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Investigation of Instability in Multiple Grid-Connected Inverters with LCL Output Filters

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Abstract

This paper deals with the instability and resonant phenomena in distribution systems with multiple grid-connected inverters with an LCL output filter. The penetration of roof-top and other types of small photovoltaic (PV) grid-connected systems is rapidly increasing in distribution grids due to the attractive incentives set forth by different governments. When the number of such grid-connected inverters increases, their interaction with the distribution grid may cause undesirable effects such as instability and resonance. In this paper, a grid system with several grid-connected inverters is studied. Since proportional-resonant (PR) controllers are becoming more popular, it is assumed that most inverters use this type of controller. An LCL filter is also considered at the inverters output to make the case as realistic as possible. A complete modeling of this system is presented. Consequently, it is shown that such a system is prone to instability due to the interactions of the inverter controllers. A modification of PR controllers is presented where the output capacitor is virtually decreased. As a result, the instability is avoided. Simulation results are presented and show a good agreement with the theoretical studies. Experimental results obtained on a laboratory setup show the validity of the analysis.

Key words: Grid-connected inverter, Harmonic compensator, Proportional-resonant controller, Resonance

I. Introduction

The application of renewable energy resources (RER) is increasing due to global concerns about environmental pollutions. This trend has also been extended to household applications such as the installation of roof-top photovoltaic systems. On the other hand, the emerging application of distributed generation (DG), such as small PV systems, has resulted in some new challenges for distribution grids. Increased harmonic pollution and resonance are among the power quality problems that can arise due to increasing the penetration of grid-connected inverter-based DGs [1]. To comply with international standards with regards to the connection of power converters to the grid, the use of high-order filters such as the LCL configuration is preferred in grid-connected inverters [2]. Consequently, the interaction of filter capacitance and grid inductance, especially in highly inductive grids, increases the possibility of resonant problems [1], [3], [4].

Unlike a single grid-connected inverter, where the resonant frequency is fixed by the inverter output LCL filter parameters, complex resonances can be excited at various frequencies in a distribution system with multiple inverters due to the distributed nature of the filter capacitances [5]-[7]. An early work on the resonance caused by the interaction between the grid and converters was presented in [1]. In this study, only the passive elements of the converter have been taken into consideration for the modeling of a multi-inverter system. Such a model verifies the potential of the resonance phenomenon. However, it lacks accuracy since the converter control system has not been modeled. In [8], a Norton model has been proposed for the proper modeling of current-controlled grid-connected inverters. In this study, the harmonic interactions between grid-connected inverters and the grid are investigated when the grid voltage has back-ground harmonic distortions. Moreover, the resonance in a system with N parallel grid-connected inverters has been studied in [9] based on a matrix transfer function.

In [5], it was shown that there are three kinds of resonances in a distribution system with multiple inverters: 1) series resonance among grid-connected inverters and the grid, 2)

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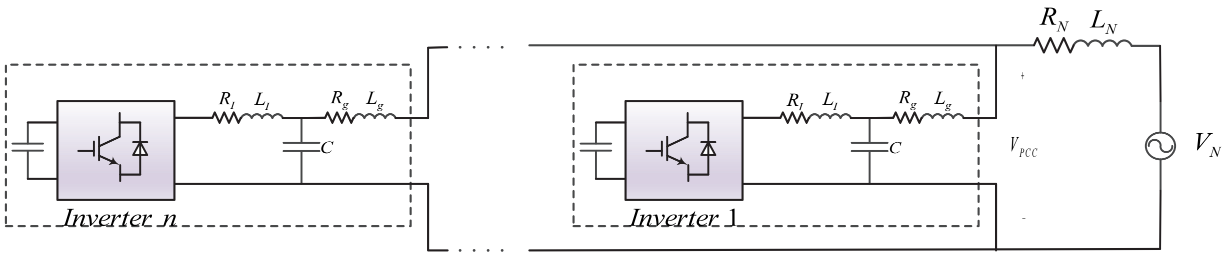


Fig. 1. Simplified distribution grid with multiple inverters.

internal resonance of each inverter and 3) parallel resonance among inverters. Unlike internal resonance which occurs in a single inverter system and parallel resonance which is the stimulated disturbance produced by other inverters, series resonance is related to the interaction between inverter output LCL filters and the grid impedance and can be stimulated by the grid background harmonics [5].

Using proportional-resonant (PR) controllers has become very popular in power electronic systems due to their good performance in sinusoidal tracking and harmonic rejection. However, the high order of these controllers can lead to undesirable overall system performance such as instability. In this paper, it is shown that when PR controllers are used in a multiple inverter system, increasing the number of inverters can result in instability. This instability is in addition to resonance and occurs even without background harmonics.

This paper presents a comprehensive study of the susceptibility of systems with several grid-connected inverters to instability. In this way, the complete transfer function of the system, including the output LCL filter and control system, is obtained. Using the root-locus method, it is shown that when the number of inverters is increased beyond a certain number, the system poles move towards the right half plane, resulting in inherent instability. Different scenarios are presented to illustrate the relationship between the instability and the number of inverters. Studies are carried out when PR controllers are used for grid-connected inverters. However, the approach can be easily extended to other types of controllers. Furthermore, it is shown that by modifying the control system, this undesirable phenomenon can be avoided. All of the theoretical studies are verified using simulations. In addition, an experimental setup with two grid-connected inverters is used to validate theoretical analysis and simulation results.

The rest of this paper is organized as follows. In Section II, the modelling of a distribution grid with multiple inverters is presented. The modelling of a system with PR harmonic controllers is considered in Section III. The theoretical aspects behind the instability due to multiple inverters with PR controllers is explained in this section. In Section IV, the modification applied to the controllers to avoid instability is discussed. Simulation results are given in Section V. These results verify the analytical studies. The results obtained from an experimental setup are shown in Section VI. Some conclusions are presented in Section VII.

II. Distribution Grid Modelling with Multiple Inverters

This section deals with the modeling of a distribution grid consisting of several parallel grid-connected inverters. This makes it possible to study the harmonic interactions between individual inverters and the grid, and to forecast potential resonant problems. Consequently, the results obtained from the modeling, analysis and simulations of such a grid can help in mitigating resonant problems.

A simplified distribution grid with multiple inverters is considered as illustrated in Fig. 1. Each inverter is connected to the grid via an LCL filter which is commonly used as the output filter of grid-connected inverters [10]-[12], where L_I and L_g are respectively the inverter-side and grid-side filter inductances, R_I and R_g are the inverter-side and grid-side resistance of the filter inductances, respectively, and C is the filter capacitance. The studies in this paper are carried out for a systems consisting of several micro-inverters [18], where the inverters are close to each other and are connected via short cables. Therefore, the impedance between the inverters has been neglected. The grid at the point of common coupling (PCC) has been modeled by its Thevenin equivalent circuit, i.e. a voltage source, V_N, and a series impedance, $Z_N=R_N+j\omega_0L_N$.

Most grid-connected inverters work in the current control mode (CCM). Therefore, they can be represented by an equivalent Norton model, i.e. a current source, $I_{eq}(s)$, and a parallel output admittance, $Y_{eq}(s)$, as shown in Fig. 2 [5], [8]. In Fig. 2, $I_g(s)$ is the inverter current injected into the grid and $V_{PCC}(s)$ is the inverter output voltage at the PCC.

The model shown in Fig. 2 can be used more accurately if the inverter control system is properly modeled. Due to the nature of LCL output filters, a two-loop control structure is generally employed in grid-connected inverters. In the two-loop control system employed in grid-connected inverters, the outer loop ensures proper reference tracking of the inverter current injected to the grid, while the inner loop is needed to damp the oscillations caused by the LCL filter [13]. A two-loop control structure block diagram is depicted in Fig. 3, where G and G_c are the outer and inner loop controllers

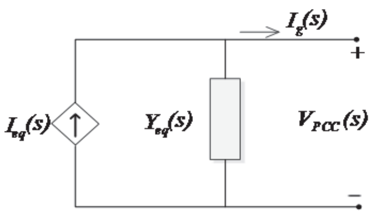


Fig. 2. Grid-connected inverter equivalent Norton model.

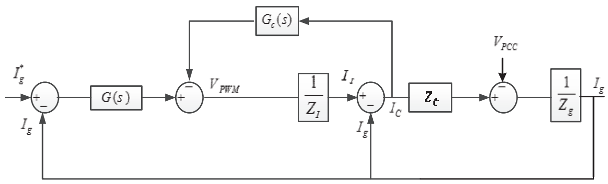


Fig. 3. Two-loop control system block diagram [14].

respectively, I_g* is the inverter reference current injected into the grid, and I_g is the inverter output current injected into the grid. In addition, V_{PWM} denotes the inverter output voltage before the output LCL filter, and Z_I, Z_C and Z_g are respectively the impedances of the inverter-side inductance, the capacitor and the grid-side inductance of the LCL filter.

The inner loop controller is usually a proportional (P) controller. However, the choice of the outer loop controller is more important. One option is to use a proportional-integral (PI) controller in the synchronous reference frame [12]. Using a PR controller, which is the equivalent to a PI controller in the stationary reference frame, is another option proposed by [11]. In this study, a PR controller is used for the implementation of the outer loop controller of the two-loop control system. The conventional PR controller transfer function is given by:

$$G(s) = K_p + \frac{2K_i\omega_b s}{s^2 + 2\omega_b s + \omega_0{}^2} \tag{1}$$

where K_p and K_i are the controller gains, ω_0 is the grid frequency, and ω_b is the controller the cutoff frequency selected based on the desired performance.

To develop a Norton model of the grid-connected inverter shown in Fig. 2, the closed-loop behavior of a grid-connected inverter with an LCL output filter and a PR controller as the outer loop controller, illustrated in Fig. 3, can be simplified as:

$$I_{eq}(s) = G_T(s).I_g^*(s) \tag{2}$$

where:

$$G_T(s) = \frac{G(s)}{L_I L_g C s^3 + K_{ic} C L_g s^2 + (L_I + L_g)s + G(s)}$$
$$Y_{eq}(s) = \frac{L_L C s^2 + K_{ic} C s + 1}{L_I L_g C s^3 + K_{ic} C L_g s^2 + (L_I + L_g)s + G(s)} \tag{3}$$

$G_T(s)$ describes the current source of the Norton model response to the reference current, $G(s)$ is the outer loop controller, and K_{ic} is the inner loop proportional controller gain ($G_c(s)$).

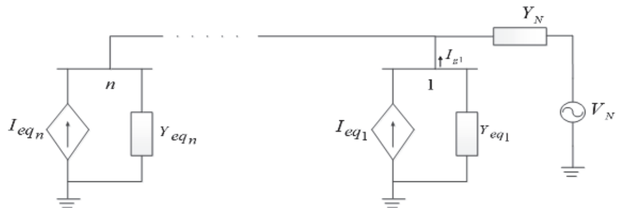


Fig. 4. Equivalent circuit of a distribution grid with multiple inverters.

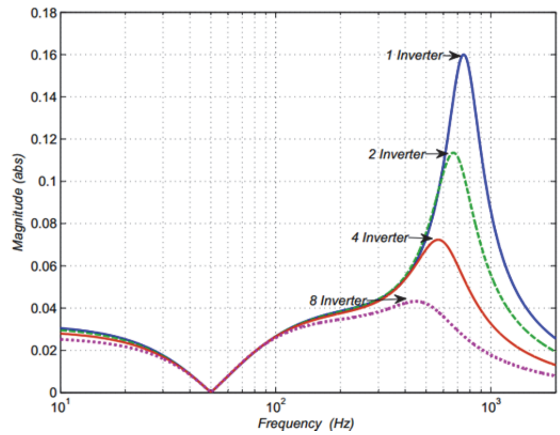


Fig. 5. Impedance diagram of the coefficient of the grid voltage in (4) for different numbers of inverters.

TABLE I
POWER SYSTEM AND CONTROL PARAMETERS

Power system Parameters		Control Parameters	
Inverter side inductor (L_I, R_I)	10 mH 0.5 Ohm	ω_b	5
Filter capacitor (C)	14 µF	K_i	1000
Grid side inductor (L_g, R_g)	0.6 mH 0.1 Ohm	K_p	30
Grid impedance (Z_N=L_N+jω_0 R_N)	1.4 mH 0.1 Ohm	K_{ic}	40
Grid voltage (V_N)	230 V		
Power	350 W		

After establishing the model of a single grid-connected inverter, the equivalent circuit of the distribution grid with multiple inverters can be obtained by replacing each of the inverters in Fig. 1 with its corresponding Norton's equivalent circuit in Fig. 2. Thus, the equivalent circuit of the distribution grid with multiple inverters can be obtained as depicted in Fig. 4.

According to Fig. 4, the inverter1 current injected into the grid can be expressed as:

$$I_{g1}(s) = I_{eq_1}(s) - \frac{Y_{eq1}(s) \times Y_N(s)}{\sum_1^n Y_{eq_i}(s) + Y_N(s)} V_N(s) \tag{4}$$

where Y_N=$1/Z_N$ and I_{eqi} and Y_{eqi} are respectively the current source and the parallel output admittance of the Norton model associated with the i^{th} inverter.

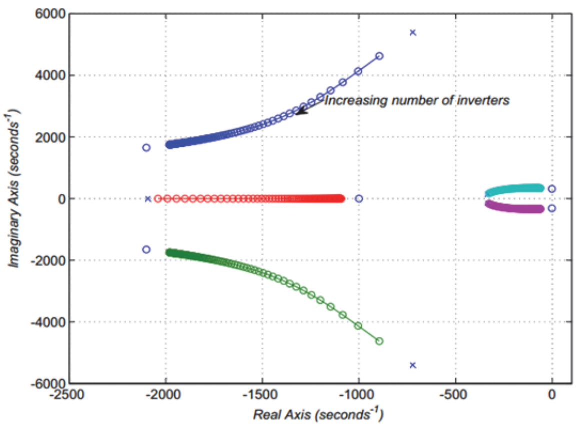


Fig. 6. Root locus plot of the coefficient of the grid voltage in (4) with the number of inverters as a parameter.

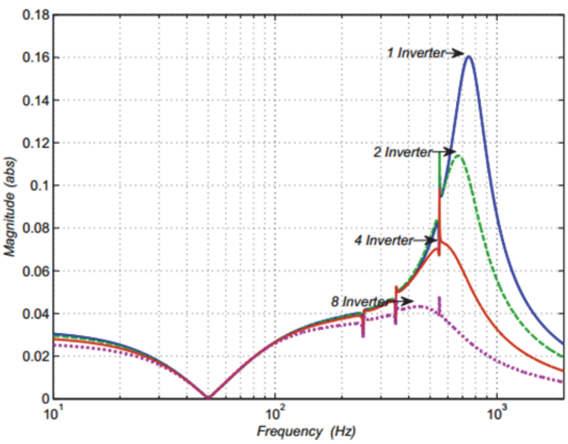


Fig. 7. Impedance diagram of the coefficient of the grid voltage in (4) for different numbers of inverters with PR harmonic controllers.

As mentioned in Section I, series resonance can occur in a distribution system in the presence of multiple grid-connected inverters due to the interaction between the grid background harmonics and the inverters. Thus, the relation between the grid voltage at the PCC and the output current of the grid-connected inverters should be analyzed. Equation (4) is used to analyze this phenomenon. In doing so, an impedance diagram of the coefficient of the grid voltage in (4) has been depicted in Fig. 5 for different numbers of inverters connected to the grid. The inverter parameters associated with this diagram are given in Table I.

Fig. 5 shows the peak value in the impedance diagrams which contributes to the series resonance. Therefore, this diagram can be used to determine the frequency of the series resonance for different numbers of inverters connected to the PCC. It can be seen that the frequency of the series resonance is affected by the number of inverters. When only one inverter is connected to the PCC, the amplitude and frequency of the resonance peak are high. When the number of parallel inverters increases, both the amplitude and frequency of the series resonance decrease.

TABLE II
PR HARMONIC CONTROLLER PARAMETERS

Harmonic Control Parameters	
ω_{bh}	10
K_{i11}	150
K_{i5}, K_{i7}	300

For a precise analysis, the root locus plot of the coefficient of the grid voltage in (4) for different numbers of inverters is depicted in Fig. 6. There are several groups of roots in this plot. The first group, which shifts left and gets near to the real axis with an increased number of parallel inverters, is related to the resonant frequency of the system. The frequency of this group of roots decreases while the damping increases with the increased number of parallel inverters, as illustrated in Fig. 5. The second group of roots, which is near the imaginary axis, is a result of the fundamental frequency of the PR controller.

III. DISTRIBUTION GRID MODELLING WITH PR HARMONIC CONTROLLERS

Almost all modern low-voltage distribution grids suffer from voltage harmonic distortion due to the presence of nonlinear loads and the network configuration. This voltage distortion, also known as background harmonics, results in an increased distortion of the injected current of grid-connected inverters. In other words, while a PR controller (the outer loop controller of a two-loop control system) is effective for fundamental current tracking, it cannot eliminate the harmonic components of the current. A method to overcome this problem is to use a PR controller with harmonic compensators [15], [16]. A PR controller with harmonic compensators, called a PR harmonic controller in this paper, reduces grid current distortions by introducing an infinite gain at selected harmonic frequencies to eliminate the steady-state error of the current harmonics. The harmonic compensators of a PR controller are usually limited to several low-order harmonics [16].

To perform more realistic studies of a distribution grid with multiple inverters, the analysis presented in Section II is performed on a system including grid-connected inverters with a PR harmonic controller. Similar to (1), the transfer function of the PR harmonic controller is given by:

$$G(s) = K_p + \sum_{h=1,5,7,11} \frac{2K_{ih}\omega_{bh}s}{s^2 + 2\omega_{bh}s + (h\omega_0)^2} \tag{5}$$

where K_p and K_{ih} are the controllers gains, h is the order of the harmonic component, ω_0 is grid frequency, and ω_b and ω_{bh} are the controller cutoff frequencies selected based on the desired performance. Substituting (5) into (2) results in an expression similar to (4), which describes the injected current of each inverter to the grid.

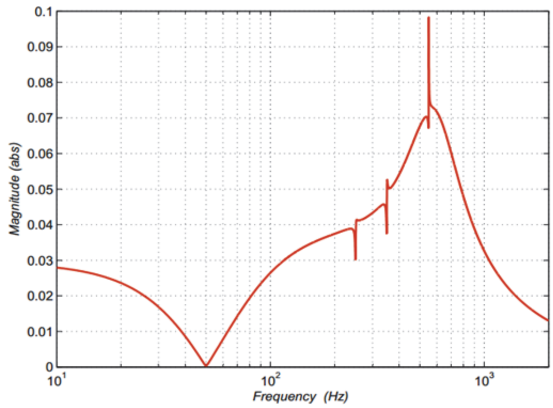


Fig. 8. Impedance diagram of the coefficient of the grid voltage in (4) in the case of a system with 4 inverters with PR harmonic controllers.

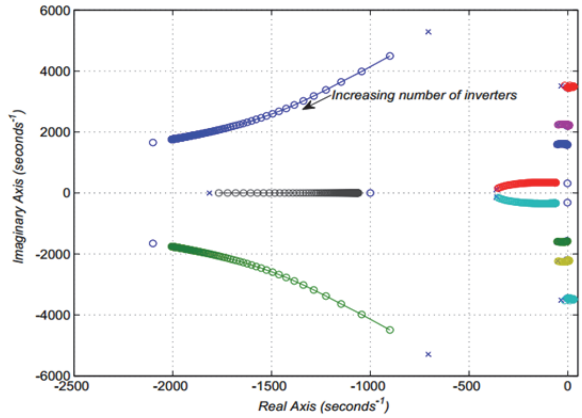


Fig. 9. Root locus plot of the coefficient of the grid voltage in (4) with the number of inverters as a parameter and with PR harmonic controllers.

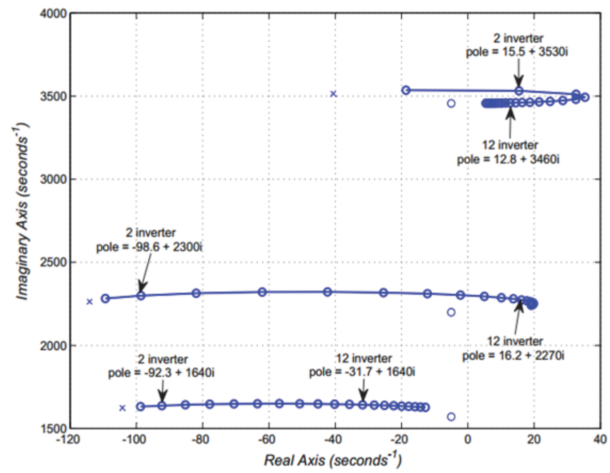


Fig. 10. Magnification of Fig. 9 for unstable poles.

Fig. 7 shows an impedance diagram of the coefficient of V_N in (4) when a PR harmonic controller is used in the two-loop controller of grid-connected inverters. The general shape of the diagram is similar to that of Fig. 5, except for the addition of some notches due to the PR harmonic controllers. As can be seen, the location of these notches is independent of the number of inverters. The parameters associated with the PR harmonic controllers are listed in Table II.

Considering Fig. 7, a problem can arise if the resonant frequency of the system becomes close to one of the selected frequencies of the PR harmonic controller. This causes a harmonic interaction between the inverters and the grid which is a potential problem for multi-inverter systems. To better illustrate this, Fig. 8 shows an expanded impedance diagram around the resonant frequency for the case of a system with 4 inverters. The alignment of the series resonant frequency and the frequency of the harmonic controller can be clearly seen at a frequency of 550 Hz.

Furthermore, Fig. 9 shows a root-locus plot of the coefficient of V_N, where the number of inverters is a variable parameter. Similar to Fig. 6, several groups of roots can be recognized in this plot. The first group, which moves left while the number of inverters increases, is related to the resonant frequency of the system. The second group of roots which is close to the imaginary axis is a result of the PR harmonic controllers. A more detailed plot associated with the second group of roots is shown in Fig. 10.

As can be seen in Fig. 9, with an increased number of inverters, the resonant frequency of the system decreases and becomes closer to the selected frequencies for the harmonic compensators of the PR harmonic controllers. Therefore, as depicted in Fig. 10, in the harmonic frequencies the root locus shifts to the right side of the imaginary axis and causes instability. If the number of parallel inverters increases, the resonant frequency drifts to lower frequencies and makes the system stable again. As illustrated in Fig. 7, with an increased number of inverters, the resonant peak amplitude and the effect of the resonance decrease.

IV. CONTROLLER MODIFICATION FOR INSTABILITY PREVENTION

It was shown in Section III that PR harmonic controllers can lead to undesirable instability and harmonic magnification in multi-inverter distribution systems. To overcome this problem, proper damping must be added to the system. Passive damping is not usually an option since it results in increased losses. On the other hand, integrating active damping into the controller is a viable solution [17].

One possible method to add active damping to the control system of grid-connected inverters, shown in Fig. 3, is to feedback the output capacitor voltage with the gain of K, as shown in the block diagram of Fig. 11. By a proper selection of K, the root locus of the multi-inverter system can be modified so that all of the poles are shifted to the left hand plane (LHP) for various numbers of inverters, as illustrated in Fig. 12. It should be noted that this feedback does not require any additional sensors since the capacitor voltage is already sensed for other tasks such as the phase locked loop (PLL) input signal.

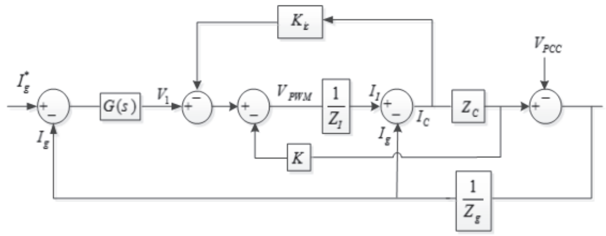


Fig. 11. Control system block diagram with active damping.

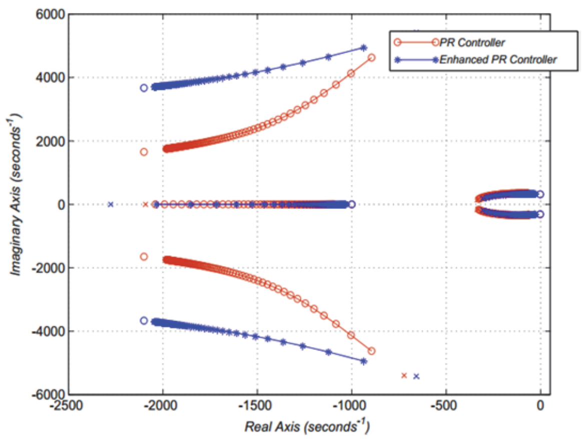


Fig. 12. Root locus plot of the coefficient of the grid voltage in (4) with the control system shown in Fig. 11.

The effectiveness of the proposed feedback can be justified as explained below. Considering Fig. 11, it is possible to write:

$$V_C = V_1 - K_{ic}C\frac{dV_C}{dt} - KV_C - V_I \tag{6}$$

$$(K+1)\,V_C + K_{ic}C\frac{dV_C}{dt} = V_1 - V_I \tag{7}$$

where V_I is the voltage drop corresponding to the impedance of the inverter-side inductance in an LCL filter. Rearranging (7) yields:

$$(K+1)\,V_C + K_{ic}C\frac{dV_C}{dt} = (K+1)\,V_C + K_{ic}\frac{C}{K+1}\frac{d(K+1)\,V_C}{dt} \tag{8}$$

Equation (8) can be envisaged as a capacitor that is equal to $(1/(K+1))C$ in series with a resistor that is equal to K_{ic}. In other words, adding the proposed feedback results in a capacitor reduction, which prevents the shift of the resonant frequency to lower frequencies and consequently avoids instability.

V. Simulation Results

In this section, the analytical studies presented in Section III are verified by time domain simulations using the PSIM simulation platform. The parameters associated with the simulated system are similar to those described in Section II and III, and shown in Table I and II. Considering Fig. 10, it can noted that a system with two inverters becomes unstable due to the 11th PR harmonic controller. The pole amplitude for a two-inverter system is equal to 3530, which corresponds to a frequency of around 550 Hz. Fig. 13(a) shows the simulation results corresponding to this scenario where the 5th, 7th and 11th PR harmonic controllers have been activated at t=10 sec. The harmonic spectra of this waveform (after entering the harmonic controllers) are illustrated in Fig. 13(b), confirming the instability with a frequency around 550 Hz, i.e. the one associated with the 11th harmonic.

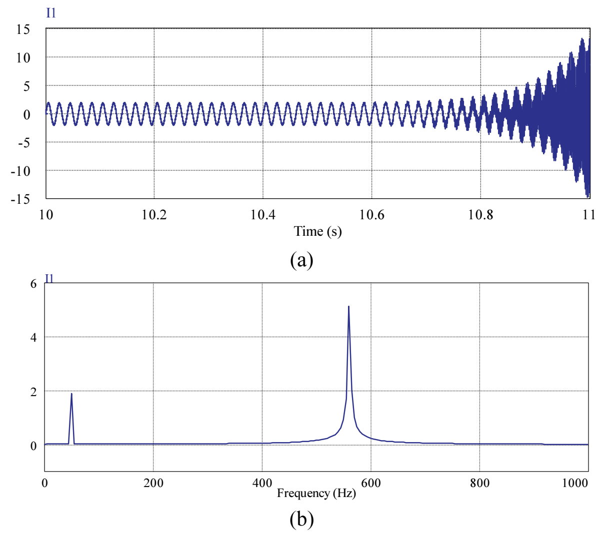


Fig. 13. Simulation results of a distribution grid with two inverters with a PR harmonic controller: (a) inverter current injected into the grid; (b) its harmonic spectra.

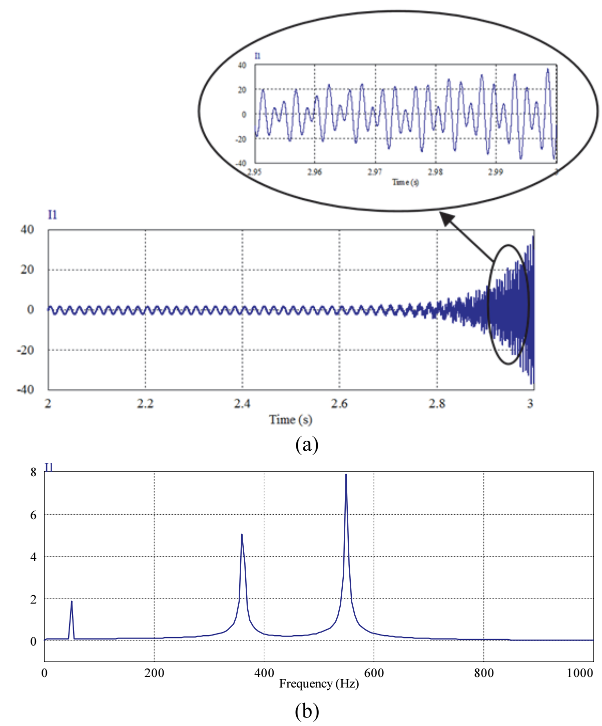


Fig. 14. Simulation results of a distribution grid with 12 inverters and with a PR harmonic controller: (a) inverter current injected into the grid; (b) its harmonic spectra.

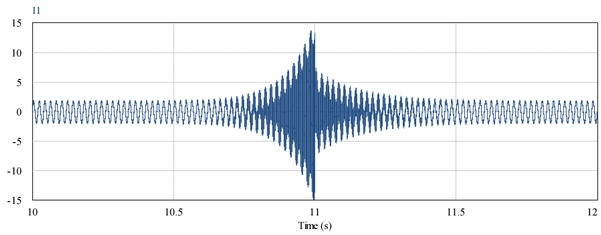


Fig. 15. Inverter current for the proposed enhanced-PR controller.

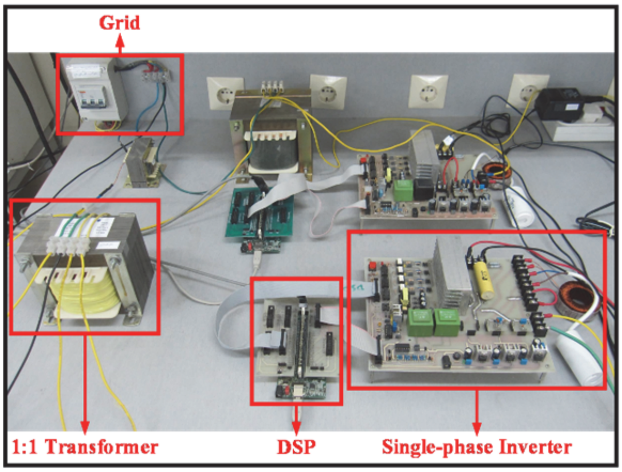
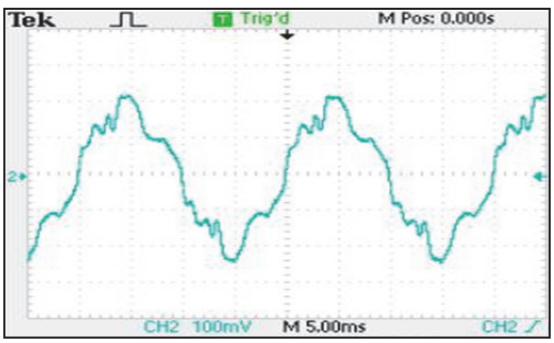
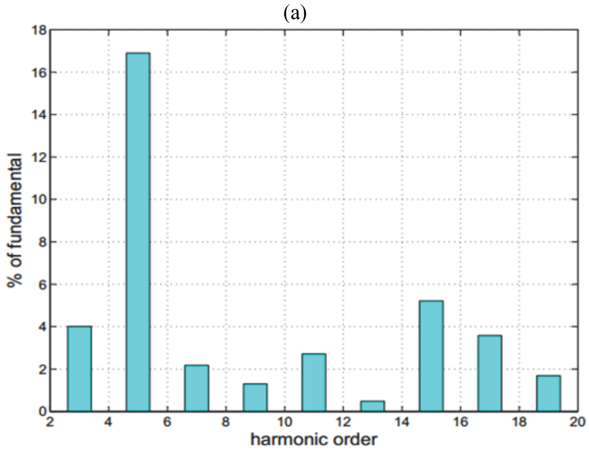


Fig. 16. Experimental setup.

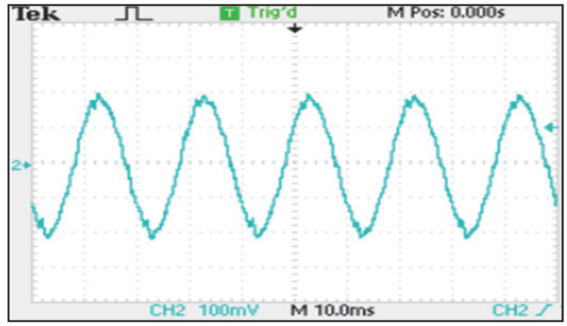


(a)

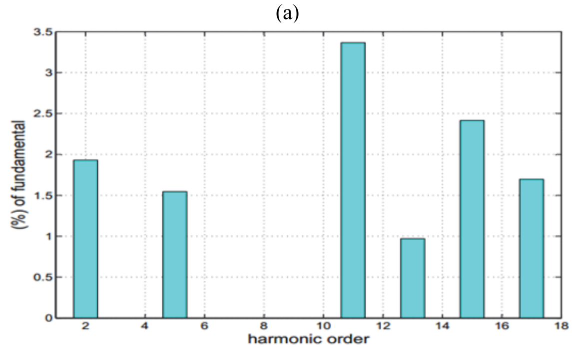


(b)

Fig. 17. Experimental results of a distribution grid with one inverter without a PR harmonic controller: (a) inverter current injected into the grid; (b) its harmonic spectra.



(a)



(b)

Fig. 18. Experimental results of a distribution grid with one inverter with a PR harmonic controller: (a) inverter current injected into the grid; (b) its harmonic spectra.

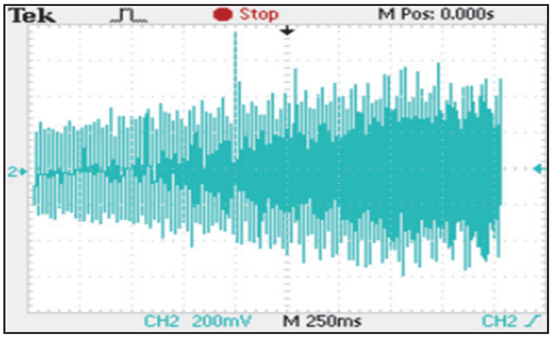
As another case, a 12-inverter system with 5th, 7th and 11th PR harmonic controllers is considered. Based on Fig. 10, two unstable pole pairs appear around these harmonics. Fig. 14 shows simulation results corresponding to this case. As can be seen, in this case both the 7th and 11th PR harmonic controllers result in instability around their corresponding frequencies, i.e. 350 Hz and 550 Hz.

Fig. 15 shows simulation results when the modified controller is activated at t= 11 sec. As can be seen, the system which has been on the verge of instability becomes stable.

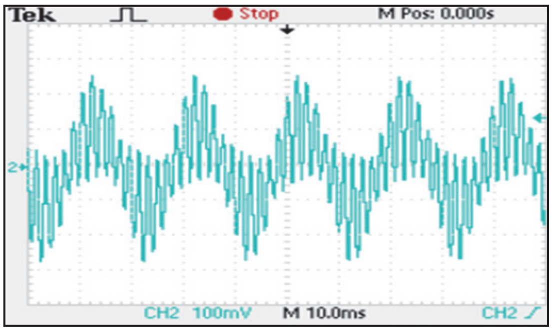
VI. Experimental Results

A laboratory experimental setup was implemented to verify the results obtained by analytical studies and simulations. For this reason, two similar single-phase grid-connected inverters were built as shown in Fig. 16. The controller system of these inverters were digitally implemented using a high performance DSP.

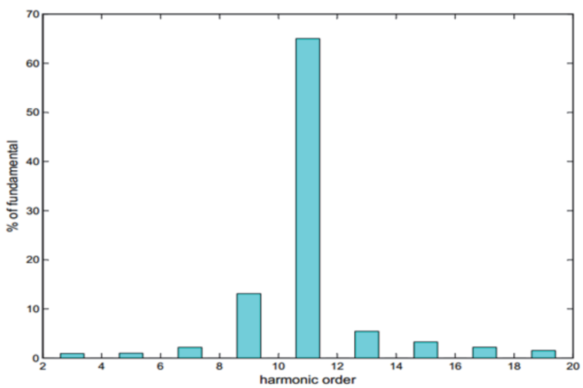
Fig. 17 shows the current injected into the grid when no PR harmonic controller has been employed in the inverter control system. The highly distorted waveform confirms the need for improving the controller performance, which is accomplished by adding PR harmonic controllers. Fig. 18 shows the current injected into the grid for one inverter when PR harmonic controllers at the 5th, 7th and 11th harmonics are added to the main controller. The significant reduction in the inverter current distortion shows the effectiveness of the PR harmonic controllers.



(a)



(b)



(c)

Fig. 19. Experimental results of a distribution grid with two inverters with PR harmonic controllers: (a) inverter current injected into the grid; (b) magnification of (a); (c) its harmonic spectra.

Fig. 19 shows experimental results when two parallel inverters have been connected to the grid and the 5^{th}, 7^{th} and 11^{th} PR harmonic controllers are activated. Instability can be observed in the inverter output current.

VII. Conclusions

This paper presented a study showing the instability and resonance when multiple inverters with proportional-resonance (PR) harmonic controllers are connected to a distribution grid. It was shown that for certain numbers of inverters connected to the grid, the overall system may become unstable. The detailed system modelling, including the inverter control system, was presented. The unstable poles and their association with the PR harmonic controllers were identified. It was shown that by modifying an existing PR controller, an acceptable damping and a stable operation can be achieved. Simulation and experimental results were used to show the validity of the theoretical analysis. It must be emphasized that the instability phenomenon shown in this paper is generally dependent on the controller type, system configuration and connecting lime impedance.

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