

Battery-less grid-forming type converter in an isolated AC microgrid

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Typically, in electrical microgrids (MG), the grid-forming type converter (GFRTC) includes a battery pack at its DC bus; thus, the GFRTC is modelled as a voltage source. In contrast with papers reported in recent literature, where the GFRTC with a battery pack is seen as a voltage source, this work proposes a GFRTC which can be used without a battery pack; with this, the GFRTC operates as a smart load to form the voltage at the point of common coupling (PCC); this is possible, as long as the smart load is supported by a grid-following type converter (GFLTC). This battery-less GFRTC proposal ensures a suitable operation of the isolated MG under linear and nonlinear load conditions. Also, this work proposes a control strategy for both GFRTC and GFLTC with a photovoltaic array. The test results showed that the control proposal allows to form a correct PCC voltage, ensuring a suitable operation of the isolated MG; this while the battery pack is: connected, disconnected, and reconnected to the GFRTC DC bus. This GFRTC proposal is very attractive for isolated MGs where the GFRTC battery pack must be replaced or reconfigured because of new demand profiles, without interrupting the isolated MG operation.

Keywords: grid-following inverters, grid-forming control, grid-forming inverters, microgrids, photovoltaic power systems

1 Introduction

Advances in the fields of Battery Energy Storage Systems (BESS) and Distributed Generation (DG) based on Renewable Energy Sources (RES), allow having the appropriate tools for the correct operation of isolated microgrids (MG) [1]. Since RES and BESS are sources interfaced by power electronics equipment, the MG structure is less endowed with synchronous generators than power electronics devices [2-4], where DG based on power electronics have a much shorter response time than DG based on rotating machines [5]. Although the MG concept is still subject of discussion in the literature, the main idea of the MG concept is based on bringing the power generation as close as possible to where the power is consumed. In most cases, this idea is not possible due to the limitations of the mains infrastructure, thus, DG based on RES is a key element for delivering power to remote areas where the implementation of isolated MG is necessary. Likewise, the power flow control is necessary to perform the MG tasks, thereby, bidirectional power electronics converters (PEC) are required [6]. Based on their functionality within the MG, PECs can be mainly classified as Grid-Forming Type Converter (GFRTC) and Grid-Following Type Converter (GFLTC) [3, 5]. Modeled as a current-source with a high parallel impedance [7], the GFLTC can be operated in both grid-tied mode and isolated mode without significant changes in the control scheme. Through a current injection control, the GFLTC can be operated as a current source which delivers power to the MG system [4]. The

operation and stability of the GFLTC depend on the voltage at the point of common coupling (PCC) as the synchronizing signal, which is obtained by using a Phase-Locked Loop (PLL) [5, 8-12]. Thus, the GFLTC is completely dependent on the existence of the PCC voltage, which is provided by the mains in a grid-tied MG.

Conversely, in absence of the mains, the GFRTC is in charge of regulating, through a voltage regulation control, the AC voltage at the PCC [9], which can be used for feeding loads and synchronizing GFLTC units. It is important to mention that the name of GFRTC is based on the objective pursued by this converter, which is the regulation of a voltage in its terminals, through a specific control scheme. The works reported in the literature model the GFRTC as a voltage source with a small series impedance [7, 10]. Thus, the GFRTC is responsible for maintaining the operation of an isolated MG, and by depending on the conditions and the dynamics of the interconnected elements, the difficulty for regulating the PCC voltage can be minor or major, where the PCC voltage must be a sinusoidal waveform. For example, regulating a sinusoidal voltage at the PCC in nonlinear load conditions becomes more complicated than under linear load conditions, this is because the nonlinear load conditions can distort the PCC voltage and compromise the operation of the interconnected electrical equipment. In terms of the GFRTC control scheme, for linear load conditions, the GFRTC only needs to control the voltage without considering the generated current waveform; conversely, for nonlinear

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load conditions, the GFRTC must include not only the voltage control but a harmonic current compensation, which prevents the PCC voltage from being distorted.

By considering the GFRTC as the voltage source which maintains the isolated MG operation with a sinusoidal PCC voltage, and the GFLTC as the current source which provides power to the MG elements, the coexistence of both GFRTC and GFLTC facilitates the fulfilment of MG tasks. In the recent literature, several works related to the interaction between GFRTC and GFLTC have been reported.

In [5], discussion about the interaction between inverter-based sources and the bulk-power system is addressed; and a distinction between GFRTC and GFLTC is given. The results showed that the GFRTC is a damping source to the frequency swings in the system, while GFLTC aggravates frequency problems due to the increased penetration. With this, including a GFRTC as a damping source within a set of GFLTC units, helps handling stability problems associated with frequency. In [9], the interaction between GFRTC and GFLTC is addressed; the results showed that robust stability is enhanced when a GFRTC is operating nearby GFLTC units. Authors in [13] develop three-phase electro-mechanical models for both GFRTC and GFLTC for large-scale distribution systems; the results showed that the high penetration of GFRTC can improve the stability of the islanded distribution systems. The power-frequency oscillations in systems with different prevalence of GFRTC and GFLTC are investigated in [14], where fundamental differences between GFRTC and GFLTC are discussed. On the one hand, this study reveals that, given the control strategy in each converter, in terms of synchronization mechanism the GFRTC is a power-based oscillator whereas the GFLTC is a voltage-based oscillator; on the other hand, because of the different way in that the inertial capability of both GFRTC and GFLTC is performed, different impacts from each converter on the oscillatory characteristics of the system are expected. In [12], a duality theory which reveals differences and similarities between GFRTC and GFLTC is proposed, this duality is analyzed based on the synchronization loops, grid-interfacing characteristics, controller gains, grid strength compatibility, and transient stability mechanism. In [15], the control design for both GFRTC and GFLTC working together as an isolated MG is presented; the results showed a voltage source behavior by the GFRTC and a current source behavior by the GFLTC. The GFLTC is synchronized with the voltage regulated by the GFRTC; and to charge the battery pack of the GFRTC, the surplus of power delivered by the GFLTC was used.

In the aforementioned works and others where the GFRTC units are implemented as Virtual Synchronous Machines (VSMs) [9, 16-20], the GFRTC is generally visualized as a voltage source where the injected power is regulated by controlling the amplitude and phase angle at the PCC voltage. Authors in [21] claim that at least one of the DG sources in the MG must be included in the GFRTC structure. This strengthens the paradigm where the power to sustain the isolated MG voltage can only come from GFRTC units, which is not strictly true. Currently, the GFRTC units of an isolated MG can also include a PV array as a DG source, however, the intermittency of the PV array can compromise the MG continuous operation. Therefore, given the great responsibility of the GFRTC for sustaining a sinusoidal voltage at the PCC, a battery pack in the GFRTC topology is always included. In this way, the battery pack ensures a continuous delivery of power for the GFRTC operation and for the rest of the MG elements.

In this work, a reduced battery usage in the GFRTC operation is pursued; and even more, the operation of a battery-less GFRTC is achieved. For this, the GFRTC AC voltage must be seen as a reference for power quality monitoring equipment and for synchronizing the GFLTC units, while the power delivery to the loads is performed by the already synchronized GFLTC units. In this way, the operation time of the GFRTC battery pack may be prolonged. The recent literature does not report a GFRTC without the battery pack or the GFRTC battery disconnection during the operation of an isolated MG; this is understandable because GFRTC units must have a properly designed battery pack to face the worst operating scenarios of an isolated MG [22], or to perform multiple ancillary services such as feeder dispatchability, and frequency and voltage regulation [23]. However, the formation of a sinusoidal voltage in an isolated MG can result very attractive with a GFRTC which battery pack can be replaced or modified without interrupting the MG operation. Even more, it can be more attractive in terms of costs when the battery pack is completely omitted from the GFRTC operation.

Therefore, in this paper a topology of an isolated MG under linear and nonlinear load conditions is presented, which includes a GFRTC and a GFLTC with a PV array. The objective is to develop a control scheme which allows the GFRTC to regulate correctly the PCC voltage of the isolated MG in the following conditions: a) when GFRTC battery pack is disconnected and connected, and b) when the battery pack is completely discarded from the GFRTC operation. This allows showing a paradigm change from the operational point of view, where the GFRTC commonly visualized as a voltage source, can be seen as a smart load that sustains a sinusoidal voltage at the PCC in an isolated MG under linear and nonlinear

load conditions. By focusing towards an isolated MG, the contributions of this paper are: i) to present a new control scheme that strengthens the codependency between a battery-less GFRTC and a GFLTC with PV array, avoiding the use of complex algorithms for the optimal PV power extraction, ii) to show that the disconnection and connection of the battery pack in the GFRTC do not affect the voltage regulation at the PCC under nonlinear load conditions, iii) to show at the operational level that the GFRTC can be seen as a smart load and not as a voltage source, iv) to show that the power for regulating the PCC voltage is not restricted to be delivered by GFRTC units. The paper is organized as follows. In Section 2, the isolated MG topology is described. In Section 3, the control proposal is explained. Section 4V shows the simulation results, and finally, in Section 5, the conclusions are presented.

2 System description

In Fig. 1, the topology and the control blocks for the isolated MG are illustrated. The topology is composed by both GFRTC and GFLTC units. Even though the MG prototype is presented only under simulation conditions, commercially available elements were used. The GFRTC includes a single-phase H-Bridge with an LC output filter at the AC bus and a battery pack at the DC bus. The battery pack is formed by the series connection of 25 “L-31T/S-190M” 12 V batteries, obtaining a battery voltage v_{bat} of 300 V. Thus, the GFRTC DC bus voltage v_{C1} is enough to regulate a voltage at the PCC with a peak amplitude of 180 V. The GFRTC is in charge of regulating, under linear and nonlinear load conditions, the AC voltage denoted as v_{C2} , as seen in Fig. 1.

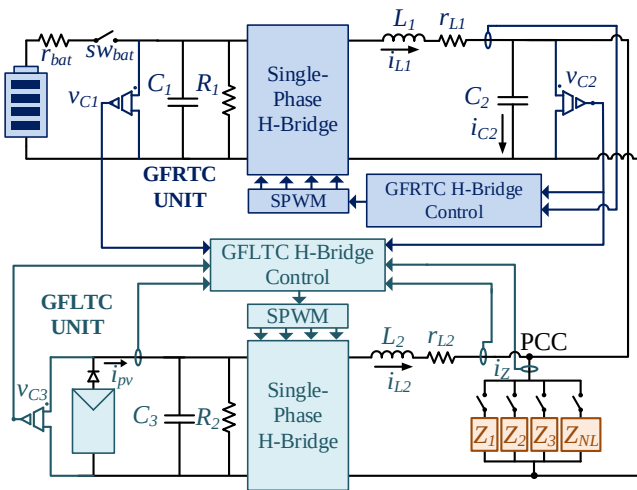


Fig. 1. Isolated MG system topology

Given the focus of this work, the disconnection and reconnection of the battery pack, and the complete operation without the battery pack are considered during the operation of the isolated MG, therefore, a switch denoted as sw_{bat} , seen Fig. 1, is used. The status of sw_{bat} is denoted as ssw_{bat} , which can take the values of one or zero. When $ssw_{bat}=1$ then sw_{bat} is closed and the battery pack is connected to the GFRTC DC bus; conversely, when $ssw_{bat}=0$ then sw_{bat} is opened and the battery pack is disconnected from the GFRTC DC bus. The logical complement of ssw_{bat} is denoted by $\overline{ssw_{bat}}$.

The GFLTC includes a single-phase H-Bridge with an L output filter on the AC bus, and a PV array at the DC bus. Based on [15, 24], the PV array is formed by the series connection of 17 “monocrystalline silicon TUV/CE PV solar cells-DBF30” 30 W modules. To perform load changes during the MG operation, linear loads denoted as Z_1 , Z_2 , and Z_3 , which demand 53.763 W, 80.645 W, and 161.29 W, respectively, are used; also, a nonlinear load denoted as Z_{NL} is included. The GFLTC is in charge of injecting a current to deliver both the reactive and active power demanded by the loads. Also, when the battery pack is disconnected from the GFRTC DC bus, the compensation for the power losses of the GFRTC is covered by the GFLTC. The description and values of the system parameters are given in Tab. 1.

Table 1. GFRTC and GFLTC parameters

Unit	Parameter	Description	Value
GFRTC	r_{bat}	Parasitic resistance of battery	1 Ω
	C_1	DC capacitor	1 mF
	C_2	output capacitor	150 μ F
	R_1	H-Bridge loss resistor	3.6 k Ω
	L_1	Coupling filter inductor	2mH
	r_{L1}	Parasitic resistances of L_1	0.25 Ω
GFLTC	C_3	DC capacitor	1 mF
	R_2	H-Bridge loss resistor	3.6 k Ω
	L_2	Coupling filter inductor	3.5 mH
	r_{L2}	Parasitic resistances of L_2	0.2 Ω

3 Microgrid control strategy

The correct operation and stability of an isolated MG is the result of the contribution of all elements within the system, however, the GFRTC carries out the most important task for maintaining the stability of the MG, which is the regulation of the AC voltage at the PCC. To achieve this, several control strategies for GFRTC have been reported in the literature [16, 25]. These control schemes can be formed by a single control-loop or by a double control-loop [19]. The single control-loop scheme only considers the dynamics of the AC voltage at the PCC, whereas the double control-loop scheme is generally a cascade control composed by an outer-loop to control a voltage and an inner-loop to control the current injected by the GFRTC. Through the double control-loop scheme is possible to regulate the AC voltage while harmonic currents are compensated.

In this work, to regulate the AC voltage at the PCC of the isolated MG in nonlinear load conditions, the cascade control, seen in Fig. 2, is employed. This cascade control is composed of an outer control-loop in charge of regulating the AC voltage v_{C2} in the DQ domain by PI controllers; the reference current denoted as i_{L2}^* is generated through the PI outputs and by using the inner control-loop with an LMI controller, the control signal u_{FR} is obtained. The LMI controller, based on [15], was chosen because of its easy and consistent tuning method. However, instead of LMI controller, any other controller, for example PI, PID, can be used.

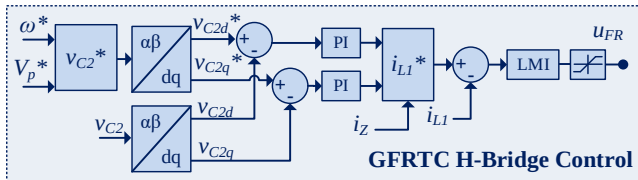


Fig. 2. GFRTC H-bridge control scheme

There is a strong reliance of the GFLTC on the GFRTC, this is because the AC voltage regulated by the GFRTC at the PCC allows synchronizing GFLTC units. Conversely, the GFRTC operation is independent of the GFLTC operation; in addition, in most cases, it is assumed that the GFRTC includes a battery pack, ensuring the regulation of the GFRTC DC bus voltage, which in turn is necessary for regulating the AC voltage. However, when the battery pack is disconnected from the GFRTC or is not included in the GFRTC design, the regulation of the GFRTC DC bus voltage is compromised, which in turn directly affects the AC voltage regulation.

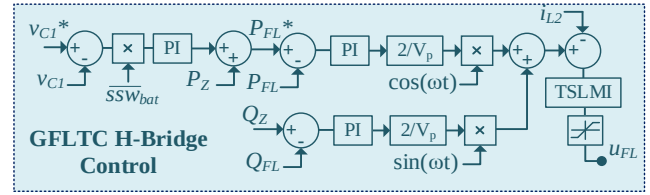


Fig. 3. GFLTC H-bridge control scheme

Based on the GFLTC control design presented in [26], this work proposes a GFLTC H-Bridge Control block, seen in Fig. 1, which corresponds to a four control-loop scheme, as seen in Fig. 3. This control scheme includes a voltage control-loop, which depends on $\overline{ssw}_{bat}$, with a PI controller for regulating the GFRTC DC bus voltage denoted by v_{C1} . Since this voltage control-loop depends on $\overline{ssw}_{bat}$, it is only used when the battery pack is not available. The output of this voltage control loop corresponds to the power losses estimation in the GFRTC. The result of this estimation plus the load active power demand, where this latter is denoted by P_Z , corresponds to an active power reference, denoted by P_{FL}^* , for the active power control-loop. Also, a reactive power control-loop is included; the reactive power reference is the reactive power demanded by the loads, denoted by Q_Z . Both active and reactive power control-loops, with PI controllers, operate in parallel such that they provide a current reference for the current control-loop; through this latter inner-loop, the injected current to the PCC is controlled; such that the power losses in the GFRTC are compensated and load demand is satisfied. As with the GFRTC H-Bridge Control, seen in Fig. 2, any controller in the inner control loop can be employed. However, given the good performance of the controllers based on Takagi-Sugeno (TS) and LMIs for signal tracking tasks [27], a TSLMI controller, based on [15], in the current control-loop is employed.

The GFLTC H-Bridge Control, seen in Fig. 3, is a proposal for isolated MGs without the battery pack in the GFRTC DC bus. In this case, GFRTC is not the only one responsible for keeping stability in the isolated MG, but this responsibility is shared with the GFLTC. On the one hand, the GFRTC supports the MG stability through the regulation of the PCC voltage, while the GFLTC supports the MG stability through both feeding loads and regulating the GFRTC DC bus voltage; thus, the MG stability depends on both the GFRTC and the GFLTC. In most of the isolated MGs, the system stability depends on GFRTC operation and less on the GFLTC operation. However, the backup of a battery pack in the GFRTC is required. Thus, with the GFLTC H-Bridge Control, seen in Fig. 3, the battery pack in the GFRTC can be connected, disconnected and reconnected during the MG operation, or completely discarded from the GFRTC design in a justifiable scenario.

4 Simulation results

Using PSIM, the MG topology shown in Fig. 1 is implemented; a switching frequency of 9.6 kHz for the H-bridges of the GFRTC and the GFLTC is used; also, for commanding the transistors a sinusoidal pulse width modulation (SPWM) is employed. To carry out simulation tests, components of a laboratory prototype implementation based on a digital signal processing (DSP) card were taken into a count; in this way, blocks of Zero-Order-Hold (ZOH), tuned to a frequency of 9.6 kHz, in voltage and current sensors of the MG system are employed. To implement the control proposal for the isolated MG, Simulink/MATLAB was used; therefore, to share both control and sensor signals between PSIM and Simulink, the SimCoupler module was employed. The simulation conditions are shown in Tab. 2, where decoupling and coupling of the battery pack and load changes during the MG operation were performed. In addition, changes in the GFRTC DC voltage reference, within the GFLTC H-Bridge Control, are carried out. As indicated in Tab. 2, to make easier the discussion of the results, each time interval of the simulation was named by the letters A, B, C, D, E, and F. The signals of interest in the discussion of results correspond to the status of the battery pack ssw_{bat} , the control signals u_{FR} , u_{FL} , the DC voltages v_{C1} , v_{C3} , the PCC voltage v_{C2} , the current of load i_Z , and the active power levels of the GFRTC, the GFLTC and the loads, denoted by P_{FR} , P_{FL} , and P_Z , respectively. To satisfy the maximum power demand of the system, in these MG operating conditions, the PV array was properly designed. Also, the nonlinear load is always connected to the PCC, and the linear loads are coupled and decoupled, as seen in Tab. 2. It is important to clarify that the MG system of this work, seen in Fig. 1, corresponds to a specific scenario for highlighting the main idea of the paper, which is to show that the GFRTC can operate without a battery pack.

Table 2. Conditions for the isolated MG simulation tests

Interval name	Time interval (s)	Battery pack	Z_1	Z_2	Z_3	Z_{NL}
A	0–0.99	✓	✗	✗	✗	✓
B	1–1.99	✗	✓	✗	✗	✓
C	2–2.99	✗	✓	✗	✗	✓
D	3–3.99	✗	✗	✓	✗	✓
E	4–4.99	✗	✗	✓	✗	✓
F	5–5.99	✓	✗	✗	✓	✓

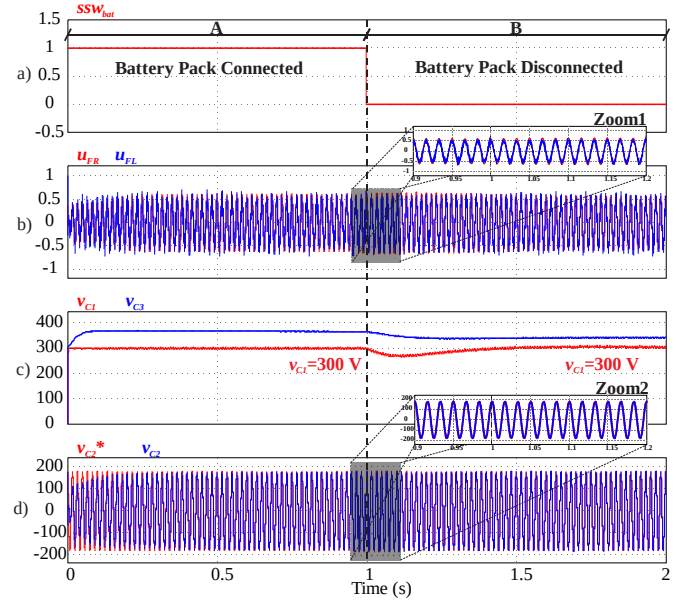


Fig. 4. Isolated MG performance during intervals A and B

In Fig. 4, the results of the isolated MG, for intervals A and B, are shown. As seen in plot a), the MG system starts with ssw_{bat} equal to one, which means that the battery pack is connected; but at the beginning of interval B ssw_{bat} is equal to zero, which indicates that the battery pack has been disconnected. Plot b) shows the evolution of the control signals u_{FR} and u_{FL} , for the GFRTC and the GFLTC, respectively, which operate within the limits of the SPWM. Remember that at the beginning of interval B, both the battery pack disconnection and the coupling of linear load Z_1 are carried out; this causes an imperceptible transient in u_{FR} , which is correctly stabilized, as seen in Zoom1. Plot c) presents the behavior of both the GFRTC and the GFLTC DC bus voltages v_{C1} and v_{C3} , respectively, where a correct evolution of them is observed. At interval B, due to the battery pack disconnection and the load change, smooth transients in both DC voltages are presented; where v_{C1} is stabilized at 300 V, approximately, while v_{C3} is automatically stabilized at 340 V, approximately, which allows adjusting the PV power extraction to the new demand; this demand includes the power losses of the GFRTC plus the demand of Z_1 . This automatic adjustment in v_{C3} is performed by the active power control-loop in the GFLTC control strategy seen in Fig. 3. This allows that the demanded power to be delivered naturally; and it is important to notice that the use of complex algorithms for the optimal PV power extraction is avoided. Plot d) shows the AC voltage regulated by the GFRTC at the PCC, this voltage denoted as v_{C2} presents a smooth evolution during the MG start-up; during interval B, where the battery disconnection and the load change is carried out, v_{C2} does not suffer significant transients, maintaining a good tracking of the reference v_{C2}^* , as seen in Zoom2 from Fig. 4.

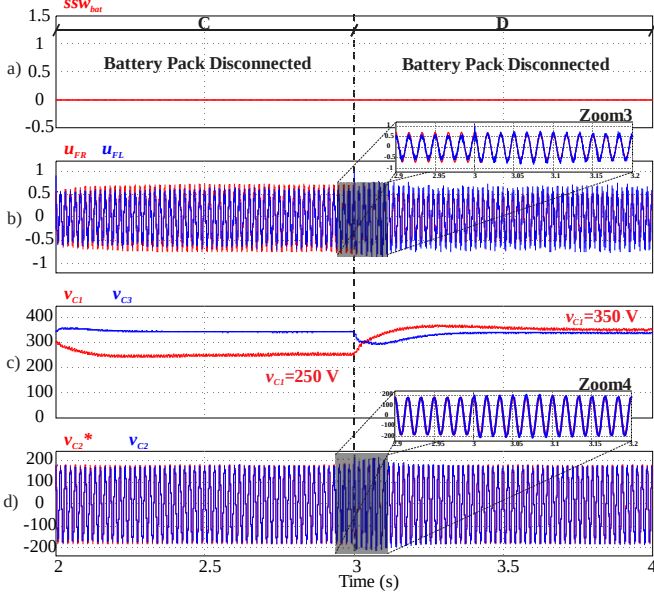


Fig. 5. Isolated MG performance during intervals C and D

In Fig. 5, the system performance during intervals C and D is shown. Plot a) shows that ssw_{bat} is equal to zero in both intervals C and D, which indicates that the GFRTC battery pack is disconnected from the GFRTC DC bus. Plot b) shows the control signals u_{FR} and u_{FL} , which have a good behavior within the SPWM limits, and they present smooth transients at the beginning of interval D, just after Z_1 was replaced by Z_2 , as seen in Zoom3. In plot c), the behavior of v_{C1} and v_{C3} is shown, where v_{C1} is changed from 300 V to 250 V in interval C, which reduces power losses in the GFRTC; at the same time, this slightly reduces v_{C3} such that the PV power extraction satisfies the new demand; for the aforementioned, although changes in the load demand are not presented, the modification of v_{C1} implies an adjustment in v_{C3} . In interval D, the load demand is changed and v_{C1} is increased to 350 V, thus v_{C3} is again modified to under 340 V. Plot d) shows a correct tracking of v_{C2} towards its reference v_{C2}^* . Also, as seen in Zoom4 from Fig. 5, there are no relevant transients in v_{C2} during the transition from interval C to interval D, showing robustness during changes in both the load demand and DC voltages.

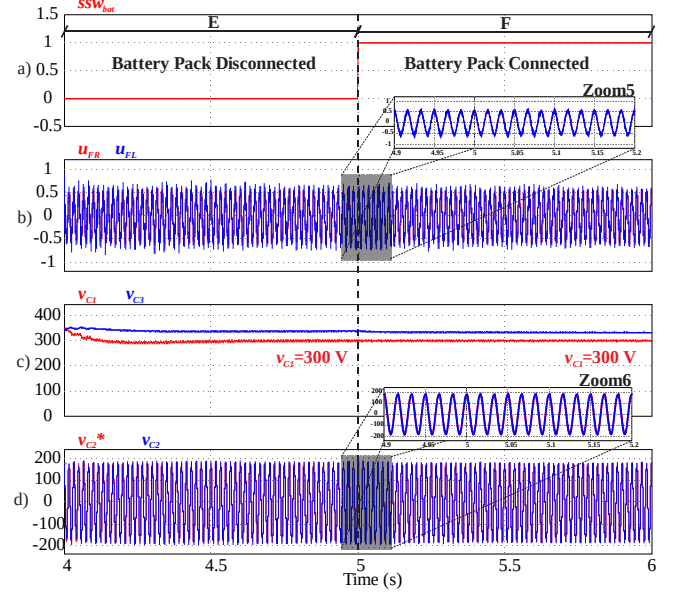


Fig. 6. Isolated MG performance during intervals E and F

In Fig. 6, the MG performance during intervals E and F is illustrated. Plot a) shows that ssw_{bat} is equal to zero in interval E due to the battery pack disconnection; however, in interval F, ssw_{bat} is equal to one, which means that the battery pack is reconnected to the GFRTC DC bus. In plot b), the control signals u_{FR} and u_{FL} are shown; these signals have good behavior within the SPWM limits and as shown in Zoom5, transients during the battery pack reconnection are not presented. In plot c), the behavior of v_{C1} and v_{C3} is shown; in interval E, previous to the battery pack reconnection, v_{C1} is regulated to 300 V. In this interval, the power losses of the GFRTC are still compensated by the GFLTC; however, once the battery pack is reconnected in interval F, the voltage control loop in the GFLTC H-Bridge Control, seen in Fig. 3, is disabled and the power losses in the GFRTC are compensated by the battery pack, thus v_{C3} is adjusted in interval F. Plot d) shows the behavior of v_{C2} , and although both a load change from Z_2 to Z_3 and the battery pack reconnection are carried out, transients in v_{C2} are not presented; and, as seen in Zoom6 from Fig. 6, the tracking of the reference v_{C2}^* is not compromised. These results highlight the system robustness provided by the control proposal, for ensuring the regulation of v_{C2} in an isolated MG while the GFRTC battery pack is disconnected and reconnected.

In Fig. 7, both the behavior of the load current and the active power performance, for intervals A and B, are presented. In interval A, plot a) shows the demand of the nonlinear load Z_{NL} whereas in interval B the linear load Z_1 is connected; thus, as seen in Zoom7, the load demand is raised. Plot b) illustrates the active power evolution during the MG start-up; in interval A, the battery pack provides the active power for the demand of Z_{NL} ; however, in interval B, the battery pack is disconnected; thus, the demand of Z_1 plus Z_{NL} is covered by the PV array of the GFLTC. Notice that, in interval B, the GFRTC power denoted by P_{FR} is negative, this is due to the power losses in the battery-less GFRTC.

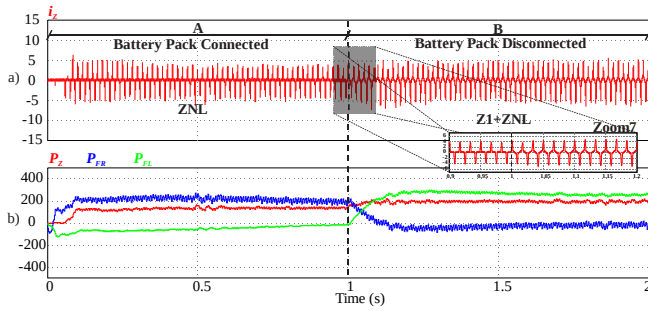


Fig. 7. Load current and active power levels during intervals A and B

Figure 8 shows the behavior of the load current and the active power in the MG for intervals C and D. In Zoom8 from plot a), the change of linear load from Z_1 to Z_2 , at the beginning of interval D, is presented. Plot b) shows the active power evolution, where in both intervals C and D, the load demand and power losses of the GFRTC are covered by the GFLTC.

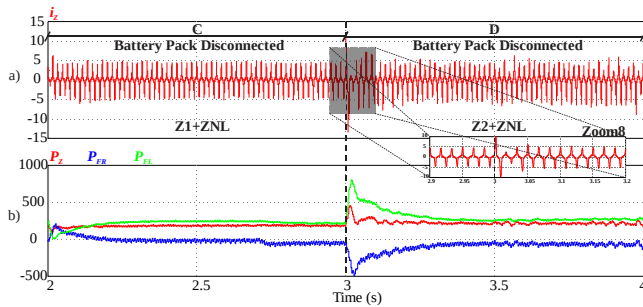


Fig. 8. Load current and active power levels during intervals C and D

In Fig. 9, the behavior of active power and the load current, for intervals E and F, is presented. Plot a) shows the increase of load demand due to the linear load change from Z_2 to Z_3 at the beginning of interval F, when at the same time, the battery pack is reconnected. In plot b), it is possible to observe that the P_{FR} is negative during interval E due to the absorption of the GFLTC active power to compensate for the power losses in the

GFRTC; conversely, once the battery pack is reconnected in interval F, the power losses in the GFRTC are compensated by the battery pack, while the load demand is covered by the GFLTC.

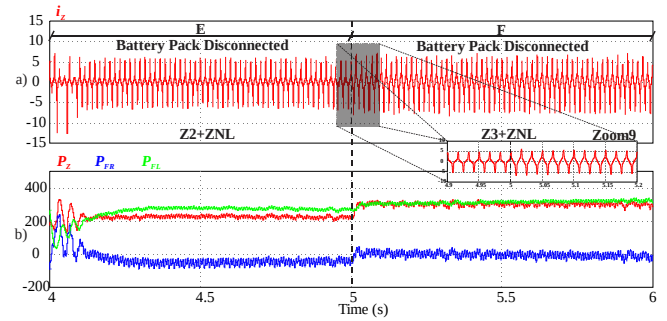


Fig. 9. Load current and active power levels during intervals E and F

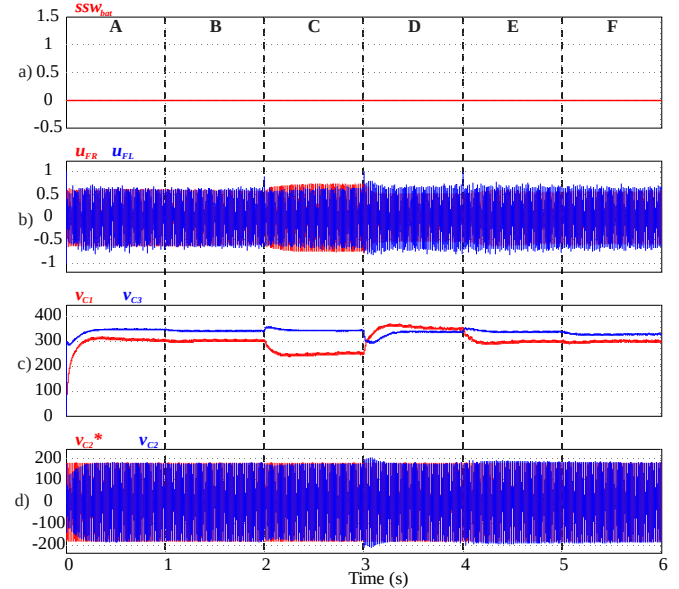


Fig. 10. Whole operation of the isolated MG with battery-less GFRTC

Finally, in Fig. 10, the results of the system behavior, when the GFRTC battery pack is completely discarded from the isolated MG operation, are shown. As seen in plot a), ssw_{bat} is zero for all intervals, which means the battery pack is not connected during the whole MG operation. However, both GFRTC and GFLTC H-Bridge control strategies, seen in Figs. 2 and 3, respectively, allow the GFRTC to behave like a smart load; while the PV power injection, performed by the GFLTC, allows regulating v_{C1} ; this allows maintaining the control signals u_{FR} and u_{FL} within the SPWM limits, as seen in plot b). Plot c) shows the regulation of v_{C1} and v_{C3} through the GFLTC H-Bridge Control proposal seen in Fig. 3. It is important to mention that changes in both v_{C1} and load demand imply an adjustment of v_{C3} for ensuring the correct PV power injection, this adjustment is performed by the GFLTC H-Bridge Control proposal.

With this correct performance in the control signals and DC voltages, the regulation of v_{C2} through the correct tracking of v_{C2}^* is ensured.

For better understanding of how the GFRTC can operate without the battery pack, an analogy with grid-tied active power filters (APF) can be considered. On the one hand, assuming that there is a voltage source, which can be the mains, the APF operates as a variable load for controlling its current consumption; in a similar way, by assuming the GFLTC as a current source, the battery-less GFRTC operates as a smart load by changing its impedance to control the AC voltage in its terminals. In this way, in contrast with most of the works reported in recent literature, where the GFRTC with battery pack is seen as a voltage source, a battery-less GFRTC can be seen as a smart variable load. This smart load is in charge of the regulation of the PCC voltage, ensuring a suitable operation of the isolated MG in linear and nonlinear load conditions.

5 Conclusions

In this work, a control strategy for an isolated MG composed of a GFRTC and a GFLTC with PV array was presented. The control proposal included: a) a cascade control denoted as GFRTC H-Bridge Control for regulating the PCC voltage in the MG; and b) a four control-loop scheme denoted as GFLTC H-Bridge Control for regulating the GFRTC DC voltage and adjusting the PV power injection to the PCC. The results showed that, under the three conditions: i) connection, ii) disconnected and iii) reconnection, of the GFRTC battery pack during the isolated MG operation does not affect the PCC voltage regulation, and thus, the MG stability in linear and nonlinear load conditions is not compromised. From a point of view of system robustness, this may result very attractive for isolated MGs where the GFRTC battery pack must be replaced or reconfigured because of new demand profiles, without interrupting the MG operation. On the other hand, in contrast with most of the works reported in recent literature, where the GFRTC with battery pack is seen as a voltage source, a battery-less GFRTC can be seen as a smart variable load. This smart load is in charge of the regulation of the PCC voltage, ensuring a suitable operation of the isolated MG in linear and nonlinear load conditions.

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