A Sensor-less Control Scheme for Grid Tied Inverters to Provide Phase Balancing Services to the Distribution Grid

Lenos Hadjidemetriou, Anastasis Charalambous, Lazaros Zacharia, Elias Kyriakides
KIOS Research and Innovation Center of Excellence and Department of Electrical and Computer Engineering, University of Cyprus
Nicosia, Cyprus
Tel.: +357/22-893450
Fax: +357/22-894555
E-Mail: {hadjidemetriou.lenos, charalambous.anastasis, lzacha02, elias}@ucy.ac.cy
URL: http://www.kios.ucy.ac.cy/

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Keywords

Phase Balancing, Photovoltaics, Sensor-less Control, Smart grids, Voltage Source Inverter.

Abstract

This work proposes a sensor-less controller for grid tied photovoltaic (PV) inverters to enable phase balancing functionalities for compensating asymmetric loading conditions imposed by building loads in low voltage distribution grids. For enabling such an advanced functional operation by PV inverter, the first step is to enable the inverter to estimate the equivalent grid impedance. Then, the grid impedance is utilized to approximate the nearby load asymmetries without using any additional current sensors. Finally, advanced control schemes have been developed for PV inverters in order to enable the new phase balancing operation mode, where the inverter can compensate the asymmetric loading conditions of a distribution feeder. The effectiveness of the proposed method has been experimentally validated in a prototype where the grid tied PV inverter is able to compensate nearby load asymmetries and maintain a purely symmetrical interaction with the grid. Further, a simulation-based investigation in a realistic distribution feeder has been performed in order to highlight the benefits of the proposed approach regarding the power quality, the energy losses and the effective utilization of distribution grid capacity.

1. Introduction

The majority of loads at a prosumer site are single-phase devices, resulting to the appearance of asymmetric loading conditions for the building, which affects the phase balancing of distribution grids. The unequal allocation of the loading conditions among the three phases of the distribution feeder can affect the power quality, the energy losses and the utilization of the grid capacity. As a result, phase balancing or asymmetric loading compensation in a distribution feeder has been recently indicated as a valuable ancillary service [1] that can relieve substation and feeder overload and can enable the effective utilization of the grid capacity. This is also indicated by recent international standards regarding the operation of micro-grids [2].

Until now, the phase balancing ancillary service is provided by shunt active power filters [3] or unified power quality conditioners [4], [5] connected in several locations within the distribution feeder. Such solutions come with a significant capital cost for extra power electronics-based converters that need to

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be covered mainly by the distribution system operator (DSO). In [6], the installation of an Energy Storage System (ESS) at the MV/LV substation is proposed, where advanced functionalities of ESS are used to regulate the power exchange with the medium-voltage distribution grid and to compensate the asymmetric loading. This solution requires a high capital investment for batteries and the converter, while space restrictions should also be considered within the substation.

Alternative solutions have been proposed in [6]-[11], where grid tied inverters of PV systems are utilized not only for injecting properly the produced power into the grid, but also for providing ancillary services to benefit the grid operation. In [6] and [7], the inverters are also used to compensate the harmonic distortion imposed by the prosumer's non-linear loads. The inverter controller receives local measurements for the load currents and subsequently an adaptive observer and a triangular function are used respectively in order to analyze the distortion that needs to be compensated. In [9], the grid tied inverter compensates the asymmetric loading conditions of the prosumer by providing phase balancing services, while in [10] and [11] the grid tied inverter compensates both asymmetries and selected harmonics of the building load. In [9]-[11], a decoupling network is used to decompose the load currents to their positive and negative sequence components in order to enable phase balancing and active filtering operation. All the aforementioned works ([6]-[11]) can maintain a high quality interaction between the prosumer and the grid. However, the use of additional current sensors is required to measure the building load by the inverter in order to activate such operational modes. The use of extra sensors imposes a small additional cost for the prosumer and in some cases technical and distance restrictions are imposed due to the electrical installation of the building, since the PV inverter and the total load may not be connected at the same distribution board (DB). Another approach is proposed in [12], [13] based on virtual harmonic resistances for single-phase PV inverters in order to compensate the effect of harmonic distorted local loads on the voltage at the Point of Common Coupling (PCC). This approach does not require another measurement device, however the approach has only been applied for harmonic distortion compensation. Further, the concept of virtual harmonic resistors may impose a steady state error regarding the fundamental power control that needs to be taken care of [13].

In this work a novel sensor-less controller is proposed for the grid tied inverter of PV systems in order to enable the phase balancing operational mode. The proposed controller does not require any additional sensors to measure the asymmetric loading conditions of the prosumer or nearby loads. The asymmetric loading conditions are estimated by considering an approximation of the equivalent grid impedance and by analyzing the grid voltage at the PCC. Initially, the method approximates the equivalent grid impedance [14]-[16] by deliberately introducing a small disturbance by the inverter for a short time and measuring its effect. During normal operation, the measured voltage at the PCC is dynamically analyzed based on a decoupling network [17] and the approximated grid impedance is utilized to estimate the asymmetric loading conditions caused by nearby loads. Then, an advanced inverter controller is composed according to [9] in order to locally generate the asymmetric loading current and thus, a phase balanced interaction between the prosumer and the grid is ensured. In contrast with the works presented in [9]-[11], the proposed approach does not require additional sensors to measure the prosumer loads in order to compensate the imposed asymmetries and can be considered as a plug and play solution since it estimates itself the required grid information. Furthermore, the proposed method can compensate not only the asymmetric loading conditions imposed by the prosumer, but also the ones derived by other nearby consumers. As a result, the proposed sensor-less controller can enable the phase balancing services by the PV inverter without an extra cost and with great benefits for the distribution grid. The effectiveness of the proposed scheme has been experimentally validated using a prototype setup for a laboratory inverter. The experimental results demonstrate that the proposed scheme can enable phase balancing functionalities by the PV inverter and can maintain a purely symmetrical interaction between a prosumer and the grid. Furthermore, an investigation has been performed in a realistic low voltage distribution grid to highlight the impact of the proposed technique in distribution grids. The sensor-less phase balancing functionality of the PV inverter can symmetrize the distribution grid loading conditions which can greatly benefit the power quality and maximize the utilization of the existing grid capacity.

The paper is organized as follows. In Section 2, the new sensor-less controller is presented to enable the inverter phase balancing mode. Section 3 demonstrates the effectiveness of the proposed method based on experimental and simulation results, while the paper is concluded in Section 4.

2. Sensor-less technique for PV inverters to enable phase balancing mode

The proposed scheme is based on three main steps: (a) Learning procedure to approximate the equivalent grid impedance (z_{eq}), (b) Estimation of asymmetric loading currents ($\mathbf{i}_L^{-1}$) of the prosumer or of nearby loads by online analyzing the voltage at PCC and utilizing the estimated grid impedance (z'_{eq}), and (c) PV inverter operating in phase balancing mode to compensate prosumer asymmetries. The operating conditions in each step are demonstrated in Fig. 1 and are analyzed in the following subsections.

2.1. Learning procedure – Approximate grid impedance

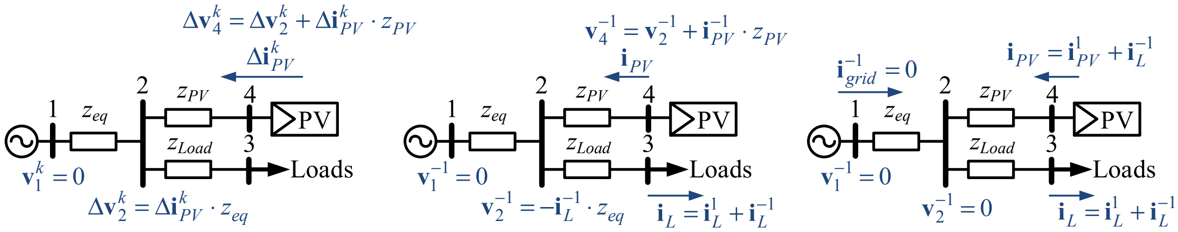
The initial step for enabling the proposed control scheme is to approximate the equivalent impedance (z_{eq}) of the grid. According to the simplified diagram of Fig. 1, z_{eq} is the impedance between an ideal equivalent source of the grid (bus 1) and the main Distribution Board (DB) of the building (bus 2). Several methods can be found in the literature [14], [15], [16] (mainly for detecting islanding conditions in microgrids) to approximate the grid impedance. These methods are intentionally changing active-reactive power or injecting a harmonic distortion by an inverter and then by measuring the impact on the voltage, they can calculate the equivalent impedance to determine islanding or grid-connected operation. In a similar way, the proposed scheme approximates the equivalent impedance by intentionally varying the injection of negative sequence current $\left(\Delta\mathbf{i}_{PV}^k\right)$ by the PV inverter (where k=-1 for negative sequence) and then it measures the impact on the negative sequence voltage $\left(\Delta\mathbf{v}_4^k\right)$ at the PCC (bus 4), as demonstrated in Fig. 1(a). By considering z_{PV} as known (impedance between the PV inverter and the main DB), the equivalent grid impedance can be approximated as,

$$z'_{eq} = \frac{\Delta\mathbf{v}_2^k}{\Delta\mathbf{i}_{PV}^k} = \frac{\Delta\mathbf{v}_4^k - \Delta\mathbf{i}_{PV}^k \cdot z_{PV}}{\Delta\mathbf{i}_{PV}^k} \tag{1}$$

In cases where the inverter is installed very close to the main DB, the z_{PV} may be neglected. It should be noted that the variation (Δ) is considered in this analysis in order to eliminate the initial offset (if it exists) in the negative sequence analysis of the circuit. The initial offset in negative sequence may occur due to asymmetric current injection by the PV or by a non-purely symmetrical grid voltage conditions. The approximation of the equivalent grid impedance $\left(z'_{eq}\right)$ is the cornerstone of the proposed sensor-less control scheme as will be demonstrated in the next subsections. The approximation of the grid impedance can be considered as an initialization procedure and it can be performed once every few minutes or hours in order to re-calculate the grid impedance in case of changes in the configuration of the grid. The learning-approximation scheme for the equivalent grid impedance enables the plug and play capabilities of the proposed sensor-less phase balancing scheme.

2.2. Estimation of asymmetric loading conditions

By utilizing the approximation of the equivalent grid impedance (z'_{eq}), the asymmetric loading conditions of the prosumer can be estimated and thus, no additional current sensors are required. As presented in Fig. 1(b), during normal operating conditions, the PV inverter injects the produced PV



(a) Step 1: Grid impedance (z_{eq}) approximation
(b) Step 2: Estimation of asymmetric loading conditions ($\mathbf{i}_L^{-1}$)
(c) Step 3: Phase balancing

Fig. 1: A simplified diagram for the operating conditions during the three main operational steps of

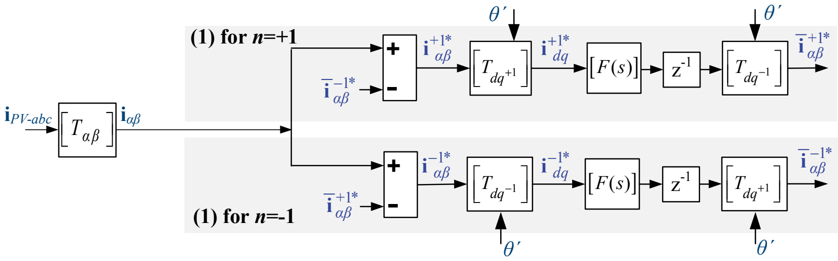


Fig. 2: A decoupling network to decompose dynamically the current injection into its positive and negative sequences.

power into the grid in a synchronized way by measuring the grid voltage at the PCC (bus 4). Therefore, the PV inverter controller can estimate the asymmetric loading conditions ($\mathbf{i}_L^{-1}$) by only measuring the voltage $\mathbf{v}_4$ at the PCC (bus 4) and the injected current ($\mathbf{i}_{PV}$). Both $\mathbf{v}_4$ and $\mathbf{i}_{PV}$ need to be dynamically analyzed in corresponding positive ($\mathbf{v}_4^{+1}$ and $\mathbf{i}_{PV}^{+1}$) and negative ($\mathbf{v}_4^{-1}$ and $\mathbf{i}_{PV}^{-1}$) sequence component. The decomposition of current sequences is enabled through a decoupling network demonstrated in Fig. 2. The decoupling network estimates each sequence of the current by combining (2) in a recursive cross-coupling way for *n*=+1, -1, as shown in Fig. 2.

$$\mathbf{i}_{\alpha\beta}^{n*} = \left(\mathbf{i}_{\alpha\beta} - \bar{\mathbf{i}}_{\alpha\beta}^{m*}\right) = \left(\mathbf{i}_{\alpha\beta} - \sum_{m \neq n} \left[T_{dq^{-m}}\right]\left[F(s)\right]\left[T_{dq^{m}}\right]\mathbf{i}_{\alpha\beta}^{m*}\right) \tag{2}$$

It should be mentioned that the decoupling network dynamically analyzes the injected current by the inverter ($\mathbf{i}_{PV}$) and it estimates the corresponding positive ($\mathbf{i}_{dq-PV}^{+}$=$\mathbf{i}_{dq}^{+*}$) and negative ($\mathbf{i}_{dq-PV}^{-}$=$\mathbf{i}_{dq}^{-*}$) sequence components. In (2), $\left[T_{dq^{m}}\right]$ and $\left[T_{dq^{-m}}\right]$ represent the forward and backward Park's transformation matrix, and [*F*(*s*)] represents a first order low-pass filter matrix with a cut-off frequency equal to $2\pi 50/3$ rad/s as defined in the controller [9], [17]. It is worth mentioning that the recursive cross-coupling structure requires a sample delay when the filtered estimation of the sequence component ($\bar{\mathbf{i}}_{\alpha\beta}^{m*}$) is subtracted in order to break the algebraic loop. The decoupling of the voltage is achieved in a similar way since a corresponding decoupling network is included in the synchronization unit DNαβ-PLL [17]. It should be highlighted that the suggested decoupling networks achieve fast dynamic response which allows the stable and proper operation of the method even during transient events.

Since the negative sequence voltage at the PCC ($\mathbf{v}_4^{-1}$) and the negative sequence current injection ($\mathbf{i}_{PV}^{-1}$) can be estimated by the decoupling network (Fig. 2) and the synchronization method [17], the asymmetric loading conditions (negative sequence) of nearby loads can be estimated according to (3), as shown in Fig. 1(b).

$$\mathbf{i}_L^{-1\prime} = -\frac{\mathbf{v}_2^{-1}}{z'_{eq}} = \frac{\mathbf{i}_{PV}^{-1} \cdot z_{PV} - \mathbf{v}_4^{-1}}{z'_{eq}} \tag{3}$$

Consequently, the asymmetric loading conditions ($\mathbf{i}_L^{-1}$) that affect the voltage (i.e., by imposing asymmetries - negative sequence component) at the main DB (bus 2) are accurately estimated by the proposed technique without requiring more current sensors to be installed.

2.3. Phase balancing mode for inverters

The estimated asymmetric loading conditions ($\mathbf{i}_L^{-1\prime}$) provided by the inverter controller (Section 2.2) are utilized as a negative sequence reference current to enable the phase balancing operation of the PV inverter (without extra current sensors) in order to compensate asymmetries imposed by prosumer loads or by nearby loads. Thus, the PV inverter should be able to inject on-purpose asymmetric currents. The positive sequence current injection ($\mathbf{i}_{PV}^{+1}$) delivers the produced power by the PV panels into the grid while negative sequence component ($\mathbf{i}_{PV}^{-1} = \mathbf{i}_L^{-1}$) aims to locally generate the loading asymmetries required by the prosumer loads. As a result, the inverter is able to maintain a purely symmetrical interaction between the prosumer and the grid ($\mathbf{i}_G^{-1} = 0$) as demonstrated in Fig. 1(c).

Therefore, an advanced inverter controller needs to be developed to enable the sensor-less phase balancing mode for PV inverters in order to compensate the asymmetric loading conditions imposed by nearby loads ($\mathbf{i}_L$). The inverter controller is integrated as shown in Fig. 3 based on:

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- a synchronization unit (DNαβ-PLL) [17] and a decoupling network [9] (Fig. 2) to decompose the positive and negative sequence of grid voltage and injected current
- a unit to estimate the asymmetric loading conditions of nearby loads as presented in Section 2.2
- a PQ controller to ensure the current limits of the converter under any operational mode
- a modified current controller to inject asymmetric currents for compensating load asymmetries
- a Q-profile unit to ensure the proper reactive support during voltage drops
- a Maximum Power Point Tracker (MPPT) to maximize the power extraction from the PV panels.

It should be noted that the PQ controller regulates the active (P) and reactive (Q) power injection according to the operation mode, maintains the DC link voltage and regulates the positive and negative current injection during phase balancing mode. In any operational mode, the PQ controller is responsible to ensure that the current limits of the converter will never be violated.

The phase balancing mode requires that the current controller will be capable for intentional asymmetric current injection. Thus, a current controller is modified according to [9] and is designed using a positive and a negative sequence frame as shown in Fig. 4. The positive sequence frame (dq^{+1}) is rotated with $+2\pi 50$ rad/s and it regulates the positive sequence current injection according to the reference $\left(\mathbf{i}_{dq}^{+1*}\right)$ (for delivering the produced power into the grid) by utilizing the positive sequence components of the grid voltage $\left(\mathbf{v}_{dq}^{+1}\right)$ and measured current $\left(\mathbf{i}_{PV}^{+1}\right)$. On the other hand, the negative sequence frame (dq^{-1}) of the current controller rotates with $-2\pi 50$ rad/s and it regulates the negative sequence current injection

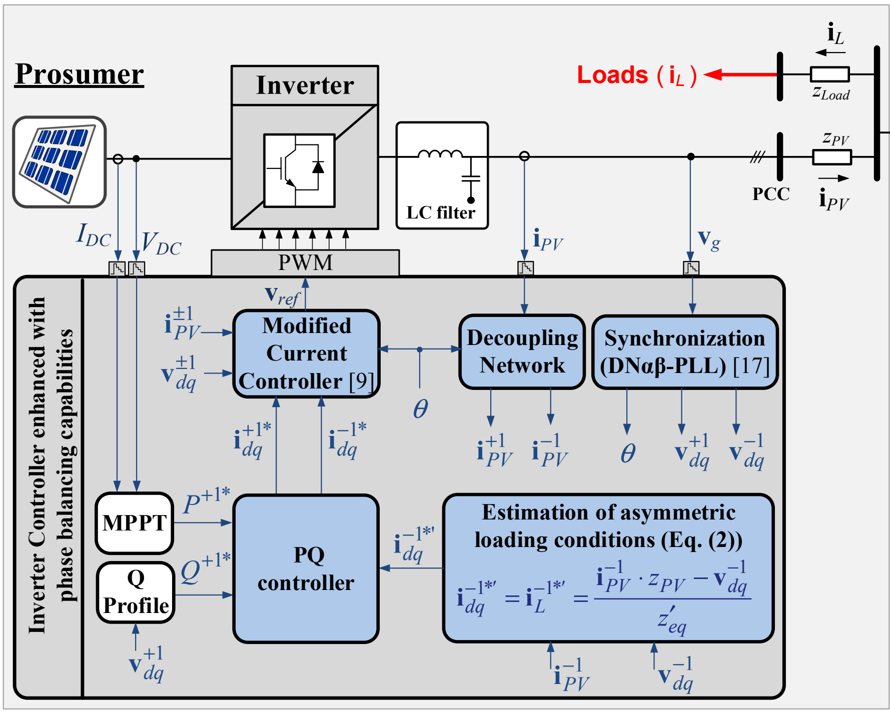

Fig. 3: Inverter structure with phase balancing capabilities.

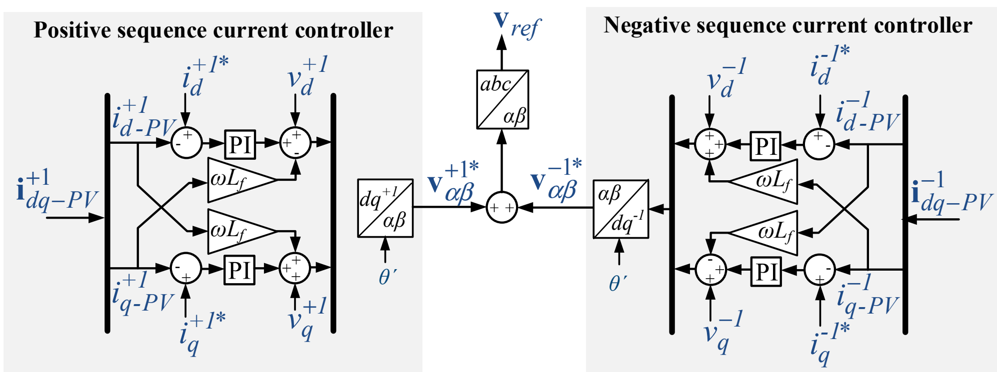

Fig. 4: A modified current controller to enable the asymmetric current injection by the PV inverter.

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according to the reference $\left(\mathbf{i}_{dq}^{-1*}\right)$ (for phase balancing mode) by utilizing the corresponding negative sequences of the grid voltage $\left(\mathbf{v}_{dq}^{-1}\right)$ and PV currents $\left(\mathbf{i}_{PV}^{-1}\right)$.

As a result, an advanced multifunctional operation of the grid tied inverter is achieved through the proposed controller. The inverter is able to deliver the available power into the grid while providing ancillary services (i.e., reactive support, phase balancing, etc.). For the phase balancing mode, the inverter requires an initial learning procedure in order to approximate the equivalent grid impedance at the PCC and then, the inverter can compensate the asymmetric loading conditions imposed by nearby loads based on the proposed sensor-less technique.

3. Validation and demonstration

This section validates the performance of the proposed sensor-less controller for enabling phase balancing services by PV inverters based on an experimental setup. Further, an investigation is performed to highlight the impact of the proposed method in a realistic low-voltage distribution grid.

3.1. Experimental validation of inverter's sensor-less controller for phase balancing

A prototype laboratory setup has been developed in order to evaluate the operation of the proposed sensor-less controller for enabling phase balancing capabilities for the grid tied inverter. The setup is demonstrated in Fig. 5. A DC power supply emulates the PV power production and a three-phase load has been connected in parallel with the inverter at the PCC in order to impose asymmetric loading conditions for the prosumer. A 5 kVA three-phase inverter based on IGBTs switching devices is utilized for this experiment and the proposed inverter controller is digitally developed within a dSPACE DS1104 control board using a sampling and switching frequency of 3.45 kHz. More information regarding the controller parameters is available in Table I.

An experimental investigation is performed utilizing the laboratory setup of Fig. 5 to validate the performance of the proposed sensor-less control scheme. During the learning procedure, the inverter is intentionally injecting a negative sequence current (i_d=2 A and i_q=1 A) for 1 s. With the aid of this injection, the controller is able to approximate the equivalent grid impedance (z_{eq}) which is provided in Table I.

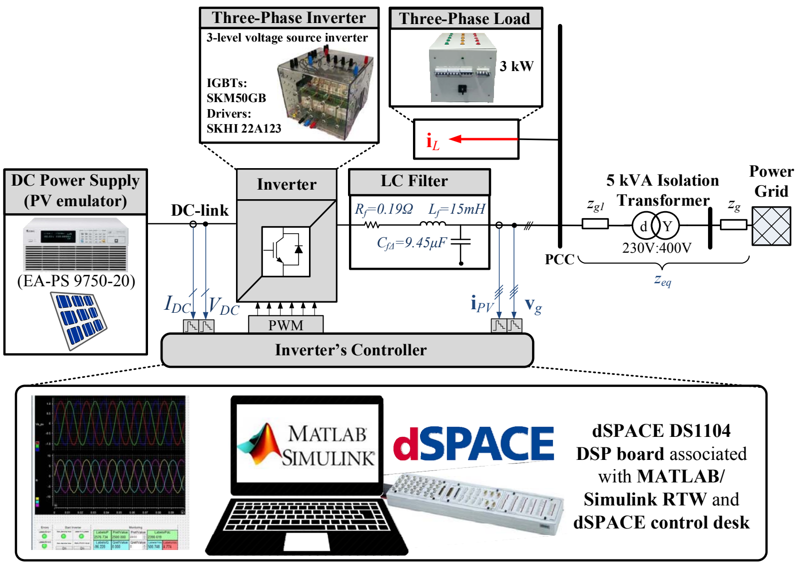

Fig. 5: Laboratory setup for experimentally validating the effectiveness of the proposed method.

Table I: Parameters of the controller

Switching and sampling frequency	3.45 kHz
Synchronization Unit	DNαβ-PLL (k_P=92, k_I=4232)
Current Controller	Positive sequence scheme (k_P=17.3, k_I=218.5) Negative sequence scheme (k_P=1.7, k_I=21.8)
Estimated equivalent grid impedance	z_{eq}=(0.9+j2.85) Ω

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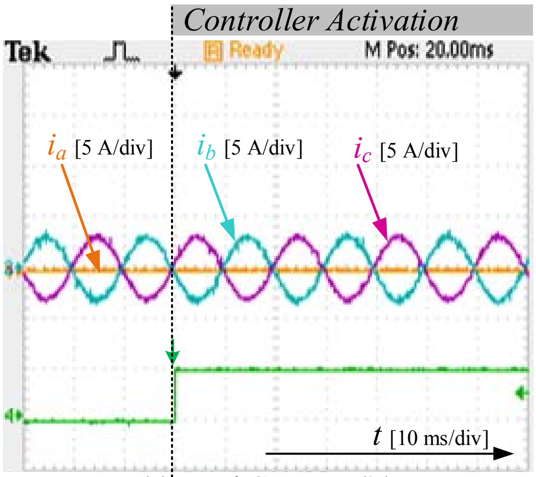
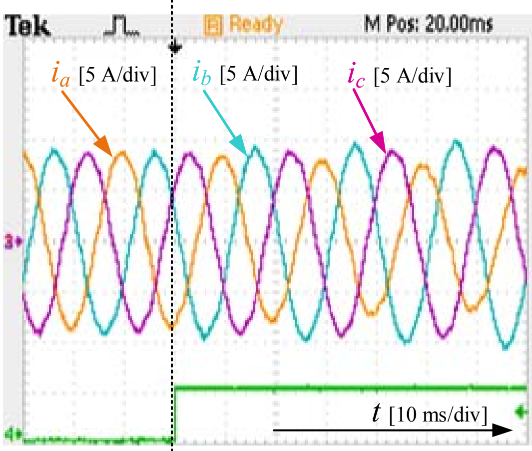
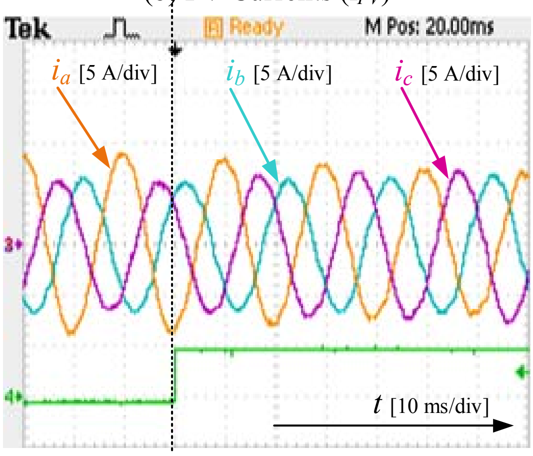
After the learning procedure, the inverter is able to provide phase balancing services to the grid and thus, to ensure a symmetrized interaction between the prosumer and the grid by enabling the inverter to compensate load asymmetries without requiring extra current sensors to measure asymmetric loading conditions. The experimental operation of the inverter according to the proposed control scheme is demonstrated in Fig. 6 and Fig. 7. Fig. 6 demonstrates the transient operation of the laboratory setup when the proposed phase balancing scheme is activated. Prior activation, the prosumer is absorbing asymmetrical current ($\mathbf{i}_L$) as shown in Fig. 6(a) and the PV is injecting symmetrical currents ($\mathbf{i}_{PV}$) as



(a) Load Currents ($\mathbf{i}_L$)

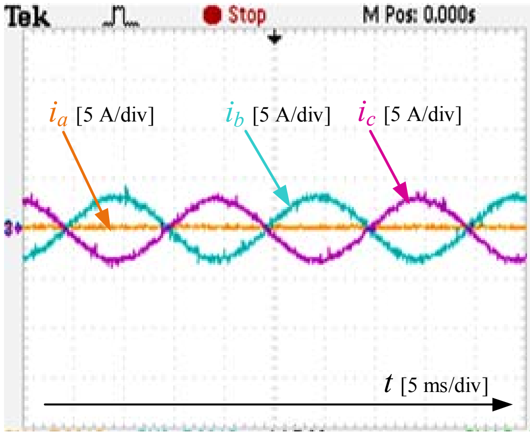


(b) PV Currents ($\mathbf{i}_{PV}$)

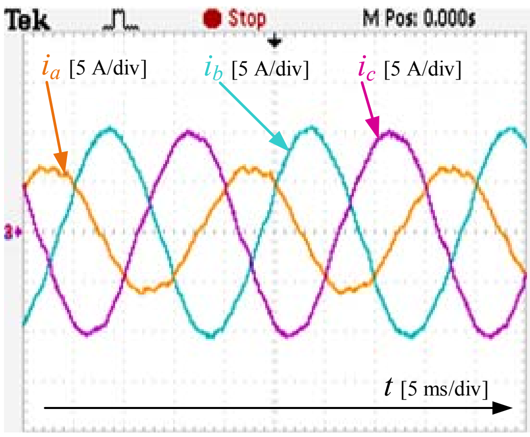


(c) Grid Currents ($\mathbf{i}_G$)

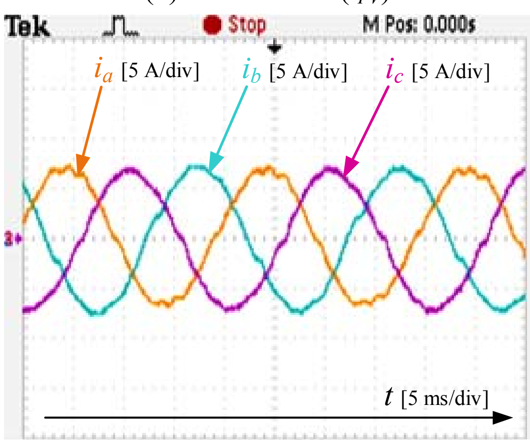
Fig. 6: Experimental results for the transient operation (when the controller is activated) of the proposed phase balancing scheme for a prosumer. Load, PV injection, and grid current are presented in (a), (b) and (c) respectively.



(a) Load Currents ($\mathbf{i}_L$)



(b) PV Currents ($\mathbf{i}_{PV}$)



(c) Grid Currents ($\mathbf{i}_G$)

Fig. 7: Experimental results for the steady state operation of the proposed phase balancing mode. The load asymmetries (a) are compensated by the PV injection (b) to maintain a symmetrized grid interaction (c).

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illustrated in Fig. 6(b) according to the conventional operation mode. Therefore, the grid interaction between the prosumer and the grid ($\mathbf{i}_G$) (Fig. 6(c)) is highly asymmetrical since the current of *phase a* is significantly higher compared to the other two phases. However, when the proposed phase balancing scheme is activated, then the PV is intentionally injecting asymmetrical currents ($\mathbf{i}_{PV}$) in order to compensate load asymmetries and to maintain a purely symmetrical interaction between the prosumer and the grid ($\mathbf{i}_G$). From Fig. 6(b)-(c), the dynamic response of the proposed scheme can be observed, where it is clear that the inverter can compensate grid asymmetries within 40 ms after its activation. Thus, the proposed scheme can provide dynamic phase balancing services even under transient changes in the loading conditions without requiring additional sensors to measure loading asymmetries.
The steady state performance of the proposed controller is demonstrated in Fig. 7. As can be observed, during phase balancing operation, the inverter is deliberately providing the asymmetries (Fig. 7(b)) required by the prosumer loads (Fig. 7(a)) and a purely symmetrical interaction between the grid and the prosumer (Fig. 7(c)) is maintained.

3.2. Impact of the proposed scheme in a realistic low-voltage distribution grid

An investigation is performed, based on simulation results obtained in MATLAB/Simulink, to validate the proper operation of the proposed method and to demonstrate its effectiveness in a realistic distribution grid. More specifically, a case study of a low voltage feeder consisting of two prosumers (with PV and loads) and one consumer (only loads) is considered as shown in Fig. 8. Note that each PV system is connected through a power electronics inverter (enhanced with the proposed phase balancing mode). Further, the main distribution line of the feeder and the building connections are based on a 4x100 mm^2 and 4x22 mm^2 overhead aluminum conductors respectively.
To illustrate the performance of the proposed scheme, various loading conditions for the three loads are considered in this case study. Based on Fig. 9, one can realize that Load 3 is always asymmetric during the simulation, while Loads 1 and 2 are initially symmetric and asymmetric loading conditions are imposed at t= 1.1 s and t=1.2 s, respectively. The aim of this case study is to demonstrate the undesired impact on the feeder's operation by the asymmetric loading conditions of buildings and the achievable improvement by utilizing the proposed method for PV inverters, which consists of a sensor-less decentralized controller in order to enable phase balancing services.
In the beginning of the simulation, the proposed phase balancing scheme is deactivated. As a result, significant oscillations occur on the active (P_{grid}) and reactive (Q_{grid}) power of the feeder (measured at MV/LV substation) due to the asymmetric loading condition of prosumer 3 (Load 3). As a result, the power quality of the system is deteriorated and the grid capacity is de-rated. All these issues are arising from the unequal loading allocation among the three phases. At t=1 s the proposed scheme is activated, forcing PV3 to inject intentionally asymmetric currents (Fig. 9(a)) in such a way to compensate the asymmetric currents of Load 3. The effectiveness of the proposed scheme is presented in Fig. 9(b), where the grid currents at the feeder level ($\mathbf{i}_{grid}$) become symmetrical and the power oscillations are dynamically compensated. This is the case until the loading conditions of Load 1 change from symmetric to asymmetric at t=1.1 s (Fig. 9(a)). Although this change should have an effect on the grid conditions (i.e., current, power, etc.), one can realize from Fig. 9(b) that the proposed methodology compensates almost instantly this asymmetric behavior, keeping the feeder operating in symmetric conditions. Once again, this is accomplished by controlling the PV1 inverter to inject suitable currents ($\mathbf{i}_{PV1}$) for eliminating the asymmetries of Load 1, as shown in Fig. 9(a). The change on the loading conditions of Load 1 has as a result the appearance of power oscillations on the active and reactive power provided by the feeder, which are again rapidly compensated due to the fact that the proposed scheme is activated in grid tied inverters of PV1 and PV3. It should be highlighted that according to the proposed methodology, each PV inverter compensates the asymmetric loading conditions imposed by the nearby loads. Thus, PV1 compensates the asymmetries imposed by Load 1, while PV3 contributes towards the phase balancing of Load 3 asymmetries.
All the aforementioned scenarios show clearly the effectiveness of the methodology in utilizing intelligently the PVs of each prosumer to compensate the asymmetries occurring by their respective loads without provision for extra current sensors. The most interesting result though is derived when the loading condition of the consumer (Load 2), which is located between the two prosumers (as shown in Fig. 8), changes from symmetric to asymmetric at t=1.2 s. Fig. 9(a) demonstrates that this change affects the injected PV currents of both prosumers ($\mathbf{i}_{PV1}$ and $\mathbf{i}_{PV3}$) in such a way to compensate the asymmetries

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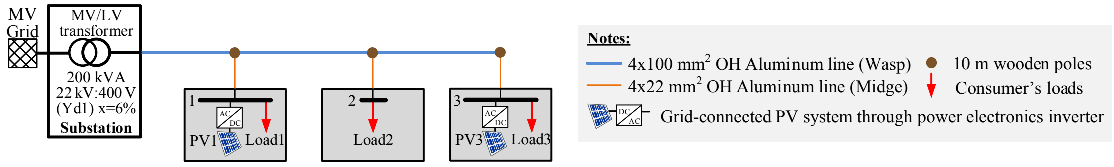
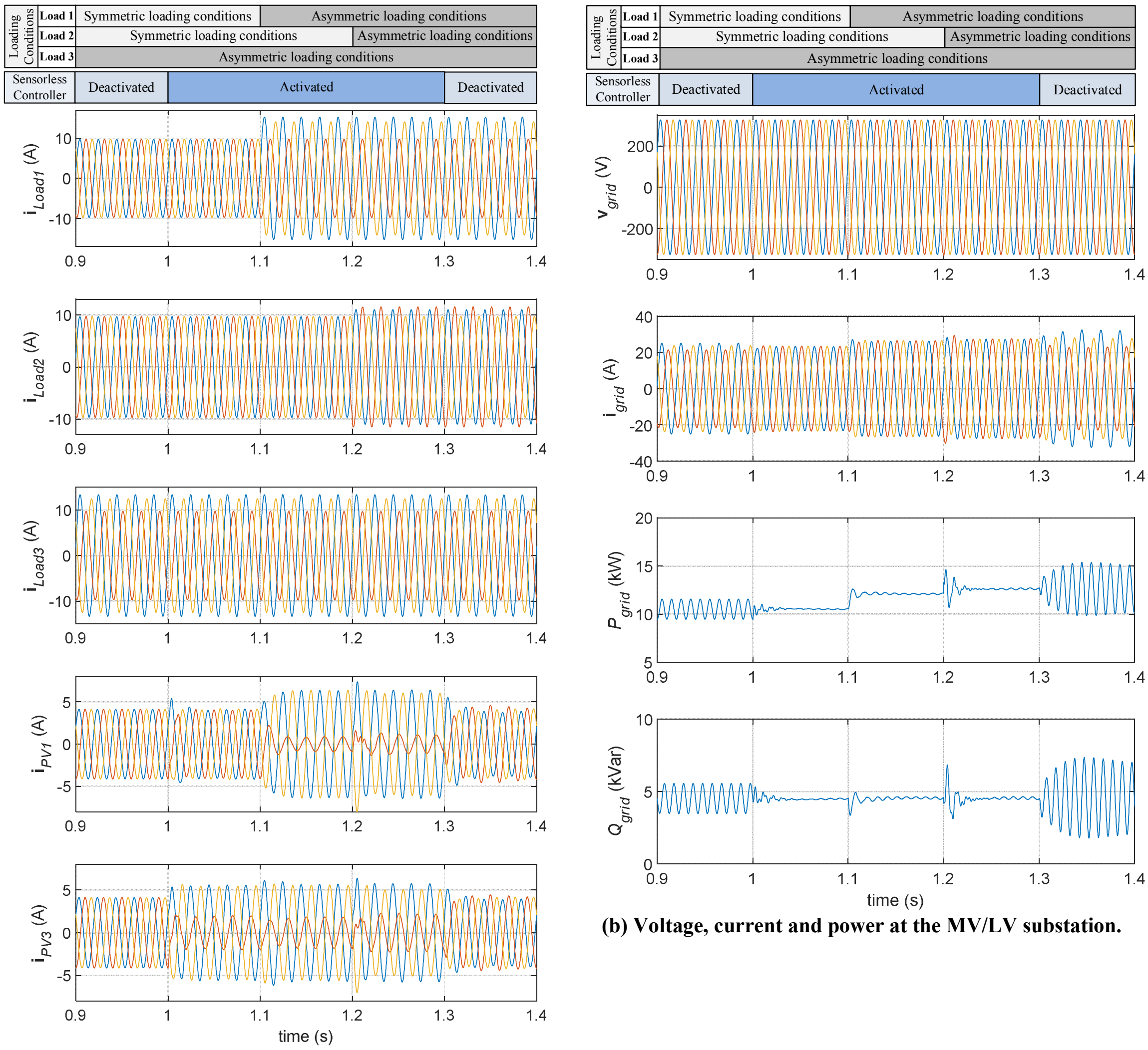


Fig. 8. A distribution feeder case study for evaluating the proposed method for phase balancing.



(b) Voltage, current and power at the MV/LV substation.

(a) Current absorption/injection for loads and PVs

Fig. 9. Simulation results for the case study: (a) current absorption and injection of each building and (b) grid performance (voltage, current and active/reactive power at the substation.

derived by the behavior of Load 2. As a result, the symmetric conditions are maintained for the feeder and hence, the high power quality, efficiency and the effective utilization of the grid capacity is ensured. Furthermore, it is worth mentioning that the contribution of each prosumer on symmetrizing the surrounding unbalanced consumers depends on the distance between them (and on the effect of each PV inverter on the grid voltage). Therefore, since Load 2 is between bus 1 and bus 3, both PVs contribute for phase balancing its currents. For example, if Load 2 was located further to the right of bus 3, then PV3 would be mainly responsible for compensating its asymmetries, since the Load 2 asymmetries would have more intense effect on the grid voltage of PV3.

Finally, the effectiveness of the proposed scheme is also demonstrated in Fig. 9 when the phase balancing scheme is deactivated in both PV1 and PV3 inverters at t=1.3 s. The deactivation of the control scheme leads to the appearance of severe oscillations in the active and reactive power provided by the feeder and intense asymmetries in the grid current. As a result, the power quality, grid capacity and efficiency of the distribution grid are degraded due to the deactivation of the proposed controller.

4. Conclusions

This work proposes a new control scheme for PV inverters to compensate the asymmetric loading conditions imposed by the prosumer's loads or by other nearby loads without requiring any additional current sensors. The solution is plug and play since any required grid information is approximated during the initialization-learning phase. During normal operation, the proposed scheme enables the PV inverters to provide phase balancing services to the distribution grid. Experimental results are provided to validate the effectiveness of the proposed scheme while an investigation is performed to demonstrate the great benefits that can be obtained regarding the power quality, efficiency and effective utilization of the existing capacity of low-voltage distribution grids.

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