A Strategy for Smooth Microgrid Transitions without Phase Misalignment and Voltage Mismatch

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Keywords

«Microgrid», «Seamless transfer», «Synchronization», «Grid-forming converters», «Voltage Source Converters (VSCs)»

Abstract

In this work, it is proposed a modified control structure to provide smooth transitions of control modes of Grid-forming Converter without phase misalignment and voltage mismatch. A background of the traditional structure is provided and a carefully description of the method is introduced. At the results, a comparison with methods in literature is carried out and it was possible to prove that with the correct phase and voltage compensations, one can almost eliminate the transients in the grid voltage due to the switching of control modes of the Grid-forming Converter and transition of the MG operating mode.

Introduction

The integration of distributed energy resources (DER) with power electronics, energy storage system (ESS), and local loads is starting to be widespread due to the diffusion of Microgrids (MG) in today's power systems. The control and management strategy of a MG depends on its objectives and modes of operations. A MG can operate either connected or disconnected from the utility grid in order to enable the grid-connected or islanded modes. The decision about which operating mode is driven by innumerous reasons, such as economic and environment issues, reliability, power quality, among others. In grid-connected mode, frequency and voltage magnitude are regulated by the main grid and the MG is responsible for the generation and consumption management. In islanded mode, the MG should be able to generate enough active and reactive power to meet local demands, frequency and voltage control, and operate within specified limits regulated by international standards.

Since a MG can operate either connected or disconnected from the utility grid, it needs to transit between the operating modes. The integration of MG at the power system started raising the questions about how secure and reliable the transitions can be to guarantee its continuity of operation. The transition between the operating modes of the MG can happen intentionally, where the islanding can be planned and controlled, producing small transients in the continuity of the MG islanded operation, or unintentionally, when islanding occurs without any predictability, making it impossible to perform previous adjustments to the MG, causing severe transients and hindering the success of its continued operation in islanded mode [1].

According to IEEE 2030-7 standard [2], the implementation approach for the transition from grid-connected to islanded mode is left to the MG designer or operator. For synchronization and grid-connected operation, IEEE 1538-1 standard stablish the limits of voltage, frequency, and phase mismatch for the reconnection at the PCC, but they lack the methodology to cover the synchronization process. During the transitions of MG, two main problems may occur: a phase misalignment resulted by the sudden change of the reference frame in the transformations of the control structure and the transients caused by the switching of the operating modes of the VSI. Although the change from grid-forming to grid-feeding operation of the inverter could be a problem, the main contribution to the transients in the MG during the transition process is due to the phase misalignment and voltage mismatch [3].

In literature, there are several methods used provide smooth transitions of MG. In Arafat [4], a dispatch unit has been utilized, which is responsible for compensation of power variations at the islanding and synchronization by adjusting its output power. In Pilehvar [5], a Smart Inverter is proposed, where the term 'smart' is due to a very carefully switching of phase during transitions modes of a droop-controlled inverter to avoid phase misalignment, large voltage, and power oscillations. In Talapur [6] , a modified PLL loop for a grid-forming converter has been introduced to avoid the aforementioned issues at the islanding, but it increased the complexity of the control structure due to several switching of modes in the structure. Alves [7] proposed an improved synchronization loop with maximum mismatch variation per unit, which could provide a smooth transition from islanded to grid-connected operation. However, the islanding was not studied, and the loop tends to fail at the worst-case scenario of synchronization. Wang [3] proposed a method to estimate the difference phase angle between the grid and VSI reference, but it was only used to synchronization and intentional islanding. In Tran [8] it was proposed a modified PLL structure that was possible to work as a phase detector (PD), providing references of phase during islanding and grid-connected operation without mismatch. However, the unintentional islanding was not investigated, and a smooth synchronization loop was not proposed.

Most of VSI in MG utilize PLLs for grid synchronization, but PLL are known to possess a poor dynamic performance, and a difficult and time-consuming tunning process, which commonly leads to large frequency transients and phase jumps [9] [10]. Besides, a constant voltage excitation for correct phase estimation is another drawback of PLLs. To overcome the problems of PLL, a windowing factor scheme has been proposed in [9] for grid synchronization. However, the estimation strategy is very complex and the tunning process was not cited. Recent trends in MG control with respect to seamless transition have been towards developing faster and advanced PLL or PLL-less solutions to attain grid synchronization [11].

Therefore, a good strategy and procedure for MG transition is essential for traditional controls to avoid large transients and provide smooth transition between the modes of operations of a MG. In this paper it is proposed a modified control structure to provide smooth transitions of modes of MG without high frequency variations, phase misalignment and voltage amplitude mismatch.

VSI Control Structure

The notion of control is central in MGs, since this is what distinguishes a MG from a distribution system with DER, so that they appear to the main grid as a controlled and coordinated unit [12]. The correct operation of the controls of the VSI is necessary for a proper operation the entire MG. In a MG, DERs with a dispatchable energy source, such a battery energy storage system (BESS), use different inverter operation modes depending upon the MG state. The operating mode of the MG determine whether the converter is working as a grid-forming or grid-feeding converter. In grid connected mode, the inverter operates in grid-feeding mode, controlling the active and reactive power that the primary source delivers to the grid, called PQ control. In islanded mode, the inverter operates in grid-forming mode, sharing power with other inverters and controlling the voltage and frequency of the MG, called Vf control. Fig. 1 illustrates the block diagram of the traditional control structure of a VSI that can operate in both modes: grid-forming and grid-feeding.

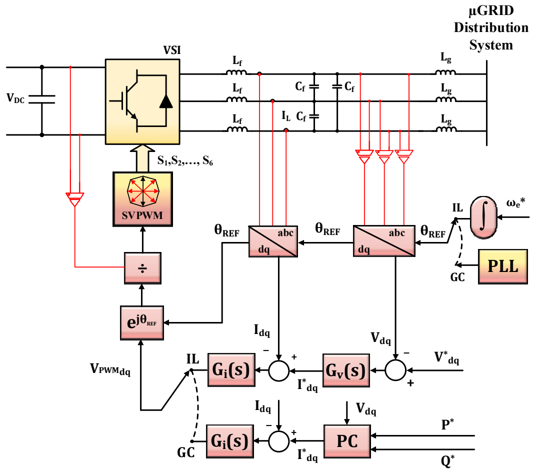


Fig. 1: Traditional control structure of a grid-forming converter with dual mode of operation (adapted from **[8]**).

The references of power and voltage can be provided by local controllers. The voltage controller (VC), represented by the block G_V and current controller (CC), represented by the block G_i, in Fig. 1 are implemented in the synchronous reference frame (SRF) and are Transfer Functions (TF) of Proportional-Integrative (PI) controllers. A power controller (PC) is added for current reference generation based on the references of power at grid-feeding operation.

There are three main problems with the structure provided in Fig. 1. First, under grid-feeding operation, the reference of phase used by the dq transform to the SRF is provided by the main grid, usually estimated by a Phase Locked Loop (PLL), while under grid-forming operation, the reference is generated by an internal oscillator in the VSI. The use of an internal generator is due to security reasons, since PLL needs voltage excitation for correct generation of phase, which is not possible during a grid shutdown. In the transition from grid-feeding to grid-forming operation, a sudden change of phase reference (θ_{REF}) in the VSI switching operation is a big problem faced during the islanding of microgrids due to the high transients of voltage, frequency and current even with no power flow between grid and MG. Second, at the time of reconnection, the lack of smooth method for synchronization of the grid and MG phases tends to provide high frequency fluctuations in the system. Third, the VSIs are programmed to control the voltage of the PCC, whereas for a smooth MG reconnection, a method to compensate the voltage drop along the MG distribution system, as illustrated in the Fig. 2, needs to be devised in order to avoid voltage distortion along the process and inrush of currents during the reconnection.

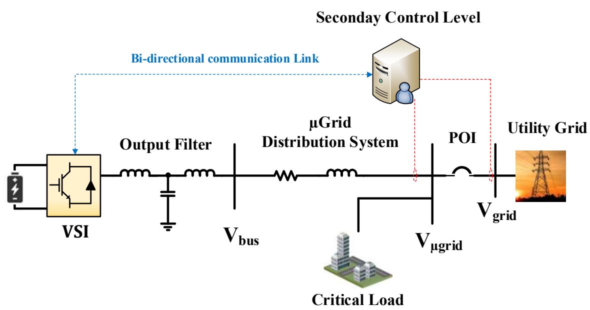


Fig. 2: Typical infrastructure of a Microgrid.

More details of the traditional structure of VC and CC presented in the Fig. 1 can be found in [13]. At the Fig. 2, the interface between the MG and the utility grid is called Point of Interconnection (POI).

Phase estimation and Synchronization Algorithm

The smooth transition between the operation modes of the converter can be summarized on the aim to avoid sudden change of operating point of the VSI. To accomplish this task, the phase reference for the transformations should not change during this process. Therefore, the difference phase angle between the grid voltage and the VSI output needs to be calculated and compensate in the internal reference of the VSI. Other techniques, described in Tran [8] and Alves [7], tried to smoothly change the references of the transformations by integrating the angular frequency over time, slightly increasing or decreasing the angular frequency to avoid sudden change of reference and make the phases match each other. In this work, it is proposed the adjusting of the difference phase angle ($\Delta\theta$) to make the phases match and θ_{REF} can be calculate by (1).

$$\theta_{REF} = \theta_{VSI} + \Delta\theta \tag{1}$$

Where θ_{REF} is the phase reference of the MG and θ_{VSI} is the internal reference of the grid-forming power converter.

If the grid voltage (V_{grid}) and VSI voltage reference (V_{VSI}) vectors rotate at the same angular frequency, they can be treated as stationary vectors. The vector cross product is determined by (2).

$$|V_{grid} \times V_{VSI}| = |V_{grid}||V_{VSI}| \sin \varepsilon_\theta = V_{grid_\alpha} V_{VSI_\beta} - V_{VSI_\alpha} V_{grid_\beta} \tag{2}$$

Where the phase error (ε_θ) between the grid phase (θ_{grid}) and the reference of phase (θ_{REF}) of the MG is given in (3).

$$\varepsilon_\theta = \theta_{grid} - \theta_{REF} \tag{3}$$

Where the α, β subscripts mean the alpha and beta components of the voltage vectors. Therefore, from [14], it is possible to derive the expression of the sine of the phase angle difference between the grid and the inverter voltage vectors. Rearranging the terms, it is possible to obtain (4).

$$|V_{grid}| \sin \varepsilon_\theta = V_{grid_\alpha} \frac{V_{VSI_\beta}}{|V_{VSI}|} - \frac{V_{VSI_\alpha}}{|V_{VSI}|} V_{grid_\beta} \tag{4}$$

From the small signal analysis, the $\sin \varepsilon_\theta \cong \varepsilon_\theta$ if $\varepsilon_\theta \cong 0$. Therefore, (4) can be linearized for small difference angles and be solved continuously, compensating the error with PI controllers. At the steady state, the difference between phase reference of the MG and main grid reference should be zero. The normalized components of the VSI voltage in (4) is obtained by the sine and cosine components of the phase reference. A drawback of this equation is that it only holds for balanced and undistorted grid conditions, since under these circumstances the resulting voltage vector does no vary with amplitude and frequency. To eliminate influence of negative sequences components, the positive sequence component extractor (PSCE) [14] can be used to filter it out of the $\alpha\beta$ components of the grid voltage. The proposed Phase Angle Estimation Block (PAEB) is illustrated in Fig. 3.

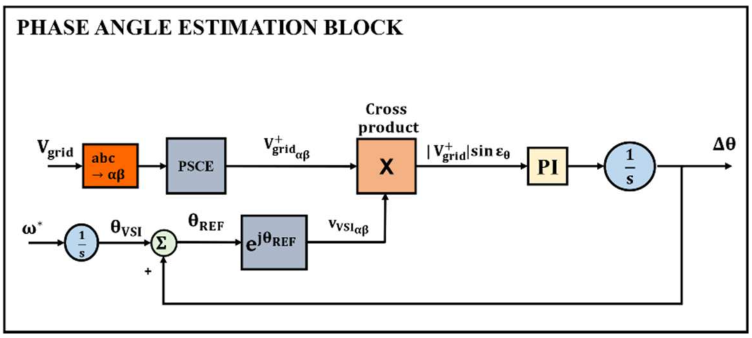


Fig. 3: Control structure of the phase angle detection algorithm.

The closed loop TF is expressed in (5).

$$\frac{\Delta\theta}{\theta_{grid}} = \frac{2\zeta\omega_n s + \omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \tag{5}$$

Where, $\omega_n = \sqrt{K_I \times |V_{grid}^{+}|}$ and $\zeta = (K_p/2)\sqrt{|V_{grid}^{+}|/K_I}$.

The block resembles the heterodyning process utilized to estimate rotor position in induction machines [15]. For synchronization, an additional loop is required in order to provide smooth variation of the difference phase angle.

Instead of estimating the phase angle at each time, the block estimates the difference phase angle between the grid voltage and the internal reference of the power converter. The advantage of the proposed block is that one can have more control over the phase, which is a mandatory requirement for low-inertia power converters, and avoids discontinuous difference phase angle ($\theta_{grid} - \theta_{REF}$) at the transitions. The integrator in the structure has the ability of memory. Therefore, at the time of islanding, the last value of the phase angle can be used by the VSI to avoid a discontinuity in phase and, hence, a sudden change of reference in the transformations of the control structure. At the time of synchronization, the phase angle of the block can be smoothly varied to avoid high frequency variation in the MG. In Fig. 4, it is illustrated the proposed smooth synchronization unit (SSU) to provide seamless reconnection of the MG.

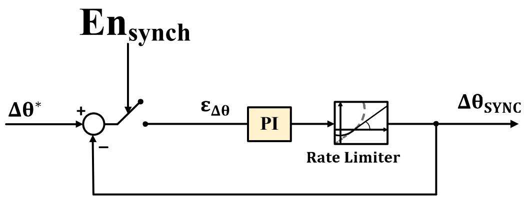


Fig. 4: Control structure of the smooth synchronization algorithm.

The main objective of the SSU is limit the first derivative of the difference phase angle from the PAEB, according to (6), to provide a safe reconnection, avoiding sudden change of reference and high frequency fluctuations in the system.

$$\left|\frac{d(\Delta\theta)}{dt}\right| \leq \lambda \tag{6}$$

Where λ is the maximum variation of the frequency in the MG during the synchronizing process, in rad/s. Limiting the module of the first derivative means to define a maximum variation of frequency (λ) around an operating point, typically 50 or 60 Hz. To guarantee the allowable range of frequency, the IEEE 1547-3 stablishes the variation of ± 1.2 Hz as a continuous operation of the MG. Therefore, the synchronization is carried out without great frequency changes to the system. For the correct operation of the smooth synchronization loop, proper tunning needs to be done. The proportional gain, K_p, is defined as (7).

$$K_p = \frac{\Delta\theta}{e_{ss}} \tag{7}$$

In order to remove steady-state error, e_{ss}, integral gain should be employed and it is evaluated by (8). The value of e_{ss} should be small, typically, in order of 0.1.

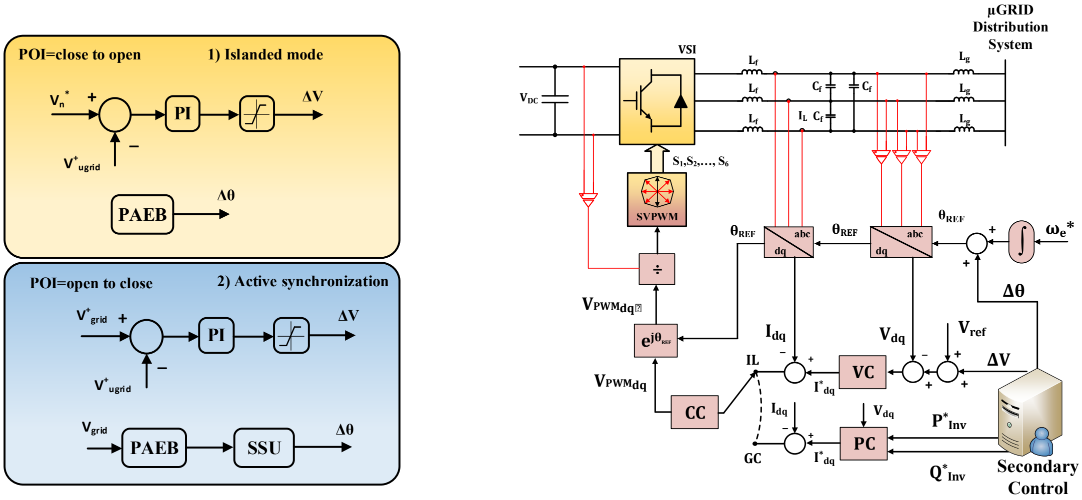
$$K_i = \frac{2\lambda}{\Delta\theta} \tag{8}$$

The proportional and integral gains are adaptive. Before the synchronization starts, the gains are calculated based on the estimated $\Delta\theta$ from PAEB, after that the gains are kept constant and the process initiates.

By using these gains in (7) and (8), the block implements a trapezoidal variation of the frequency for synchronization, which minimize variation and abrupt frequency changes over critical loads. Also, this method possesses a simpler and practical implementation than the one presented in [16].

Control Structure

For correct synchronization and islanding process of the MG, hierarchical control needs to be employed, which, in turns, refers to secondary control level. The secondary control level seeks to manage different operating modes of the MG and prescribe the compensations signals (ΔV and $\Delta\theta$) for primary control level in order to improve the dynamic response of the MG [17]. In Fig. 5 (a), it is shown the controllers used by the secondary control to correctly manage the operation of the MG.



(a) (b)

Fig. 5: (a) Secondary control structure of synchronization and islanding algorithm; (b) Modified control structure in the grid-forming power converter.

At islanded mode, the secondary control is responsible for voltage amplitude correction to the nominal value and the PAEB compensates the phase in order to avoid misalignment during the transitions and switching of mode of the MG and VSI. During the transition from islanded to grid-connected, the SSU, the PAEB and a smooth voltage controller is employed to smoothly vary phase and voltage amplitude of the MG to eliminates high frequency variation and voltage distortion.

The structure of the controller for the grid-forming converter is illustrated in Fig. 5 (b) and possesses the following modification: generation of phase is internal of VSI and is only compensated by the secondary control for operation synchronized to the grid; the voltage reference is compensated by the secondary control based on measurements at the PCC in order to compensate voltage drops along the system; to avoid misalignment of the VSI voltage reference (V_{VSI}) and voltage sags and swells during the switching of operation of the power converter, only the current reference is changed, which is provided by the VC, at islanded operation, while, at the grid-connected mode, by the PC.

The method employed for the PC was the Balanced Positive Sequence Control (BPSC) [18], which provides balanced and positive sequence components to the output current, thus, contributing to the MG power quality. However, this method comes at the cost of a greater oscillatory output power during grid-fault conditions compared with others power control methods [19]. The VC structure was the same implemented in Fig. 5 (b) with feedforward of the current capacitor [20] and state-feedback decoupling [21] to improve MG stability during islanding, specially, unintentional.

Performance Evaluation and Analysis

In order to evaluate the performance of the proposed controllers, comparison with others method in literature were carried out and also the worst-case scenarios, either for synchronism (180 degrees of displacement) or islanding (unintentional), were considered. The system considered for analysis is the same illustrated in Fig. 2, where the parameters are summarized in Table I.

Table I: Parameters for the MG system

Description	Simbology	Values
Current Controller Gains	K_{pc}, K_{ic}	$11.3,\ 2.63 \times 10^3$
Voltage Controller Gains	K_{pv}, K_{iv}	$0.0157,\ 0$
Hierarchical voltage control gains	K_{phc}, K_{ihc}	$0,\ 25$
Filter parameters	L_f, C_f, L_g	$1.8\ mH, 25\ \mu F, 1.8\ mH$
Frequency	f_e	$60\ Hz$

Maximum frequency variation	λ	$7.54\ rad/s$
Rated RMS line-to-line Voltage	V_{line}	380 V

Microgrid reconnection

In this section, the proposed synchronization algorithm is compared to one used in literature [16], illustrated in Fig. 6 (a). A frequently method of MG synchronization utilized in literature is based on sine of phase error between the grid and MG reference, $\sin(\theta_{grid} - \theta_{REF})$. The sine is calculated, since the difference of phases provided is a discontinuous and oscillating function, therefore smooth synchronization cannot be done with it. This method attempts to compensate a difference of phases by minimizing the sine. However, for a 180 degrees of phase difference, no proper synchronization is carried out, as shown in Fig. 6 (b).

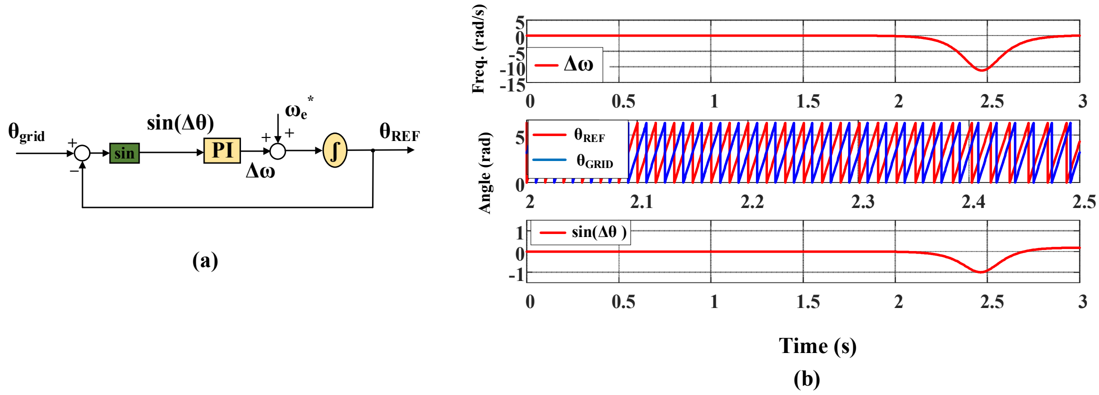
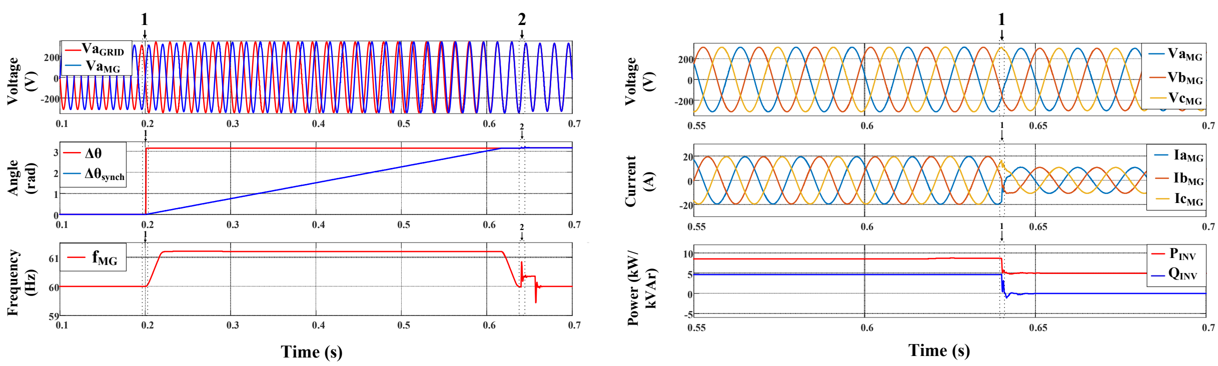


Fig. 6: (a) Classical control structure of synchronization algorithm; (b) Variation of frequency and angle in the MG with synchronization starting at the time of 0 seconds.

The main problems of this loop are the unconstrained frequency variations and low bandwidth response. Better performance could be attained increasing the bandwidth. However, this would mean in a higher oscillation and peak in frequency response of the MG. This is a crucial drawback of this loop, since no proper performance is obtained in the worst-case scenario of displacement. The proposed smooth synchronization loop in Fig. 4 mitigates this problem, insofar as the angle of displacement, Δθ, is utilized for synchronization and the proposed block for angle estimation can correctly estimate the angle of displacement advanced or delayed. Also, it permits lesser variations of frequency in the MG. The Fig. 7 shows the performance of the proposed synchronization loop.



1: At the time of 0.2s, the synchronization starts and the grid voltage is measured for angle and amplitude estimation.
2: At the time of 0.64s, the microgrid is synchronized in both phase and amplitude, then the PCC switch closes and the VSI changes to current source operation.

(a)

1: At the time of 0.64s, the microgrid is synchronized in both phase and amplitude, then the PCC switch closes and the VSI changes to current source operation.

(b)

Fig. 7: (a) Smooth synchronization process; (b) Voltage, VSI power and current outputs during transition of modes of VSI.

At time of 0.2 s, the synchronization starts. The standard allows a reconnection to the grid if the voltage is within a maximum of 110 % of the nominal voltage. Therefore, the grid voltage was programmed to experience an increase of 0.1 pu in the voltage amplitude to evaluate the performance of synchronization. As can be seen, the control permits a smoothly adjustment the references of the VSI without distortion at the MG. Also, the increase in frequency in the MG present a maximum of 1.2 Hz, which is the limit stablished for continuous operation of a MG. At the time of 0.64 s, the MG is synchronized both in amplitude and phase, then the command of closing the POI is sent to the transfer switch and VSI to changes its operation mode. A small oscillation in frequency is experienced in the MG at the time of 0.64 s due to power injection changes from islanded to grid-connected operation and switching of modes of operation. In islanded operation, the VSI is injecting about 8.5 kW and 5 kVAr of active and reactive power, respectively, in the MG distribution system to supply the loads. When the MG migrates for grid-connected operation, the VSI is set to inject only active power, which was pre-defined as 5 kW.

Microgrid disconnection

The unintentional islanding is the worst-case scenario of disconnection of a MG. The decision of the disconnection is usually driven due to grid power quality degradation. The most common degradation of the utility grid power quality happens due to grid faults. When a grid fault occurs at the utility grid, the MG should be disconnected and operate in islanded mode. However, if the transients are highly severe, the system may not be capable of recovering from such conditions and can become unstable, causing a MG blackout and a drop of reliability of the system. The performance of proposed controller was compared to a similar in literature during a phase to ground short circuit at a point near the POI, but in the utility grid, as illustrated in Fig. 8. For a fair comparison, the same bandwidth was utilized, given the similarity in VSI low level control structure. The differences in the proposed method and the one in [6] sum up to the grid phase estimation, the power controller and the feedforward of the output current.

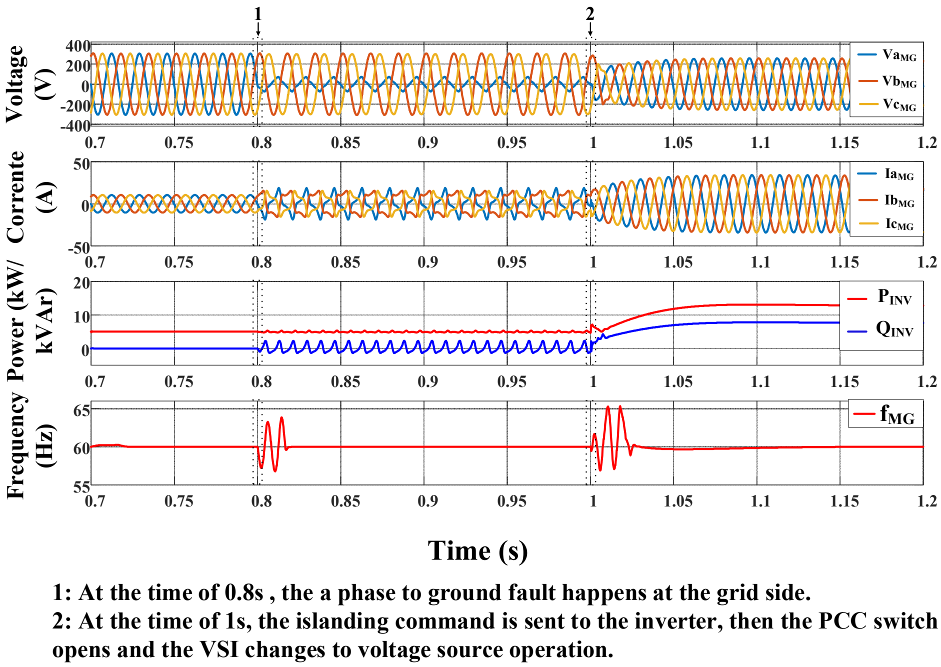


Fig. 8: Voltage, current of VSI, power and frequency in the MG amidst a grid fault with the method proposed by **[6]**.

At the time of 0.7 s, the power drawn by the load is changed to 16 kW and 12 kVAr nominal of active and reactive power, respectively, to simulate a stochasticity with that the controllers need to handle. At 0.8 s, a grid fault occurs at the grid side subjecting the system to a high unbalanced condition. As can be noted, this causes a high distortion of the current injected by the inverter. In [6], the power controller is a simpler one, which did not take into consideration unbalanced conditions and distortion at the MG voltage. As an advantage, the authors proposed a modified PLL structure to avoid phase misalignment during MG islanding. However, the lack of the feedforward of the output current degrades the performance of the controller, so as to during the islanding, the VSI controls takes more time to recover the system and restore the frequency. Also, the load acts as a perturbation and its influence is very high in the output voltage of the VSI, so that a huge gap of the MG voltage at the POI is encountered from the nominal voltage value. The authors did not propose a secondary control to correct the difference of voltage amplitude to the nominal at the POI caused by the influence of the load and the drops along the system. In the case of a real MG, the stochasticity of the loads would bring about voltage fluctuations in the system. The performance of the proposed controllers is illustrated in Fig. 9 during the unintentional islanding with the same scenario and controller gains.

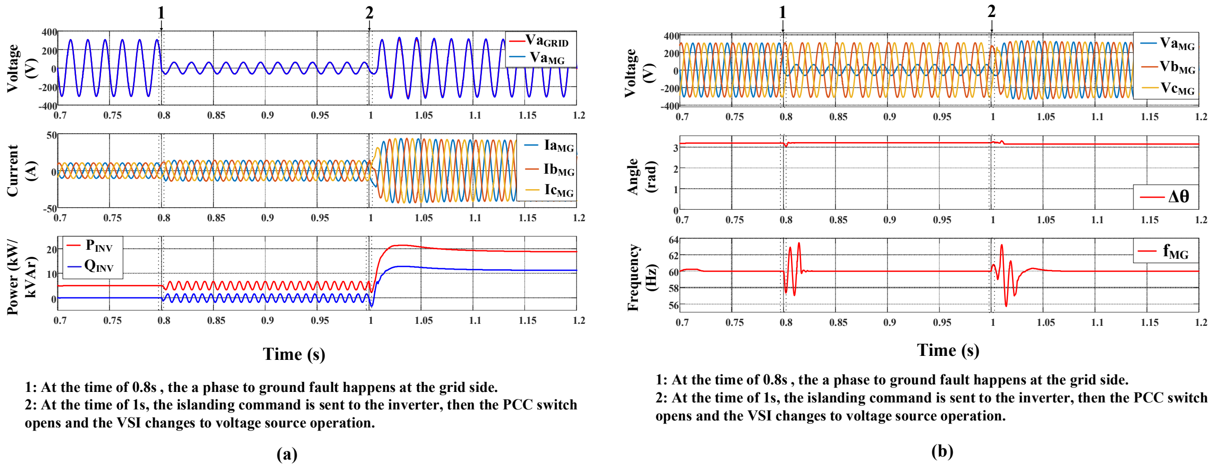


Fig. 9: (a) Voltage, current and VSI output power in the MG amidst a grid fault with the method proposed in this article; (b) Voltage, phase angle and frequency in the MG during the unintentional islanding.

As can be seen in the Fig. 9 (a), the BPSC maintains sinusoidal current components at the output current of the inverter, which it is very important in order to avert damaging the hardware of the VSI, contribute to MG power quality and comply with IEEE standards. Even though, it comes at the cost of a more oscillatory power output, but they are very small, so that the influence on power quality and frequency oscillation is negligible. The MG restoration of voltage and frequency is also very fast, owing to modified controllers employed in the VSI control structure, which improve the dynamic response and ability to resist against perturbations. Besides, the hierarchical control structure, described in Fig. 5, keeps the voltage amplitude to the nominal value.
In the Fig. 9 (b), one sees that the angle estimated by the PAEB hardly changes under the abnormal conditions faced by the MG. This guarantees that the MG does not faced misalignment of phase during the islanding, which would avoid sudden change of reference at the VSI control structure. In turns, providing a seamless intentional islanding and a smooth unintentional one, since the transitory are great minimized.

Conclusion

In this work, it was presented a methodology to avoid phase misalignment and voltage mismatch at the MG transitions. It was shown that the estimation of phase angle has the advantage of avoiding the discontinuous phase, which facilitates the synchronization, even in the worst-case scenarios, where the most techniques fails. By using the SSU, it was able to provide a smooth variation of phase by limiting the variation in frequency in order to comply the IEEE standards and averting large frequency variations due to an instantaneous change of reference. The control structure proposed also was able to increase the resilience of MG amidst abrupt grid conditions, such as faults, load changes, and provide smooth variation of amplitude voltage for synchronization and islanded operation in order to eliminate voltage distortion in the MG.

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