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Digital Object Identifier (DOI): 10.1109/ECCE.2014.6954124

Energy Conversion Congress and Exposition (ECCE), 2014 IEEE; September 2014
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Suggested Citation

G. Buticchi, M. Liserre, D. Barater, C. Concari, A. Soldati and G. Franceschini, "Frequency-based control of a micro-grid with multiple renewable energy sources," *2014 IEEE Energy Conversion Congress and Exposition (ECCE)*, Pittsburgh, PA, 2014, pp. 5273-5280.

Frequency-Based Control of a Micro-grid with Multiple Renewable Energy Sources

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Abstract—Stand-alone micro-grids need a proper management of the active power exchange. This work is focused on the parallel operation of multiple grid-connected converters in an island-grid system. The proposed solution features a master inverter which emulates the grid and multiple grid-connected converters operating in parallel. The current sharing and overload protection is achieved by small frequency variations of master inverter's output, that are detected by the grid-connected converters. This mechanism exploits the behavior of the derating characteristics embedded in grid-connected inverters, that must reduce the output power if the grid frequency increases. In this case, standard grid-connected equipment can be used to realize micro-grids without the need of digital communication between the power units. Two possible scenarios are analyzed: low-power microgrid with master/slave converters, and low voltage grid fed by a Smart Transformer (ST) which performs the frequency control.

I. INTRODUCTION

The importance of distributed power generation systems (DPGS) has increased over the years due to the modifications of the electric grid caused by a still increasing penetration of renewable energy sources and the increasing cost of the distribution. Among the renewable energy sources employed in this framework, photovoltaic is receiving a great attention. Photovoltaic systems can be divided into island-grid, or stand alone, where the converters supply local loads, and grid-connected, where the power produced by the panels, that is not absorbed by local loads, is transferred to the electrical grid. Stand-alone photovoltaic (PV) systems feature a DC/AC inverter for supplying the AC local loads and a DC/DC converter that regulates the charge of the battery pack. The two power converters are supplied by the photovoltaic field and are usually integrated in a single power structure. This paper is focused on photovoltaic converters, but the same results can be extended to other renewable energy sources.

Two scenarios will be analyzed in this work:

- 1) Grid-interactive micro-grid, a fully decentralized grid where multiple DPGSs are present and the management of the active power must be realized, Fig. 1.
- 2) Smart Transformer, a semi-decentralized approach where the LV grid is separated by the MV grid by the power electronics, and the voltage/frequency of

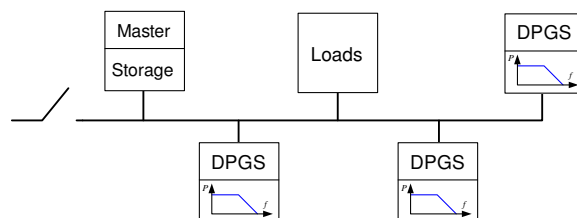


Fig. 1. Structure of the fully-decentralized system with multiple DPGS.

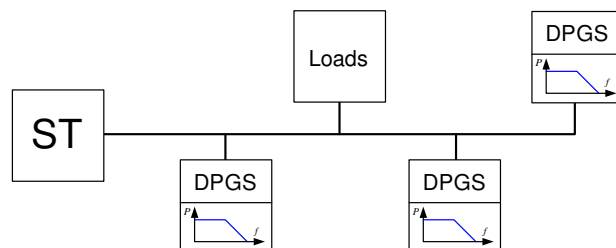


Fig. 2. Structure of the semi-decentralized system with multiple DPGS and ST.

the micro-grid can be controlled independently, Fig. 2.

With respect to a fully-decentralized micro-grid, the scenario number 2 holds particular interest, as it investigates the possibilities of such a system, that faces the problem of the existing electronic equipment already present in the LV grid. This grid topology does not need the realization of a custom micro-grid, and still retains the characteristics of actual distribution grid, where the power distributor still holds the ability to control the grid parameters. Moreover, with the ST the degrees of freedom of the grid's owner can be increased, allowing finer controls, as described in this paper.

As the main problem that such systems face is the parallel operation of multiple inverters, in the following a short review of the state of the art is reported.

Parallel operation of multiple photovoltaic inverters is adopted in island-grid systems. It allows to increase the rated power, adds modularity to the system and improves the power harvesting from the panels, as multiple inverters can implement

separate Maximum Power Point Tracking (MPPT) algorithms in case of partial shading of the PV panel field. The parallelization of multiple Voltage Source Converters (VSC) was analyzed in literature and several means of synchronization were proposed. In [1] each VSC is controlled by a dedicated current loop. The total load current is measured and a separate synchronization and control unit generates current set-points for each converter. In [2] each inverter is controlled by three nested feedback loops. The innermost current loop is used to control the output current. Its reference is generated by a voltage controller which ensures that all the inverters output the same voltage. The problem resides in the fact that differences in the output impedances can generate large differences in the output current of each VSC. For this reason there is an additional outer current loop that corrects the voltage reference to ensure a balanced current sharing among the VSCs. A similar approach was exploited in [3], while in [4] a supervising controller generates a common analog reference signal for all the parallel converters to attain power sharing and to limit the circulating currents among converters. The above proposals need some means of communication among the different power stages, in order to share and dispatch the various current and voltage set-points.

In [5] the authors propose a Master-Slave approach. A master converter is controlled by an inner current loop and an outer voltage loop that fixes the load voltage. The slave converters implement only the inner current loop. The current sharing between the modules is ensured by the fact that each converter measures the total load current. Then, the slave converters generate the current set point by dividing the total load current by the number of nodes. This architecture operates without communication between the stages, but each converter must measure the load current and needs information about the system topology. In literature several applications of the droop control, normally used for synchronous generators, are reported [6], [7] for the parallelization of multiple inverters without any kind of communication.

In this work a frequency-based master/slave synchronization method is used to avoid overload without the need for any kind of communication among the power stages. Differently from other master/slave approaches, the grid frequency acts as a common signal, allowing to exploit the characteristic of commercial inverters that decrease the output power in case of grid frequency increase. The advantage of this solution with respect to other paralleling choices is that it can suitably work even under the hypothesis of non-sinusoidal currents. In fact, the widespread presence of non-linear loads invalidates the assumption of load linearity, so while the grid-connected inverters provide the fundamental current component, the voltage controlled grid-emulating inverter can provide the current harmonics to the loads. It is important to note that, although in the future high-speed communication between the power converters will probably be available, due to the increasing interest in smart grids, the solution described in this paper could be employed in the transition time, when existing electronic equipment is still connected to the grid and must be integrated in a more flexible grid scenario.

In section II the concept of frequency depending power derating is presented, in section III the stability analysis of the system is addressed. Simulation and experimental verification

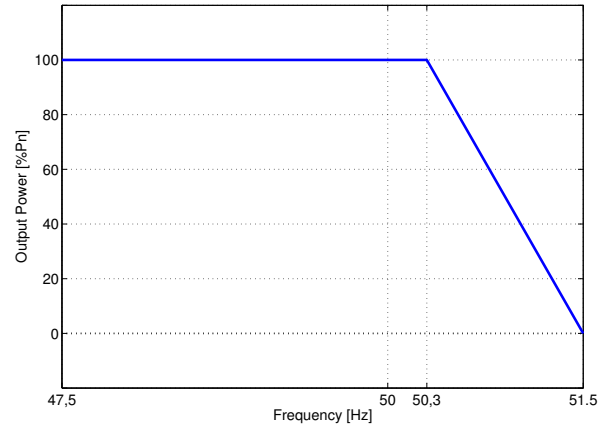


Fig. 3. Derating curve of a grid-connected inverter as a function of the grid frequency.

are shown in sections IV and V. A discussion regarding the required power rating of the master converter is reported briefly in section IV, and the applications scenarios are discussed in section VII. Section VIII draws the conclusions.

II. FREQUENCY-BASED POWER LIMIT

Since in this work the behavior of commercialized grid-connected inverters is exploited for realizing an island-grid system, an overview of the main constraints imposed to these inverters is requested. As a matter of fact, the increasing penetration of renewable energy conversion systems into the low-voltage distribution grid is causing problems with the stability of the grid itself. There have been several cases where the power produced by grid-connected inverters was above the local consumption. In these conditions a reverse power flow occurs in the MV-LV transformer with a corresponding increase of the grid voltage amplitude and frequency [8]–[10].

For this reason, recent regulations specify a linear derating characteristic of the power supplied by the converters to the grid as the grid frequency increases. In particular, considering the Italian CEI 0-21 [11], at the maximum operating frequency of 51.5 Hz, the grid-connected equipment must inject no active power into the grid (Fig. 3).

Moreover, the curve shown in Fig. 3 may be followed only towards decreasing output power levels. If the frequency starts decreasing after the 50.3 Hz threshold has been crossed, the converter must not instantaneously increase back the output power, it must keep the minimum value previously reached. Then, after a specific amount of time, the inverter can return to its original value of output power. The derating curve is a kind of droop characteristic that can be used also in island operations to share the load among several power converters.

The structure of the island converter, that emulates the grid, is reported in Fig. 4. The DC/DC converter regulates the DC-link voltage V_{DC} , providing or absorbing power depending on the sign of the output power of the island converter, whereas the DC/AC inverter generates the nominally 50 Hz sinusoidal voltage waveform. When the power produced DPGS exceeds the power absorbed by the local loads and the battery pack is

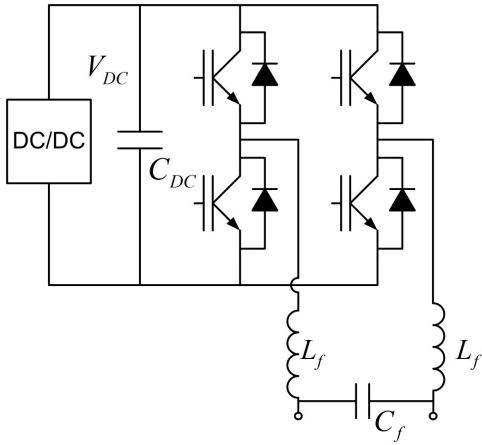


Fig. 4. Topology of the DC/AC converter that emulates the grid.

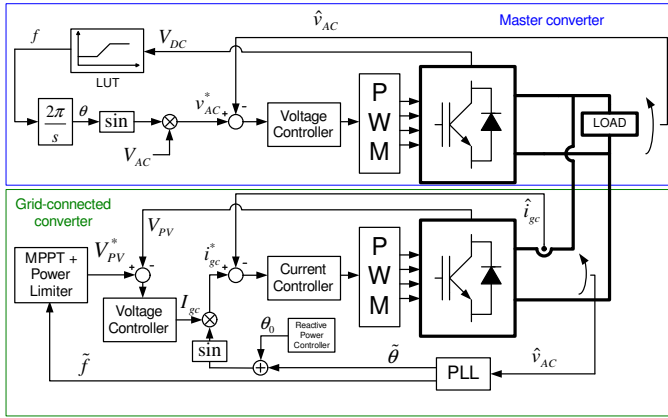


Fig. 5. Block scheme of the control system with the DPGS and Master converters

fully charged, or the input power exceeds the battery charging current, the DC-link voltage increases.

Therefore, an overload condition can be detected by monitoring the DC-link voltage. Upon the detection of the overload, the DC/AC inverter increases the frequency of the output voltage, thus reducing the power injected by the grid-connected stages by exploiting their derating curves. Fig. 5 shows the block diagram of the proposed solution.

It is important to note that the actual implementation of the described output power derating characteristic in commercial inverters may vary, and fast control of the DC-link voltage cannot be ensured in every cases. It can't be excluded, in case of a slow response of the grid-connected inverters to a change of frequency, that some part of the energy will still need to be dissipated in a resistor to avoid DC-link overvoltage, decreasing the total system efficiency. Nevertheless, this represents the worst case scenario, the results shown in this work demonstrate that the proposed synchronization mechanism can work satisfactorily with commercial inverters with pre-programmed derating characteristic. Obviously, a further smart and efficient management of the produced power could be obtained if the grid-connected inverters were specifically programmed.

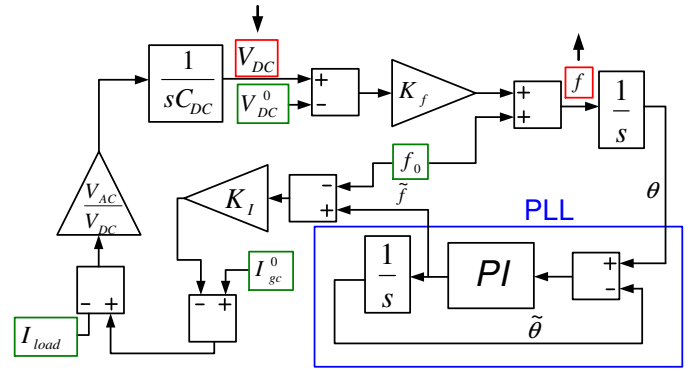


Fig. 6. Simplified block diagram for the stability analysis of the system in Fig. 5.

III. STABILITY ANALYSIS

In order to analyze the controller requirements for this application, a simplified model was realized to study the system's dynamics. Fig. 6 shows the simplified block scheme. The part enclosed by the blue bracket refers to the master converter, that selects the output frequency by following the overload curve, in which to an increase of the DC-link voltage above a threshold value V_{DC}^0 corresponds a variation of the frequency according to a linear function. The slope of the frequency variation is indicated as K_f , whereas f_0 is the nominal frequency of the system, i.e. 50 Hz. The frequency is then integrated and the phase θ of the output signal is changed accordingly. The constant parameters are highlighted by green colors, the open-loop input (V_{DC}) and output (f) are highlighted in red. In fact, the stability analysis can be regarded as a proportional control of gain K_f that tries to regulate V_{DC} to the reference V_{DC}^0 by modifying the frequency f .

The Phase Locked Loop (PLL) of the DPGS detects the change of frequency according to the coefficients of its Proportional-Integral (PI) regulator. The system can be studied using a small signal analysis, so that the input of the PLL PI regulator is the phase displacement between the two sinusoids (grid and reference). Upon the detection of the frequency, the grid-connected inverter changes its output current following the derating curve, with parameters i_{gc}^0 and slope K_I . The current flowing into the DC-link of the master converter is the grid-connected current minus the load current with a scale factor equal to the ratio between the V_{DC} and the RMS value of v_{AC} .

The stability of the system can be addressed considering the feedback system of Fig. 6, where the constants of the PI regulator of the PLL (tuned with 1Hz bandwidth) are multiplied by a gain k . As a matter of fact, when the pole of the PLL is correctly placed, the gain k can be used to select the bandwidth of the PLL.

The stability study was carried out considering a small signal analysis. The characteristic equations of the system can be written as in (1), therefore the equation used to evaluate the root locus (Fig. 7) is given in (2).

$$A(s) = \frac{K_f K_I V_{AC}}{s^2 V_{DC} C_{DC}} \quad (1)$$

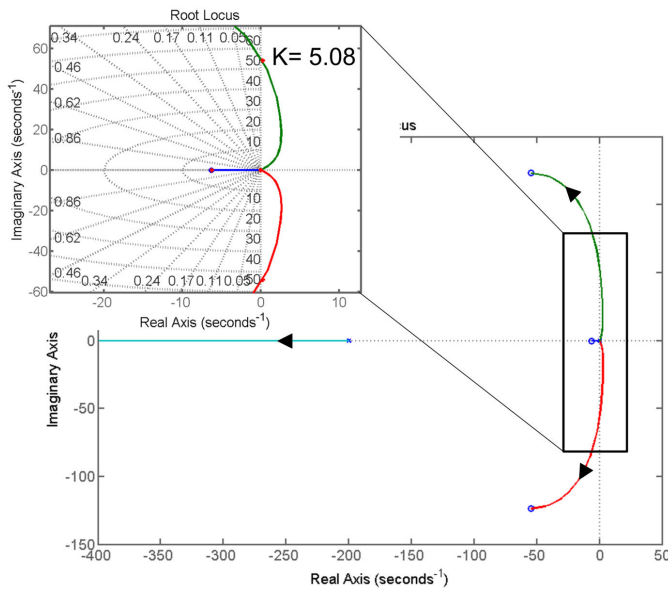


Fig. 7. Root locus of the system representing the frequency control of a DPGS and the master.

TABLE I. SIMULATION PARAMETERS

| | | | |
|-----------|-----------|----------|-------------|
| V_{src} | 400 V | V_{PV} | 400 V |
| C_{DC} | 2 mF | L_f | 0.75 mH |
| C_f | 7 μ F | R_f | 1 Ω |
| V_{AC} | 315 V | R_l | 50 Ω |

$$1 + A(s) \left[\frac{ksPI(s)}{s + kPI(s)} \right] = 0 \quad (2)$$

A first order Pade approximation for a 10 ms delay was inserted in the loop to account for the low pass filtering usually applied at the output of the PLL. The parameters refer to the derating curve of a 4 kW inverter with $V_{AC} = 230V_{RMS}$. As can be seen, a narrow bandwidth of the PLL (small gain) leads to poles with positive real parts. Nevertheless, as the grid synchronization is a key feature for grid-connected inverters, it is reasonable to expect that the bandwidth of the PLL be sufficiently broad to make the entire system stable.

IV. SIMULATION RESULTS

The proposed strategy applied to a photovoltaic island-grid system was simulated using the MATLAB/Simulink environment with the aid of the PLECS toolbox. The control scheme of Fig. 5 was implemented, and Fig. 8 shows the power circuit considered for the test. The parameters are listed in TABLE I. The DC/DC converter is modeled as a constant DC source V_{src} with a series diode, that represents a valid model for a unidirectional boost converter with voltage control. The local load is composed of power resistors R_l , one of them can be inserted or excluded. For the island-grid converter the frequency set-point was generated with a linear lookup table, where the frequency varies from 50 Hz to 51.5 Hz when the DC-link voltage varies from 410 V to 460 V.

The current control of the grid-connected converter is realized with a Proportional Integral (PI) regulator. The rated power is considered to be 4 kW and the derating characteristic

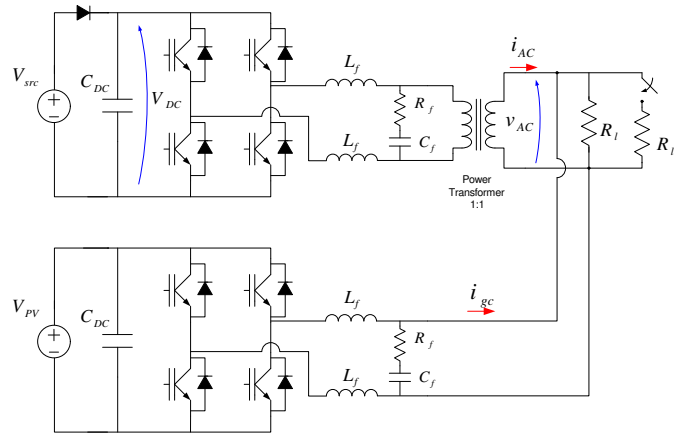


Fig. 8. Circuit employed for the simulations, representing the master converter, a DPGS and a local variable load.

is shown in Fig. 3. The master converter worked with a 10 kHz PWM, while for the grid-connected one the PWM frequency was 8 kHz, for consistency with the experiments. The grid-connected converter measured the grid frequency by means of a Phase Locked Loop (PLL).

Fig. 9 shows the grid voltage v_{AC} , the grid-connected converter current i_{gc} , the DC-link voltage V_{DC} and the frequency f when one of the loads is removed at the time 0.2 s and is re-inserted at 0.8 s. The overload condition is detected by the master inverter, that increases the frequency, commanding a limitation of the power of the grid-connected inverter.

V. EXPERIMENTAL RESULTS

In order to test the feasibility and effectiveness of the proposed solution, a micro-grid was realized with multiple VSCs and a local load. One VSC was a CEI 0-21 compliant grid-connected inverter, that was supplied with a DC generator with a series resistance emulating the photovoltaic panels. The other VSC was supplied by a Agilent DC power supply with a series diode, in order to be consistent with the simulation results. This VSC generated the grid voltage and implemented the frequency variation mechanism. Both converters are based on a Freescale MC56F8323 low-cost DSP, that implements the controls shown in Fig. 5. The parameters of the circuit and the test-bed setup reflect the simulation schematic of Fig. 8. The dynamic response of the grid-connected converter's frequency detection system is of paramount importance in order to obtain a response similar to the one in Fig. 8b. Usually, commercial grid-connected inverters are not programmed to detect very fast variations of the grid frequency, and for this reason the regulation specifies that the derating characteristic must be traveled only downwards.

Fig. 10a shows a step variation of the grid-connected output current that leads to a DC-link overvoltage. The frequency is increased accordingly, and the grid-connected inverter current decreases. Fig. 10b shows a magnification of the grid voltage and current. After the frequency increase, the DC-link returns to the previous voltage, but, accordingly to CEI 0-21, the inverter keeps the reduced value of active power for some more time.

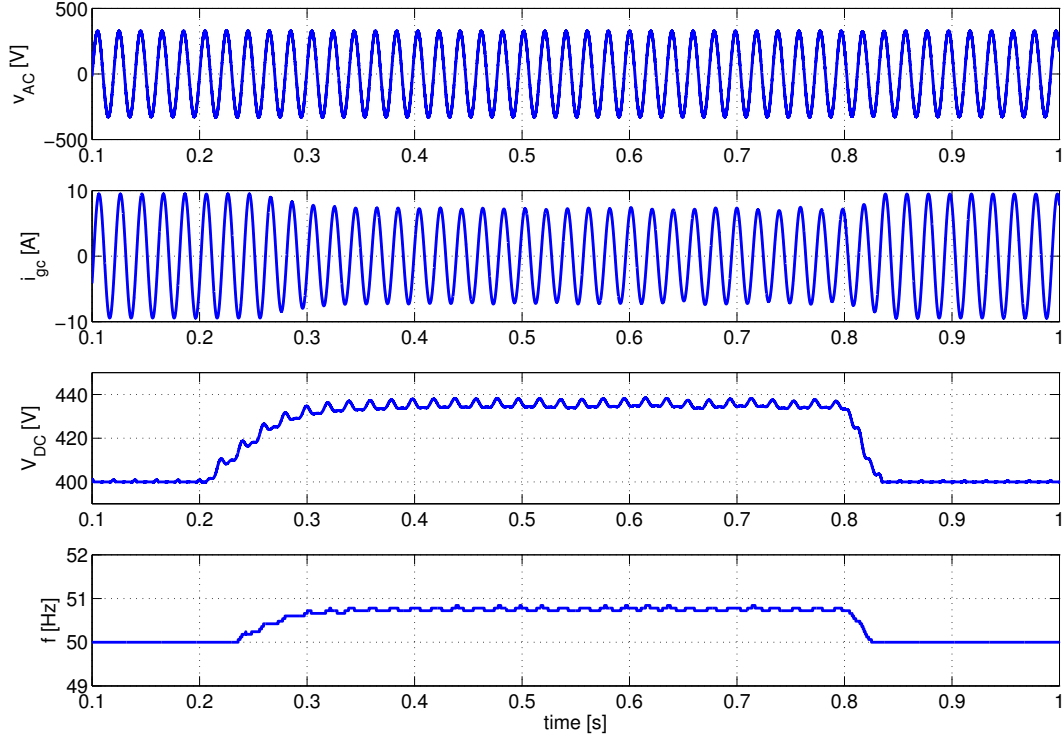


Fig. 9. Simulation results of overload condition and behavior of the master inverter.

As a matter of fact, even without a fast detection of the frequency variations, the overload condition was avoided by the proposed mechanism. If a custom firmware can be embedded in the grid-connected converter, allowing to travel the derating ramp in both directions and with a faster PLL, results similar to the ideal case of the simulations can be obtained. Fig. 11a and Fig. 11b show, respectively, the overload start and end transients. As can be seen, the island-grid converter generates a frequency that allows to keep the DC-link voltage constant.

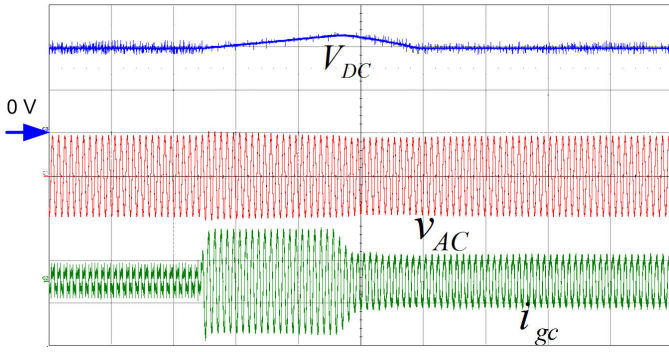
VI. DISCUSSION ON THE RATED POWER OF THE MASTER INVERTER

For completeness, the issue of the rated power of the master converter should be addressed. As a matter of fact, the whole micro-grid is regulated by only a voltage-controlled inverter, for this reason it must be investigated if the master inverter can still control the frequency in the case of multiple grid-connected inverter, where the total power of the current-controlled inverters exceeds the master's one. In order to investigate this matter, the circuit represented by the block scheme of Fig. 12 is analyzed. The master inverter is modeled by a AC source, while the grid-connected converters are modeled by a current-controlled AC source, whose reference angle is given by the same PLL structure of the previous simulations.

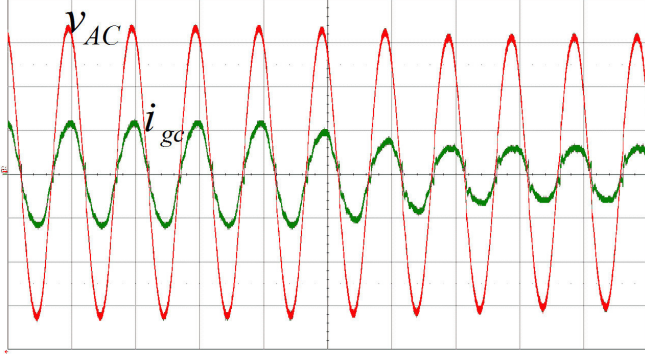
The local impedance represents a resonant load at the nominal frequency, and a step variation of the frequency is realized, so that the master inverter current could be monitored. From extensive simulations, it was shown that the behavior is

strictly dependent on the dynamic of the PLL employed by the grid-connected converter. In fact, during a frequency change, the master inverter is absorbing active and reactive power, thus shifting the frequency of all the other converter. During the time where the frequencies are out-of sync, the current absorbed by the master inverter can present a great amplitude. Instead, if the PLL bandwidth is selected sufficiently high, a small overcurrent is present.

This effect is shown in Fig. 13, where the effect of the PLL bandwidth on the output of the master inverter current, i_{AC} is clearly visible. The tuning of the four different PLL was realized with a pole-zero placement, and in each case the phase margin of the control was $\frac{\pi}{4}$. The PLL is realized in the synchronous reference frame and an adaptive transport delay is used for the quadrature system generation. This structure does not allow to achieve high values for the bandwidth. Ten grid-connected converter is injecting 320A (equivalent to 10 grid-connected converters of the same rating of the master one) of active current on a resonant load of 1Ω with a quality factor $Q = 0.3$. At the time $t = 5s$ a frequency step from $50Hz$ to $51Hz$ is realized by the master inverter. In steady-state conditions the master inverter has an output current of peak amplitude 20A. If the bandwidth is 1 Hz, the master inverter has to absorb a great share of the grid-connected current during the frequency step, and this performance would be unacceptable for an actual system, as that transient would damage the semiconductor. If the PLL bandwidth is 5 Hz, a small overcurrent (twice the steady-state value) occurs for 100 ms. As a matter of fact this behavior could be already



(a) v_{AC} , 350 V/div, Time base 200 ms/div.



(b) v_{AC} , 100 V/div, Time base 20 ms/div.

Fig. 10. Overload transient. V_{DC} , 200V/div, I_{gc} , 5 A/div.

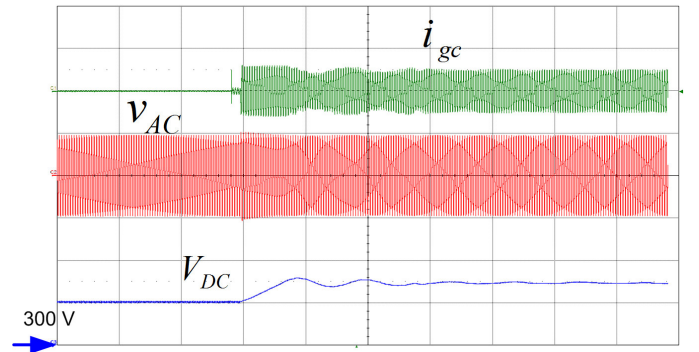
acceptable, as such a transient is unlikely to damage the devices. Instead, if the bandwidth of the PLL is 10 Hz or above, there is almost no overcurrent. Similar results were obtained with a SOGI PLL structure [12], suggesting that the controllability of the system does not depend on the PLL structure but only on its bandwidth.

This behavior can be explained by the fact that the micro-grid described in this paper is different from a droop-controlled micro-grid, where a change in the frequency by a single generator can happen only if this generator rated power is greater than the total power of the other generators. Otherwise, a generator with a little output power cannot cause a marked shift in the frequency. Grid-connected inverters do not feature a droop control, and it is mandatory from international regulations that they must be disconnected from the grid in the case of islanded operation. Several anti-islanding algorithms were reported in literature, but the basic fact is that grid-connected inverters are very sensitive to frequency changes. For this reason, if the bandwidth of the PLL is sufficiently high, it is possible for a single master inverter to control the frequency of a whole micro-grid, even if the power rating is inferior to the total power of the current-controlled inverters.

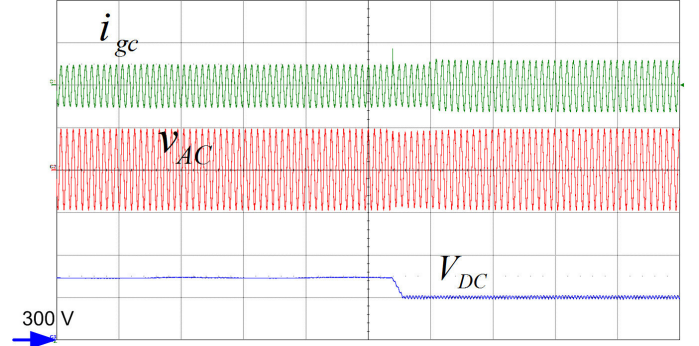
VII. SCENARIOS OF APPLICATION OF THE PROPOSED SOLUTION

A. Islanded micro-grid

The proposed frequency control can be adopted in an islanded micro-grid (Fig. 1) under the assumption that the grid-connected inverters can detect frequency changes with



(a) Overload insertion. Time base 500 ms/div.



(b) Overload removal. Time base 200 ms/div.

Fig. 11. Experimental waveforms of the overload start transient with fast frequency detection. I_{gc} , 10 A/div, v_{AC} , 350 V/div, V_{DC} , 100V/div.

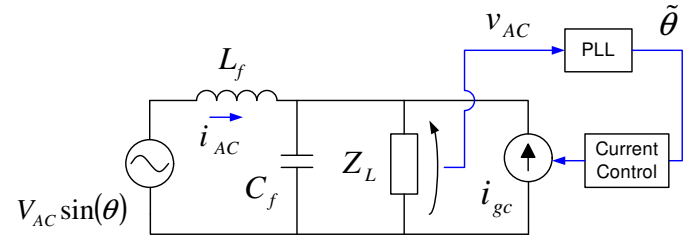


Fig. 12. Simplified schematic for the analysis of current requirements.

sufficient bandwidth. In such case it was shown that the frequency can be properly controlled by a VSC, even if the total power of the micro-grid exceeds the master inverter power rating.

Nevertheless, the solution proposed presents also some drawbacks. As a matter of fact, the differences among grid-connected inverters from different manufacturers regarding current control and PLL may deteriorate the frequency control, increasing the current requirements of the master inverter. A simulation was run where multiple grid-connected inverters with different PLL (considering SOGI, fixed transport delay, adaptive transport delay) structure. In this case, the bandwidth of the fixed delay PLL must be kept lower than the other structures in order to prevent unacceptable frequency oscillations. As can be seen from Fig. 14, at time $t = 5$ s, when the frequency changes from 50 Hz to 51 Hz, the master inverter must supply a considerable amount of current, rendering impractical the micro-grid realization.

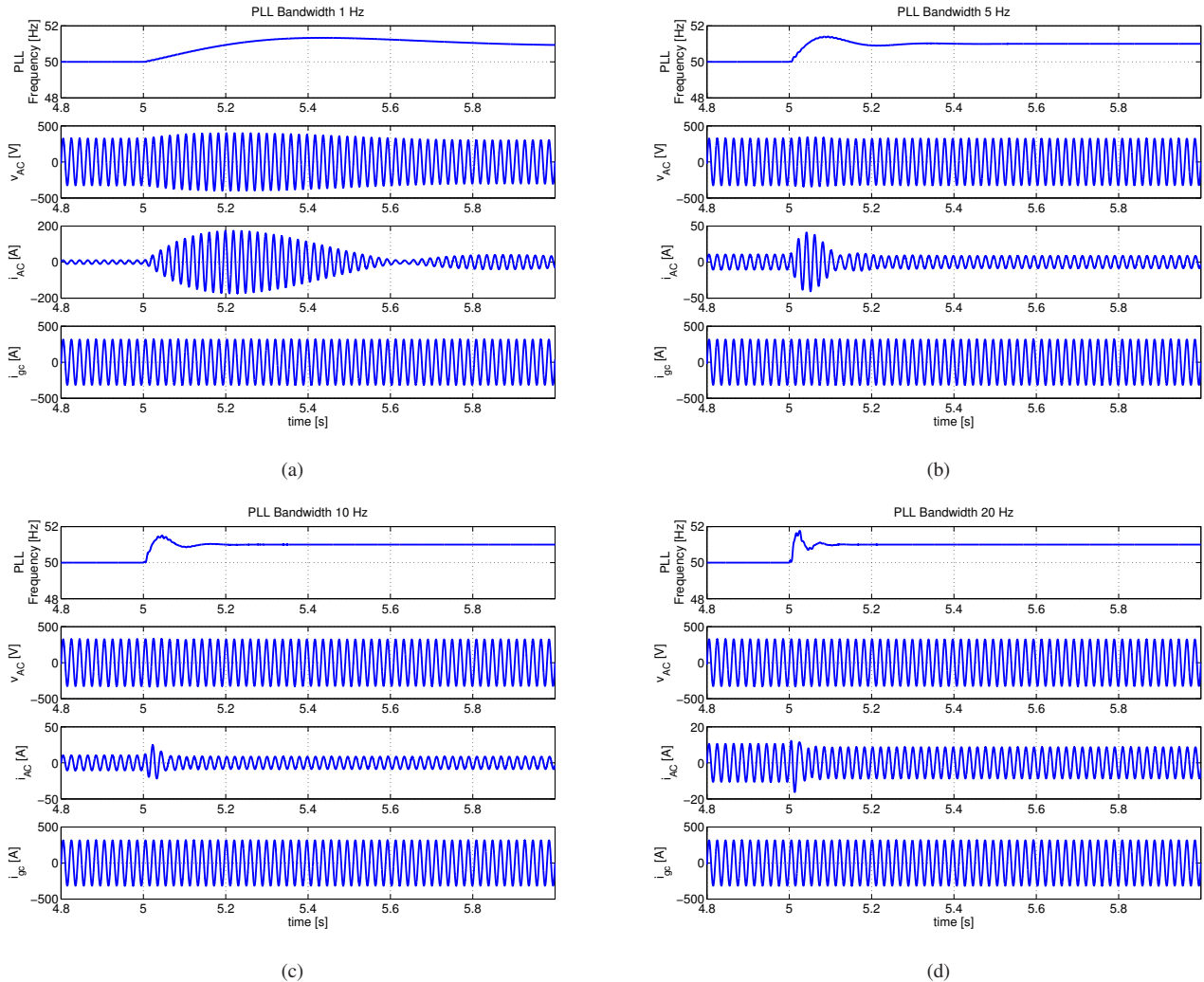


Fig. 13. Effect of different PLL bandwidth on the current rating of the master inverter.

Moreover, the considerations stated above are valid only in case of grid-connected converters featuring a current loop control, such as commercial PV inverters. In term of generality, if droop-controlled generators would be connected to the micro-grid, the frequency control mechanism would require that the master inverter had a power rating similar to the total micro-grid power.

B. Smart Transformer LV Distribution

Having a high-power master converter for a micro-grid could not be economically feasible, but, if an independent LV grid fed by a Smart Transformer (ST) is considered, it could perform the frequency control. In this scenario the frequency control could be employed to control the total power of the micro-grid, and prevent the reverse power flow if the power production from renewable energy source exceeds the local consumption.

In this case, also the control of the power delivered by Synchronous Generators connected to the LV grid could be realized by properly controlling the frequency. As a matter of fact, a LV distribution grid with a solid state transformer

presents several advantages with respect to a decentralized micro-grid. In fact, the renewable energy production can continue to be realized with standard grid-connected converters. With respect to droop-controlled inverters, this intermediate scenario allows the realization of a LV micro-grid without changing the power converters, but only the transformer.

VIII. CONCLUSION

In this work a frequency-based master/slave synchronization method is used to realize an island-grid system, without the need for any kind of communication among the power stages. The proposed mechanism exploits the features of the newest grid-connected converters, which incorporate frequency-depending power derating characteristics.

Imitating this mechanism of the mains a VSC generates the grid voltage, and several grid-connected inverters transfer active power to the micro-grid. The voltage controlled VSC increases the output frequency in case of overload, forcing the grid-connected converters to reduce their output power, thus stabilizing the system.

Experiments, realized with commercial CEI-021 compliant

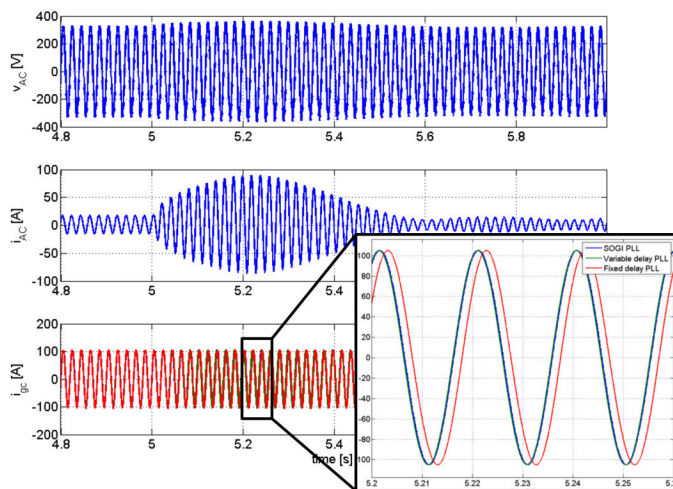


Fig. 14. Simulation results of the master inverter with multiple grid-connected converters with different PLLs.

grid-connected converters, highlight the fact that the effectiveness of the proposed solution depends on the ability of the grid-connected inverters to rapidly detect a change of the grid frequency. Moreover, a custom firmware for a grid-connected converter was realized. It enhances the concept of power derating developed in CEI-021, allowing the grid-connected inverter to regulate the output power more effectively according to the actual frequency value. This approach guarantees better performances in spite of a loss of generality. Simulations and experimental results show the feasibility of the proposed solution.

Finally, some considerations are given regarding the actual feasibility of this micro-grid with commercially available power converters. In fact, if multiple grid-connected converters are present, the total power is likely to exceed by a great margin the power of the master inverter that is realizing the frequency control. Extensive simulations were performed and the results show that the feasibility of the proposed solutions relies on the PLL bandwidth of the grid-connected inverters. Values above 5 Hz of the PLL bandwidth allow a good control of the frequency without exceeding the current limits of the master inverter. Under the hypothesis that the master inverter has enough power rating to control the micro-grid regardless the characteristics of the grid-connected inverters, this mechanism could be used in a LV distribution grid where the frequency control is realized by the Solid State Transformer supplying the grid.

ACKNOWLEDGMENT

This study was funded under the ERC Consolidator Grant 2014-2019 in the project "Highly Efficient and Reliable smart Transformer" (HEART).

REFERENCES

[1] D. Shanxu, M. Yu, X. Jian, K. Yong, and C. Jian, "Parallel operation control technique of voltage source inverters in ups," in *Proceedings of the IEEE 1999 International Conference on Power Electronics and Drive Systems, 1999. PEDS '99.*, vol. 2, 1999, pp. 883–887 vol.2.

[2] X. Sun, Y.-S. Lee, and D. Xu, "Modeling, analysis, and implementation of parallel multi-inverter systems with instantaneous average-current-sharing scheme," *IEEE Transactions on Power Electronics*, vol. 18, no. 3, pp. 844–856, May 2003.

[3] T. Lazzarin, G. Bauer, and I. Barbi, "A control strategy for parallel operation of single-phase voltage source inverters: Analysis, design and experimental results," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 6, pp. 2194–2204, Jun. 2013.

[4] Y. Chen and K. Smedley, "One-cycle-controlled three-phase grid-connected inverters and their parallel operation," *IEEE Transactions on Industry Applications*, vol. 44, no. 2, pp. 663–671, Mar.-Apr. 2008.

[5] W.-C. Lee, T.-K. Lee, S.-H. Lee, K.-H. Kim, D.-S. Hyun, and I.-Y. Suh, "A master and slave control strategy for parallel operation of three-phase ups systems with different ratings," in *Nineteenth Annual IEEE Applied Power Electronics Conference and Exposition, 2004. APEC '04.*, vol. 1, 2004, pp. 456–462 Vol.1.

[6] K. De Brabandere, B. Bolsens, J. Van den Keybus, A. Woyte, J. Driesen, and R. Belmans, "A voltage and frequency droop control method for parallel inverters," *IEEE Transactions on Power Electronics*, vol. 22, no. 4, pp. 1107–1115, Jul. 2007.

[7] D. De and V. Ramanarayanan, "Decentralized parallel operation of inverters sharing unbalanced and nonlinear loads," *IEEE Transactions on Power Electronics*, vol. 25, no. 12, pp. 3015–3025, Dec. 2010.

[8] A. Cagnano, E. De Tuglie, M. Liserre, and R. Mastromauro, "Online optimal reactive power control strategy of pv inverters," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 10, pp. 4549–4558, Oct.

[9] G. Celli, F. Pilo, G. Pisano, and G. G. Soma, "Optimal operation of active distribution networks with distributed energy storage," in *2012 IEEE International Energy Conference and Exhibition (ENERGYCON)*, Sept., pp. 557–562.

[10] E. Demirok, P. Casado Gonzalez, K. Frederiksen, D. Sera, P. Rodriguez, and R. Teodorescu, "Local reactive power control methods for overvoltage prevention of distributed solar inverters in low-voltage grids," *IEEE Journal of Photovoltaics*, vol. 1, no. 2, pp. 174–182, Oct.

[11] "Reference technical rules for the connection of active and passive users to the lv electrical utilities," CEI 0-21, Dec. 2012. [Online]. Available: <http://www.ceiweb.it/doc/norme/12333.pdf>

[12] P. Rodriiguez, A. Luna, I. Candela, R. Mujal, R. Teodorescu, and F. Blaabjerg, "Multiresonant frequency-locked loop for grid synchronization of power converters under distorted grid conditions," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 1, pp. 127–138, Jan 2011.