100-m line. The main grid parameters are summed up in Table 1.

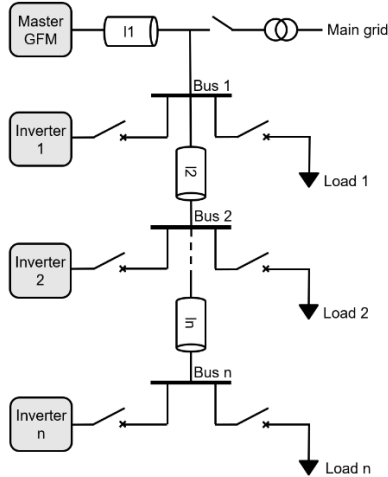


Fig. 3: Simulated microgrid (with  $n=9$ ).

Table 1: Main grid parameters

Parameter	Symbol	Value
Line $l$ length	$l_1$	500 m
Line $i$ length, $i \in [2, 7]$	$l_i$	100 m
Line resistance	$r_{line}$	0.4429 Ohm/km
Line inductance	$l_{line}$	0.3183 mH/km
Line capacitance	$c_{line}$	0.1945 $\mu$ F/km
Nominal RMS L-L voltage	$V_{nom}$	400 V

On each bus, an inverter rated at 6kW and a load are connected via a circuit breaker. The inverter can be controlled either in GFM or GFL. Additionally, on Bus 1, the Master GFM inverter is connected, which is the first inverter to be restarted according to the procedure described in Section II. The Master GFM has a special communication canal with the DSO, and it does not need a synchronization loop since it provides the synchronization reference for the other GFMs.

## III- METHODOLOGY

### Tuning

In most industrial inverters, the tuning parameters are unknown and different from one supplier to the other. Therefore, it did not seem relevant to the authors to look for the optimal tuning of the converter controllers. For the GFM controller, the tuning parameters validated by the MIGRATE project [9] were used; for the GFL controller (identical for all GFL units), the same parameters were varied in a small range around the initial value. The tuning parameters of the PI controllers can be found in Table 2.

The subscript symbol indicates the proportional, integral or derivative gain, while the superscript one indicates the voltage or current control loop.  $m_p$  and  $n_q$  are the active and reactive droop gains, respectively. It is important to note that all parameters are implemented in pu. Therefore, the inverters can easily be scaled up or down.

Table 2: Main tuning parameters for the controllers and filter

GFM control		GFL control		RL-C filter	
$K_p^i$	0.74 pu	$K_p^i$	2 pu	R	0.005 pu
$K_i^i$	1.19 pu	$K_i^i$	1.785 pu	L	0.15 pu
$K_p^v$	0.52 pu	$K_p^{DC}$	0.3 pu	C	0.066 pu
$K_i^v$	1.16 pu	$K_i^{DC}$	0.2 pu		
$m_p$	0.02 pu	$K_p^{PLL}$	0.573 pu		
$n_q$	0.0001 pu	$K_i^{PLL}$	10.191 pu		
		$K_d^{PLL}$	0.003 pu		

### Re-energization procedure

The complete re-energization procedure, inspired by [2], can be seen in Fig. 4. The black start phase consists of two steps: provision of synchronization voltage by the Master GFM, and synchronization and connection of the other GFM inverters. Then, the restoration phase can start with the partial connection of loads and GFL inverters. Block loading is avoided to prevent GFM inverter saturation due to power imbalance. In this paper, the main focus is put on the GFL reconnection step, as described in the following paragraph. There is no intention to define an optimal reconnection strategy: loads and GFL inverters are reconnected in turns, until stability is lost due to an inadequate proportion of GFM power inverters in the grid.

### Variation of the ratio of GFM/GFL

During the restoration phase, it is important to maintain the power balance by making sure that the power injected by the GFLs is never larger than the power consumed by the loads. Indeed, there is no load curtailment algorithm in the GFL inverters.

Therefore, some loads have to be connected before the GFLs; this process can be done partially and repeated (cf. loop in Fig. 4). Consequently, it is necessary to first connect GFM units that can adapt the power supply to the load demand, and then let the GFLs take over. It is important to note that it would be easier to have all units controlled in GFM mode, but it would imply changing all inverters of the LV grid, which is contrary to the change minimization goal.

In this paper, the main focus is on the step highlighted in Fig. 4. In the following section, the implementation of this step in different scenarios is studied, with a focus on the amount of GFL and GFM power connected. To do so, three scenarios are simulated, each one with different repartition of GFM power.

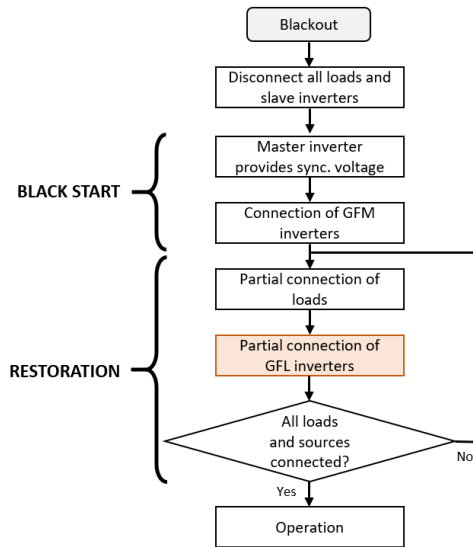


Fig. 4: Flow-chart of the re-energization procedure.

Table 3 describes these scenarios. First, the Master inverter is connected to the microgrid and impose a voltage. The size of the Master is indicated in Table 3. After that GFM1 and GFM2 are connected, depending on the scenario considered. Then a succession of load steps and GFL inverters connections is applied. This sequence is the same for each of the three scenarios, and is indicated in red in Fig. 5. The time between two connections has been chosen long enough so that the voltage has time to stabilize. All the load steps are applied on Load 5, which has a central location in the microgrid. Other loads are disconnected. During the whole procedure, it is made sure that the GFM inverter is not saturated (it never hits its current limits while trying to maintain the power balance).

Table 3: GFM repartition in the three scenarios

	Master GFM	GFM 1	GFM 2
Scenario A	6 kW	/	/
Scenario B	6 kW	6 kW	/
Scenario C	2 kW	2 kW	2 kW

## IV- RESULTS

The microgrid pictured in Fig. 3 is simulated using MATLAB Simulink R2022a, with a fixed time-step of 0.1 ms. The RMS voltage at the output of the master GFM is plotted in Fig. 5. Two main conclusions can be drawn, which are further analysed in the following sections:

- *Comparing Scenarios A and B:* Increasing the GFM power enables the connection of more GFLs while maintaining stability;

- *Comparing Scenarios A and C:* The total GFM power matters, not the number of GFM units. Having the same total rated GFM power located in one or three devices does not change the system behaviour.

Additionally, comparing Scenarios A and B shows that doubling the total GFM power reduces the voltage drop

when connecting the load: this behaviour stems from the virtual impedance control, which creates a voltage drop proportional to the current injected by the inverter. When two inverters are used, the current of each device is divided by two (power is shared proportionally thanks to the droop control) and so is the voltage drop.

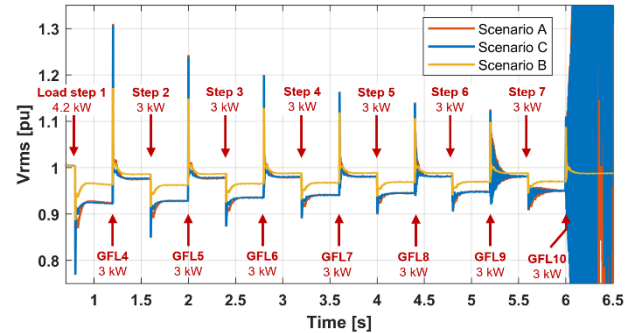


Fig. 5: RMS voltage at the output of the master GFM under Scenarios A, B, and C (All steps are applied to Load 5).

### GFM/GFL ratio: Scenarios A & B

In Fig. 5, for Scenario A, it can be seen that from the connection of GFL8, the transient duration starts to increase substantially, and at  $t=6$  s, when GFL10 is connected, the grid becomes unstable. On the contrary, in Scenario B, the stability is maintained until the end of the simulation. However, if more GFLs are connected in Scenario B, the grid finally becomes unstable (cf. Fig. 6).

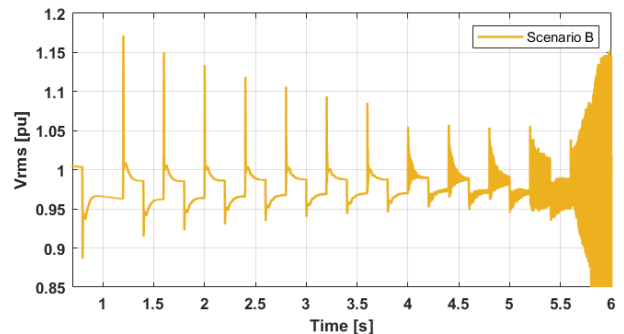


Fig. 6: RMS voltage at the output of the master GFM under Scenario B when connecting up to 12 GFM inverters (the time interval between two connections has been reduced to 0.2s).

To assess the stability improvement brought by the connection of an additional inverter, a metric is developed to measure the duration of a voltage transient: the transient starts when the GFL is connected and ends when the amplitude of the high-frequency (500 Hz) voltage oscillations generated by the connection falls below 0.01 pu. The measurements are gathered in Table 4. The ratio between the GFM available power and the GFL injected power is also calculated. Although this metric is not a criterion for stability, it helps to visualize how fast the system is heading toward instability.

The results from Table 4 show that a critical ratio between GFL and GFM is located between one-quarter and one-

third. However, further simulations have shown that the critical ratio does not only depends on the GFL power injected, but also on the number of GFL devices connected. The spatial location of the connection seems to have no role to play in the selected grid.

Table 4: Transient duration and GFM/GFL ratio in Scenarios A and B in the case with a damping resistor

GFL #	P <sub>GFM</sub> /P <sub>GFL,inj</sub> (%)		Transient duration (ms)	
	Sc. A	Sc. B	Sc. A	Sc. B
4	175.0	350	5	5
5	87.7	175.4	9	5
6	58.4	116.8	13	5
7	43.9	87.8	23	7
8	35.1	70.2	45	9
9	29.2	58.4	183	11
10	25.0	50.0	∞	16
11	-	43.9	-	59
12	-	39.0	-	110
13	-	35.1	-	>200
14	-	31.9	-	>200
15	-	29.2	-	∞

### Capacity and number of devices: Scenarios A & C

In Scenarios A and C, the total GFM capacity connected is the same, but it is located only on one device in Scenario A and spread over three devices in Scenario C. The blue and green lines in Fig. 5 are superposed, showing that there is no difference in the measured RMS voltage between those two scenarios. Therefore, it can be concluded that for this particular grid, it makes more sense to consider the total GFM capacity rather than the number of GFM devices. This result, which has to be confirmed with other configurations and fault events on the grid, is encouraging as it suggests that it would be possible to black start an LV microgrid by using multiple small-capacity GFM inverters, for example, residential solar inverters.

### V- CONCLUSION

This paper is part of ongoing work, which goal is to propose a simple and robust procedure to re-energize an islanded portion of the LV grid without the use of external sources such as a diesel generator and minimizing the need for a storage system (if considering one at all). Simulations have been conducted to identify the limits of GFM inverters when it comes to setting the voltage and frequency in a grid that is substantially larger than the total GFM nominal power. A limit was identified for a ratio of GFM capacity over GFL injected power located between one-quarter and one-third.

Further simulations also suggested that the number of GFL inverter (independently from the total GFL power) could have an impact on the stability, whereas the number of GFM devices not so much. This constitutes a preliminary result in the establishment of a black start procedure for an inverter-based portion of the distribution grid, although many other issues are yet to be solved, regarding intermittency and security for example.

Future work, in which the inverter controllers could

include advanced algorithms such as virtual inertia, virtual synchronous machine, etc., will further investigate those preliminary results. Sensitivity analysis will be carried out by varying parameters such as inverter tuning parameters, line parameters, load characteristics and load step size.

### ACKNOWLEDGMENTS

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