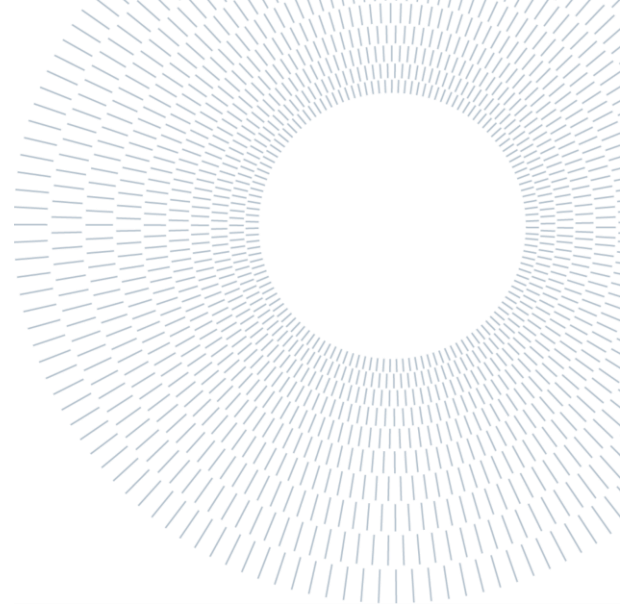




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EXECUTIVE SUMMARY OF THE THESIS

Grid Forming Converter design and application in Distribution Networks with a focus on protection systems

TESI MAGISTRALE ELECTRICAL ENGINEERING – INGEGNERIA ELETTRICA

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1. Introduction

The spread of renewable energy sources has driven the transition from a centralized power system, relying only on traditional synchronous machines (SMs), to a distributed generation power system. Nowadays and in the next years, the power systems are expected to change significantly, with a substantial portion of electricity generated by Inverter Based Resources. The change in generation mix presents significant challenges that must be addressed to ensure a stable and reliable system, but also to enhance system security, efficiency, and continuity in Distribution System Operators (DSO) networks. In this context, innovative inverter operating configurations are making a significant contribution to mitigating the challenges of intermitted power generation [1]. Based on properties and functions of a SM, the Grid Forming Converter (GFC) is envisioned to be the cornerstone of future power systems [2].

In this project, the contribution of Grid Forming Converter into a distribution system with a focus on protection systems is studied.

The first two sections expose the design of the Grid Forming Converter model implemented in DigSilent PowerFactory, and a comprehensive description of the distribution grid structure and its protection systems.

In the third section, three scenarios analyze the GFC and the protection responses to some operational events or fault conditions: a GFC reconnection, a response to a short circuit and an undesired island operation.

Finally, the results section summarizes the main conclusions reached through this research.

2. GFC model

The GFC plays one of the most important roles in the DigSilent PowerFactory model, therefore particular attention has been given to its block scheme, in Figure 2.1. It is based on a Virtual Synchronous Machine (VSM) control enriched with virtual impedance and voltage control.

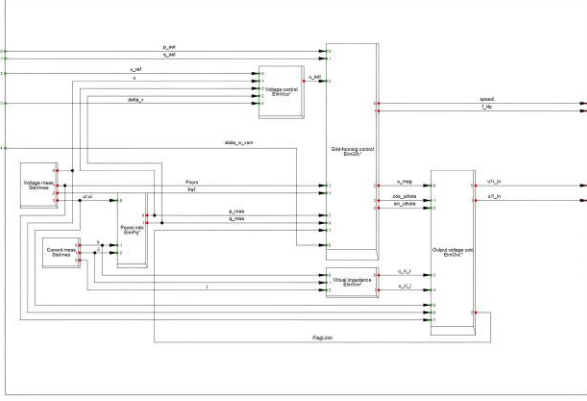


Figure 2.1: GFC block diagram.

The VSM control system works decoupling active and reactive power controls; the first one relies on the swing equation (Eq. 2.1); while the reactive power is controlled by an automatic voltage regulation (AVR) equation (Eq. 2.2).

$$\begin{cases} J \frac{d\omega}{dt} = \frac{P_{set}}{\omega} - \frac{P_{mea}}{\omega} - D_p(\omega - \omega_0) \\ \frac{d\theta}{dt} = \omega \end{cases} \quad (2.1)$$

$$k_q \frac{dE^*}{dt} = Q_{set} - Q_{mea} + k_v(U_n - U) \quad (2.2)$$

An active power primary regulation is introduced in model according to:

$$P_{prim} = P_{set} - P_{mea} - P_{fric} \quad (2.3)$$

Where P_{mea} is the power flowing into the user lines, P_{fric} is the power coming from the primary regulation feedback loop, which can be modified according to the damping coefficient. P_{set} represents the active power setpoint, defined according to the power of the day-ahead market. The VSM voltage inputs are given by a PI controller, based on parameters in Table 2.1.

To limit the over-currents in GFC, a virtual impedance is modelled. Through an algorithm, whenever currents above a predefined limit are detected, it simply produces a voltage to indirectly limit the currents. This effect mimics a series impedance contribute, that is the reasons why it has been called virtual impedance.

The output voltage calculation block gives control signals for the static generator by controlling the real and imaginary parts of the voltage. It combines the voltage coming from the VSM and the one from the virtual impedance.

Considering the maximum current limit, even if the fault current is usually only 1 to 1.5 times the inverter rated one, to better mimic the SM capability of fault drive-through [3], the GFC maximum current limit has been increased up to 3 p.u., allowing for better management of transient overload behavior.

In Table 2.1, some of the most relevant parameters of the model are divided according to the block implementation: general data, VSM parameters, virtual impedance data, output voltage calculation values, and PI controller parameters.

Parameters	Values
Rated Apparent Power [MVA]	0.5
Nominal Voltage [V]	400
Frequency [Hz]	50
Setpoint Power [p.u.]	-0.25
Acceleration time constant [s]	4
Damping coefficient [p.u.]	100
Damping filter frequency [rad/s]	0
Low-pass filter time constant [s]	0.003
Initial speed setting [p.u.]	1
Basic virtual resistance [p.u.]	0.006
Basic virtual reactance [p.u.]	0.006
Overcurrent threshold [p.u.]	1.01
Resistance factor [p.u.]	8
Reactance factor [p.u.]	8
Filter time constant [p.u.]	0.0001
Maximum current [p.u.]	3
Series resistance [%]	0
Series reactance [%]	10
Measurement filter constant [s]	0.02
Voltage regulator gain [p.u.]	50
Integral voltage regulator [1/s]	50
Proportional feedback gain [p.u.]	1
Proportional feedback time [p.u.]	0.01

Table 2.1: GFC parameters.

3. Grid and protection model

In this study case, a tree-shaped single radial network with feeders distributed along the path has been modeled, as displayed in Figure 3.1.

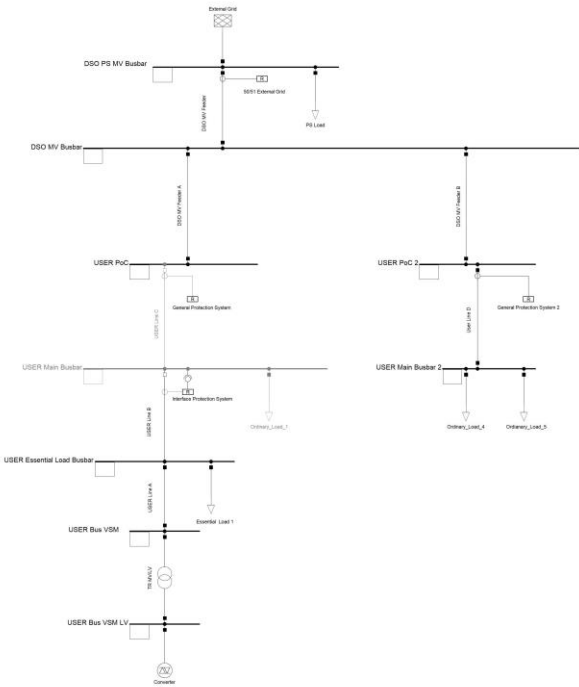


Figure 3.1: Grid diagram.

Protection system

According to CEI 0-16 [4], the grid has been equipped with some protection systems. Specifically, for the MV side of the Primary Station (PS) an overcurrent protection has been installed (50/51 External Grid Protection). While, for both the Active and Passive Users, a General Device (GD and GD 2 respectively) has been designed to disconnect the user's installation from the network, if a fault occurs. The control logic of the just mentioned protections is visible in Figure 3.2, where 50/51 External Grid Protection presents all three thresholds, i.e., $I>$, $I>>$, $I>>>$, while the GDs have just $I>>$ and $I>>>$. The values involved in each logic are available in [4].

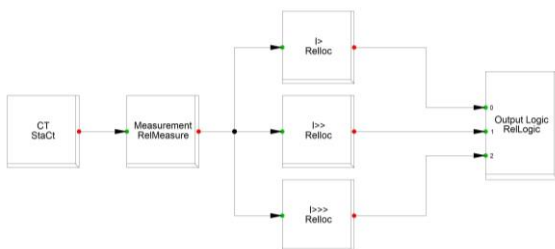


Figure 3.2: Overcurrent protection block scheme.

Nevertheless, GD is not sufficient; an Active User must be provided with other devices such as the Interface Protection System (IPS). Acting on the Interface Device, it disconnects the generation site

from the distribution network. It should avoid unintentional islanding operation, and it prevents the User from sustaining the fault current. The IPS block diagram in Figure 3.3 and all parameters imposed into the logic are taken from the standards of CEI 0-16.

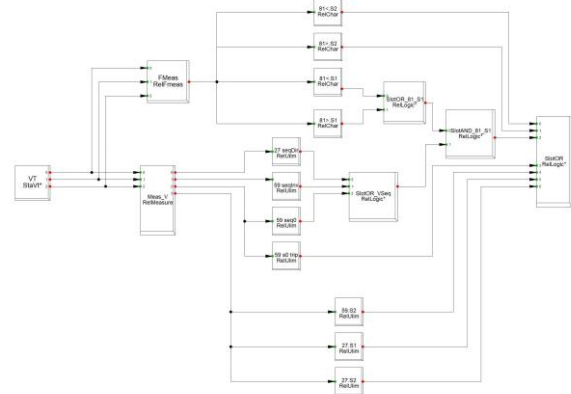


Figure 3.3: IPS block diagram.

In order to better understand the following sections, in Table 3.1 some useful IPS parameters are reported.

Protection	Tripping Threshold	Tripping Time [s]	Reset Time [s]
27.S1	0.85 p.u.	1.50	0.02
27.S2	0.15 p.u.	0.20	0.02
59.S2	1.20 p.u.	0.60	0.02
59V0	0.05 Urn	25.00	3
59Vi	0.15 Un/En	/	3
27Vd	0.70 Un/En	/	3
81>.S1	50.20 Hz	0.15	0.02
81<.S1	49.80 Hz	0.15	0.02
81>.S2	51.50 Hz	1.00	0.02
81<.S2	47.50 Hz	4.00	0.02

Table 3.1: IPS parameters.

Synchro-check

If a transition from a GFC grid-connected operation to an islanded one needs to be done, any differences in frequency, phase and voltage amplitude at the connection point must be eliminated before the breaker is operated. Thus, a resynchronization, called synchro-check, has been implemented, following the model in [5]. Its aim is

to add an incremental reference $\Delta\omega_{VSM}$ to the external frequency reference of the VSM, and a voltage increment ΔV to the VSM voltage control. To compute this, Figure 3.4 shows that the synchro-check needs: the voltages measured on the user network, both on the GFC side and towards the main grid (USER Essential Busbar and USER Main Busbar respectively), the GFC speed and the User frequency measured through a Phase Locked Loop.

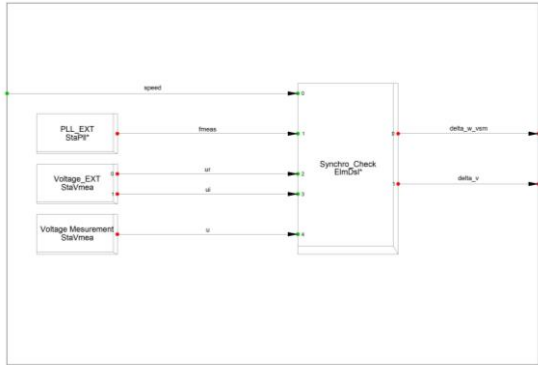


Figure 3.4: Synchro-check block diagram.

4. Simulations

Three different scenarios analyze the GFC behavior into a distribution network, with a focus on the protection system responses.

GFC reconnection

The DigSilent PowerFactory network model is exploited to mimic the reconnection of GFC to the main grid, in a time interval of 15 seconds.

Before the simulation starts, the external grid is feeding the Primary Station Load and Passive User side, while the GFC is taking care of its Essential Loads, working as an island. The General Device is open, as well as the Interface Device.

Simulating a real process of reconnection, first the upstream network (Ordinary Load) is re-powered by the external electric system; then, the GFC is reconnected to the main grid.

In the time interval between 0 s and 15 s the GFC is supplying just the Essential_Load_1, as evident in Figure 4.1. The network powered by the GFC is connected to the main grid, through the reclosure of the Interface Device. After a transient, a new steady-state condition is established and the power goes back to a constant value lower than the previous one, since now the external grid is supporting the load too. As visible from the

reactive power trend, the inductive contribution of the load has more impact on the grid supplied by the GFC. While, after 15 s, a bigger capacity contribution of the cable lines makes the GFC absorb inductive reactive power.

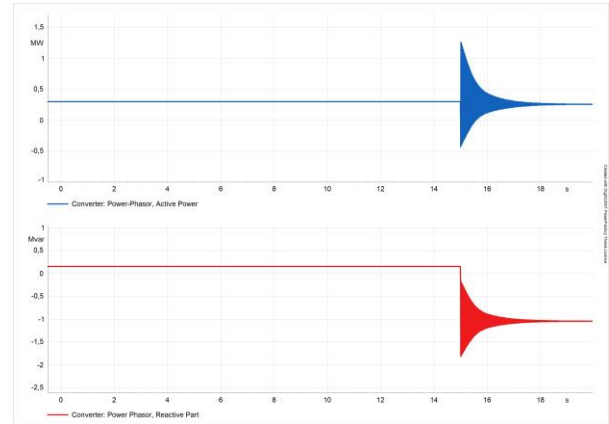


Figure 4.1: GFC active and reactive power.

The frequency, the voltage and the current on the GFC, measured on LV side, have a relevant variation at 15 s, due to the connection of the GFC to the main grid. However, all of them succeed in reaching a steady-state condition. The current transient follows a similar profile to the power transient, as it is largely influenced by it.

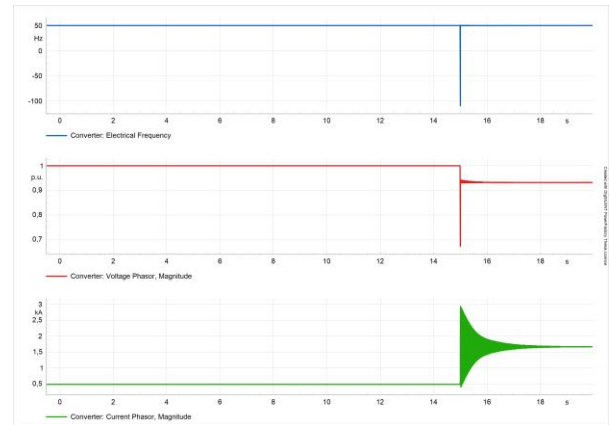


Figure 4.2: GFC frequency, voltage and current at LV side.

Figure 4.3 shows the IPS response at 15 s, once the GFC is connected to the main grid. The frequency overcomes both the restrictive lower and upper frequency limits; however, since the conditions last less than the response time of the switch, none of the logic is triggered.

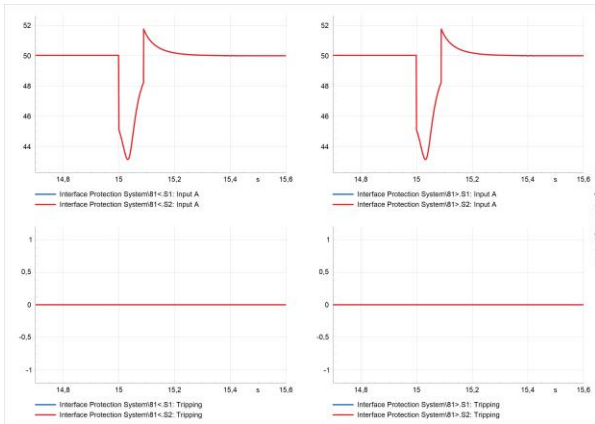


Figure 4.3: 81 logic of IPS.

In Figure 4.4 both the 27 and 59 thresholds are overpassed but the time in which the overvoltage occurs is not enough to trip the protections. For this reason, the output of the tripping protections remains zero. Hence, the GFC has been able to correctly reconnect to the main grid.

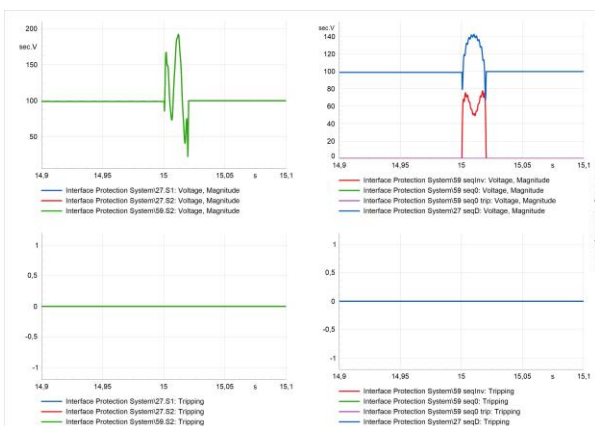


Figure 4.4: 27 and 59 logics of IPS.

Short circuit on Passive User

At 20 s a three-phase short circuit occurs on the Passive network, specifically on the USER Main Busbar 2. Once the short circuit is solved, the process of grid re-powering begins. Specifically, the main grid re-powers the upstream loads, then the island supplied by the GFC can be reconnected to the main grid and, at the end, the faulted network can be reconnected too.

In a real network, the fault might need more than a few seconds (sometimes hours) to be solved and to re-establish the ordinary distribution network operation. However, due to computational time requirements, the three-phase short circuit has been extinguished at 25 s, which means 5 s after the fault event.

In this study case, the short-circuit is characterized by a fault resistance of 5 Ω and causes the trip of three relays of the protection system:

- t = 20.0408 s: General Device 2
- t = 20.0414 s: 50/51 External Grid Protection
- t = 20.3904 s: Interface Device

In Figure 4.5, it is visible that once the three-phase short circuit occurs at 20 s, the active power drops for the time interval in which the protections are tripping. After that, both active and reactive power reestablish their trend to supply the essential loads. At 45 s, the GFC is reconnected to the main grid, therefore a transient arises. At 50 s, the GD 2, protection of the Passive User, closes and a small perturbation is detected, after that the system is back in steady-state conditions.

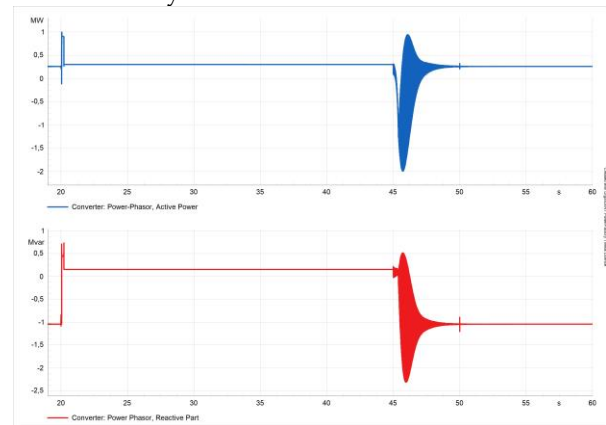


Figure 4.5: GFC active and reactive power after the short circuit.

In Figure 4.6, the GFC frequency is mostly perturbed by the short circuit at 20 s. Even if the frequency has considerably high peaks, this does not create any problems since it lasts for less than 150 ms. Another small transient is noticeable at 50 s, once the Passive User is reconnected to the main grid. The voltage magnitude falls almost to zero when 50/51 External Grid Protection opens. Then, it immediately establishes at 1 p.u. because, also due to the opening of the Interface Device at 20.3904 s, GFC supplies only the Essential Load and the voltage drops along the lines can be considered null. At 45 s, the reconnection to the main grid generates some oscillations which end after the GD 2 reclosure at 50 s. The oscillations of the current measured on the GFC reaches at most 1.85 kA, during the tripping of the protections around 20 s, while once the GFC is reconnected to the main grid its transient peaks in much higher

values. Then the current stabilizes to 1.667 kA, mainly due to the power flow into the entire grid.

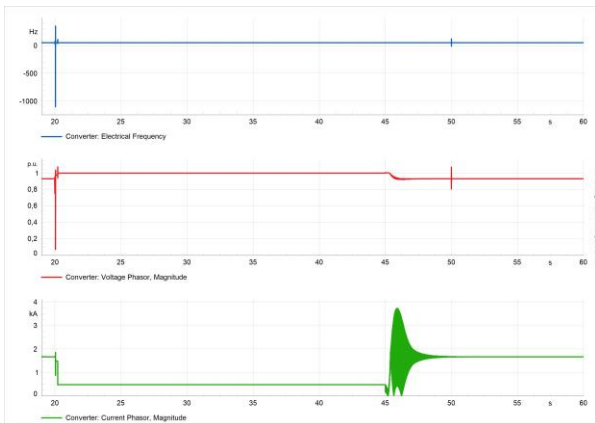


Figure 4.6: GFC frequency, voltage and current magnitude after the short circuit.

Figure 4.7 illustrates the responses of the overcurrent protection. In particular, on the left side there is the 50/51 External Grid Protection response to the overcurrent flowing in DSO MV Feeder, the feeder coming from the Primary Station, at 20.0414 s. Same behavior can be seen on the right plots, the relay of General Device 2 reacts to the overcurrent on the passive side of the network, at 20.0408 s. While the GD keeps its condition unchanged since the current flowing in the active grid side is lower than the limits.

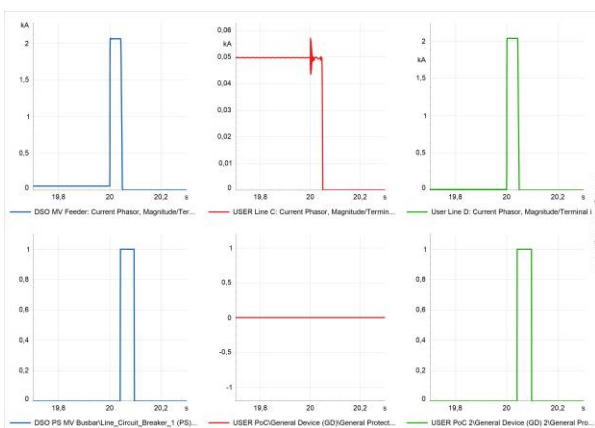


Figure 4.7: 50/51 External Grid, GD and GD 2 tripping outputs.

The three phase short circuit at 20 s causes a variation of frequency into the whole grid. Especially, the frequency transient on the USER Main Busbar triggers the 81>.S1 logic (Figure 4.8). Then, according to the Reset Time reported in Table 3.1, the control logic of the protection returns to its initial state.

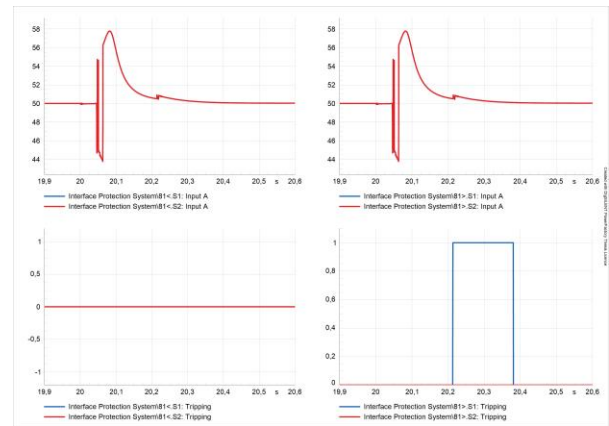


Figure 4.8: 81 relay inputs and outputs.

At 20.07 s, which means 70 ms after the short circuit event, the output of the 27.SeqD becomes 1, since the voltage level dropped below the limits imposed by the logic. This trend, along with the other voltage control logic, is visible in Figure 4.9. It is clear that none of the other voltage relays is triggered in this simulation.

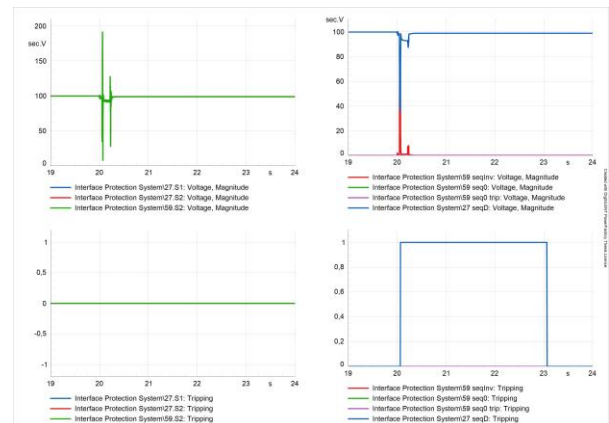


Figure 4.9: 27 and 59 relay inputs and outputs.

According to the IPS logic, the triggering of 27SeqD and 81>.S1 imposes the opening of the Interface Device at 20.3904 s, which means 390 ms after the short circuit event.

Undesired Islanded Operation

This scenario differs from the previous one only by the change of the Ordinary_Load_1: it is now imposed to 0.2 MW. A three-phase short circuit takes place on a busbar on the Passive User network. The overcurrent caused by the short circuit was supposed to trigger the protection devices of the External Grid, while the variation of voltage and frequency was supposed to trigger the Interface Protection System. However, the IPS did not trip, since neither the over/under frequency nor

the over/under voltage withstood long enough to trip the Interface Device, through the operation of the IPS. On the other hand, the 50/51 External Grid Protection has been triggered; hence, the MV busbar of the Primary Station disconnected from the Passive User faulted area. Due to the non-triggering of IPS and the trip of the 50/51 External Grid Protection, the most unwanted event occurred: the instauration of an unintentional island.

The three-phase short circuit with a 5Ω fault resistance, occurred on the USER Main Busbar 2 of the Passive User, caused the trip of only two protection systems:

- $t = 20.0408$ s: General Device 2
- $t = 20.0415$ s: 50/51 External Grid Protection

Figure 4.10 displays that the GFC is feeding autonomously both the Essential and Ordinary Loads between 20 s and 30 s, which means it is sustaining an unintentional island. At 30 s, the Line_Circuit_Breaker_1 of the Primary Station (through the trip of the 50/51 External Grid Protection) is closed, therefore the main grid is reconnected to the undesired island powered by the GFC. This process leads to a transient in both active and reactive power, which brings the power to a new steady-state condition.

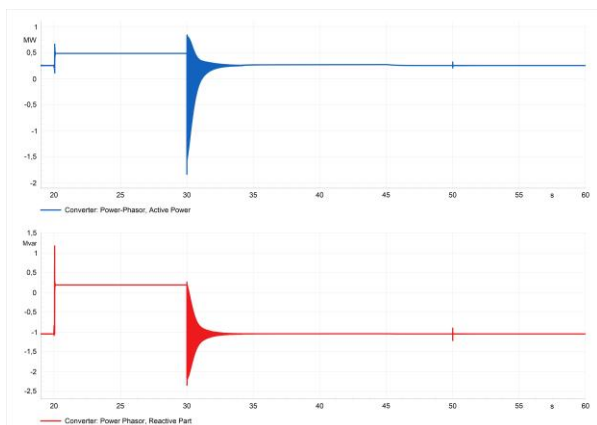


Figure 4.10: GFC active and reactive power.

The GFC frequency is mainly altered at 20 s, when the short circuit occurs and the 50/51 External Grid Protection trips, and at 30 s when the undesired island is reconnected to the main grid. Similar trend can be detected in the voltage magnitude in the middle plot of Figure 4.11. Between 20 s and 30 s, interval in which the undesired island operation takes place, the voltage magnitude of the GFC rises to values close to 1 p.u., thanks to the inner logics

of the converter. In the bottom plot of Figure 4.11, at 30 s the current transient mimics the trend of the reactive power.

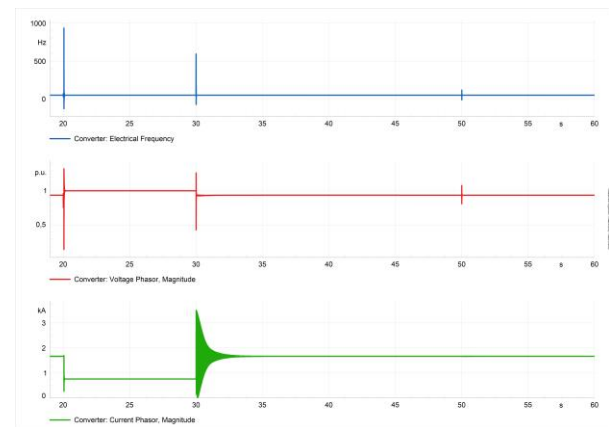


Figure 4.11: GFC frequency, voltage and current magnitude at LV side.

5. Conclusions

This study demonstrates that the integration of Grid Forming Converter into a distribution power system presents both notable benefits and challenges. Key advantages include its ability to contribute to fault current responses and its frequency regulation, effectively mimicking the behavior of Synchronous Machines. These contributions support the overall system stability and enhance performance during disturbances. However, the study also highlights a significant drawback: the risk of unintentional islanding, a condition that is highly undesirable in distribution systems. Hence particular attention should be put on this topic in future research, to ensure the safe and efficient integration of GFCs in distribution networks.

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