Flexible power control scheme for interconnected photovoltaics to benefit the power quality and the network losses of the distribution grid

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***Abstract*—Photovoltaic (PV) systems are integrated into the distribution network (DN) through the grid tied inverter. This paper proposes a flexible power control scheme (FPCS) for three-phase inverters which can compensate the load asymmetries imposed by the nearby residential loads. The development of the control scheme is based on: a dynamic estimation of the load current sequences through a Compensator of Prosumer's Loads (CPL); a power analysis to limit the current injection within the inverter ratings; and an advanced current controller for injecting on purpose unbalanced currents. The proposed scheme can fully exploit the inverter capabilities for benefiting the operation of the DN and its effectiveness has been evaluated through simulation and experimental results. Further, a novel investigation is performed for indicating the impact of the proposed scheme on a realistic low-voltage DN. The investigation shows that the flexible inverter can improve the power quality, reduce the power losses, and decrease the required network capacity of the DN.**

Keywords—Grid tied inverters, load asymmetries, network losses, low voltage distribution grid, power quality.

I. Introduction

The competitive price of photovoltaic (PV) systems and the environmental impact of fossil fuels are only some of the main drivers for the massive penetration of PVs (more than 227 GW installed capacity by 2015). A significant portion of the solar energy is produced by rooftop PV systems installed in residential units, which transform the electricity consumers into "prosumers" [1] (consumers who can produce and consume energy to/from the grid respectively at the same time). The PV produced power is fed into the grid through a grid side converter (GSC), which is usually a three-phase inverter [2] for PVs higher than 4 kW rated power. On the other hand, residential or commercial three-phase consumers/prosumers are mainly based on several single-phase loads and as a result, they should be considered by their nature, as unbalanced loads. This unbalanced loading imposes several problems on the operation of the Distribution Network (DN) [3]: the power quality of the grid is decreased with asymmetric voltage and current conditions, the power losses of the DN are increased along with the grid loading (e.g., of distribution transformers, lines, and cables), the operation of machines is negatively affected with possible overheating and torque vibrations, etc. This paper proposes a flexible power control scheme for the GSC of PVs (Fig. 1), which tries to symmetrize the prosumer loads in order to overcome these issues, ensure a high quality DN operation, and enable a smooth and seamless interaction between the grid and the prosumer.

An alternative way to achieve such a high quality, efficient and symmetrical operation of the DN is to install shunt active power filters [4], [5] in several locations of the grid to compensate the intense asymmetries and harmonics. An active power filter is actually a three-phase inverter with a capacitor on the DC-link that operates in a way to compensate the asymmetries of nearby loads. It is to be noted that active filters with three-wire interconnection [5] can compensate the negative sequence components while the active filters with four-wire interconnection [5] (two additional switching components are required) can compensate zero and negative sequence currents. Both solutions come with a significant additional cost for the inverter's power electronic components. It is worth mentioning that the power electronics setup of the GSC (used for the PV integration) and of the active filter are identical. Therefore, it is cost-effective to use the existing GSC not only for delivering the PV produced power into the grid but also for compensating the load asymmetries.

Such a cost-effective approach has been discussed in [3], [6]-[8]. In [6], [7] a single-phase GSC for PVs is also used for compensating the harmonic distortion of nearby non-linear loads. In this case, the single-phase configuration of the GSC cannot contribute for symmetrizing the prosumer's loads. An innovative method proposed in [3] injects both positive and negative sequence of currents to compensate the voltage asymmetries of the DN. This method does not require extra sensors for measuring the prosumer loads but it requires the knowledge of the grid impedance at the Point of Common Coupling (PCC), which most of the times is unknown. An interesting method is presented in [8], where the GSC is used for compensating both asymmetries and selective harmonics of the prosumer. Specifically, a cascaded delayed signal cancellation method for estimating the reference currents and a modified deadbeat current controller (which can limit the bandwidth of the controller) are used. Alternative methods for estimating the reference currents, according to the prosumer's load currents, are proposed in [9] and [10] based on physical component analysis and conservative power theory, respectively. Both methods are very complex and present a slow response.

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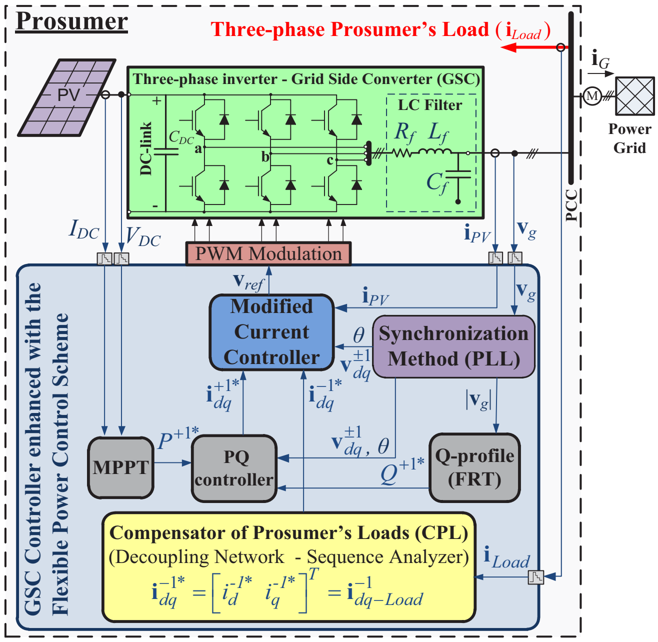

Fig. 1. Prosumer's architecture and the structure of the GSC controller to enable the flexible power control scheme of the PV system.

A flexible power control scheme (FPCS) for the GSC is proposed in this paper for compensating the prosumer's load asymmetries and the effect of such a flexible operation is investigated on a realistic DN. The control scheme is presented in Section II and is based on: an advanced synchronization method [11], a Compensator of Prosumer's Loads (CPL) for estimating the reference currents, and a modified current controller for injecting "on purpose" unbalanced currents. The suggested CPL can analyze the prosumer's load currents for dynamically estimating its negative sequence components that need to be compensated. It is worth mentioning that the CPL can straightforwardly be used as well for estimating the references for harmonic compensation in case is needed. In Section III, simulation and experimental results are demonstrated to evaluate the operation of the proposed FPCS on the prosumer's level. Section IV presents a novel investigation for the impact on the DN, when the FPCS is applied on several PV systems installed in a realistic low-voltage DN configuration (based on the Cyprus grid). The investigation demonstrates significant benefits for the DN, regarding the power quality, the losses and the required capacity of the grid.

II. Proposed Flexible Power Control Scheme for GSC

The proposed FPCS for the GSC of PVs, as shown in Fig. 1, tries to compensate the prosumer's load asymmetries by injecting "on purpose" unbalanced currents to improve the quality operation of the grid. The FPCS according to Fig. 1 is achieved by: an advanced synchronization unit, a modified current controller, and a proposed CPL.

A. Synchronization Method and Current Control

The proposed FPCS requires an advanced synchronization method that enables a fast and accurate operation under unbalanced and harmonic distorted conditions. For the purposes of this work the DNαβ-PLL [11] is used, which is based on a dynamic decoupling network implemented in $\alpha\beta$-frame, that can analyze/decouple the grid voltage on its main components (i.e., positive sequence, negative sequence, and the main low order harmonic components). The fast and accurate estimation of the phase angle of the positive sequence grid voltage (θ) is useful for the synchronization while the analysis of the voltage in its components will be utilized for developing the modified current controller and the proposed FPCS as shown in Fig. 2.

The FPCS requires that the current controller should be able to inject "on purpose" unbalanced currents. Thus, a modification of the current controller presented in [12] is proposed in this paper in order to enable a more effective control and accurate injection of unbalanced currents by the GSC. The proposed current controller is presented in Fig. 2 and is based on a Proportional-Integral (PI) controller designed in two synchronous rotating frames: the dq^{+1}-frame rotating with the positive and the dq^{-1}-frame rotating with the negative fundamental speed. For the modified current controller, it is necessary to analyze/decouple the current in its main components (positive and negative sequence) in order to ensure a proper control in each $dq^{\pm1}$-frame. Thus, the same decoupling network proposed in [11] for fast analyzing the grid voltage is used here for analyzing the injected current as well. The decoupling network is based on the multiple use of (1) for n=+1, -1 to achieve the dynamic decoupling of the current.

$$\mathbf{i}_{dq}^{n*} = \left[T_{dq^n}\right]\left(\mathbf{i}_{\alpha\beta} - \sum_{m\neq n}\left[T_{dq^{-m}}\right]\left[F(s)\right]\left[T_{dq^m}\right]\mathbf{i}_{\alpha\beta}^{m*}\right) \quad (1)$$

In (1), $[T_{dq^n}]$ represents the Park's transformation matrix and $[F(s)]$ represents a first order low-pass filter. It is worth mentioning that the same decoupling network can be used for analyzing selective harmonics ($h_1,\ldots,h_k$) of the current by using (1) for n=+1, -1, $h_1,\ldots,h_k$. However, this work does not focus on compensating harmonic components, so the decoupling network is used only to analyze the fundamental components. As a result, the decoupling network can dynamically analyze the injected current $\mathbf{i}_{PV}$ into its positive ($\mathbf{i}_{dq-PV}^{+1}$) and negative

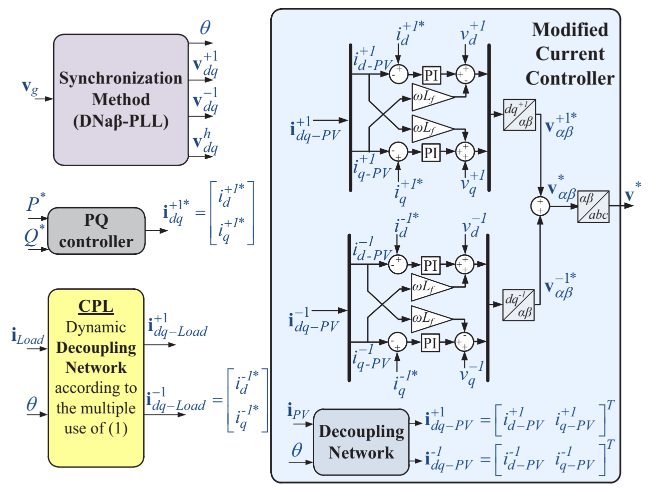

Fig. 2. The proposed flexible power control scheme with the advanced current controller and the decoupling network to generate the reference currents that will compensate the prosumer's load asymetries.

($\mathbf{i}_{dq-PV}^{-1}$) components, as shown in Fig. 2. These components are used as inputs on the modified current controller in order to track the corresponding reference currents $\mathbf{i}_{dq}^{\pm1*}$. Furthermore, the current control scheme uses the $\mathbf{v}_{dq}^{\pm1}$ vectors, estimated by the DNαβ-PLL, as feed-forward terms in order to minimize the control effort of the PI controllers. As a result, the part of the controller designed in dq^{+1}-frame regulates the positive sequence currents injection where the part designed in the dq^{-1}-frame regulates the "on-purpose" injection of negative sequence currents. It is noted that the tuning of the PI controller can be selected according to the parameters of the LC-filter (R_f and L_f), the second-order transfer function response, and the zero-pole cancellation method as described in [13]. It should be mentioned that different tuning parameters can result to a different performance for the current controller.

B. Compensator of Prosumer's Loads (CPL)

As shown in Fig. 1, the current controller requires the positive and negative reference currents in order to control the overall operation of the GSC of PVs. The PQ controller is responsible for generating the positive sequence reference currents $\mathbf{i}_{dq}^{+1*}$, to ensure that all the produced PV power is properly injected into the grid according to the MPPT and Q-profile (conventional controller). In addition, a CPL scheme is utilized for analyzing the prosumer's load currents in order to define the required negative current injection needed for the compensation of the prosumer's asymmetries.

Thus, Fig. 2 shows that for compensating the prosumer's asymmetries, the same decoupling network that is presented in [11] and Section II.A can be used as CPL, for analyzing the prosumer's load current ($\mathbf{i}_{Load}$) into positive ($\mathbf{i}_{dq-Load}^{+1}$) and negative ($\mathbf{i}_{dq-Load}^{-1}$) components by the multiple use of (1) in a cross-coupling way for n=+1, -1. Therefore, as shown in Fig.2, the accurately estimation of the negative sequence of the prosumer's current can straightforwardly be used for generating the negative sequence reference currents of the GSC, as $\mathbf{i}_{dq}^{-1*} = \left[i_d^{-1*}\ i_q^{-1*}\right]^T = \mathbf{i}_{dq-Load}^{-1}$. In this way, all the asymmetric currents imposed by the prosumer's loads will be directly and locally produced by the GSC and thus, the current exchange between the prosumer and the grid ($\mathbf{i}_G$) will be automatically compensated (symmetrized).

It is worth mentioning that under specific cases (intense prosumer's asymmetries) the injection of $\mathbf{i}_{dq}^{-1*}$ can cause violation of the GSC current ratings ($\hat{\imath}_n$). In these cases, the injection of the negative currents will be reduced by the proposed FPCS in order to avoid the limit violations, but without reducing the injection of the PV produced power. According to advanced power analysis [14], under worst-case scenario the maximum negative current injection is determined as $\left|\mathbf{i}_{dq}^{-1*}\right|_{max} = \hat{\imath}_n - \left|\mathbf{i}_{dq}^{+1}\right|$. Hence, in case $\mathbf{i}_{dq}^{-1*} > \left|\mathbf{i}_{dq}^{-1*}\right|_{max}$, then there is a possibility of violating the GSC limits and the $\mathbf{i}_{dq}^{-1*}$ must be reduced by $\mathbf{i}_{dq}^{-1*}/\left|\mathbf{i}_{dq}^{-1*}\right|_{max}$ in order to ensure the proper operation of the GSC without risking the converter's integrity. Note that the current limits introduced here, are actually representing the operation limits of the proposed control scheme.

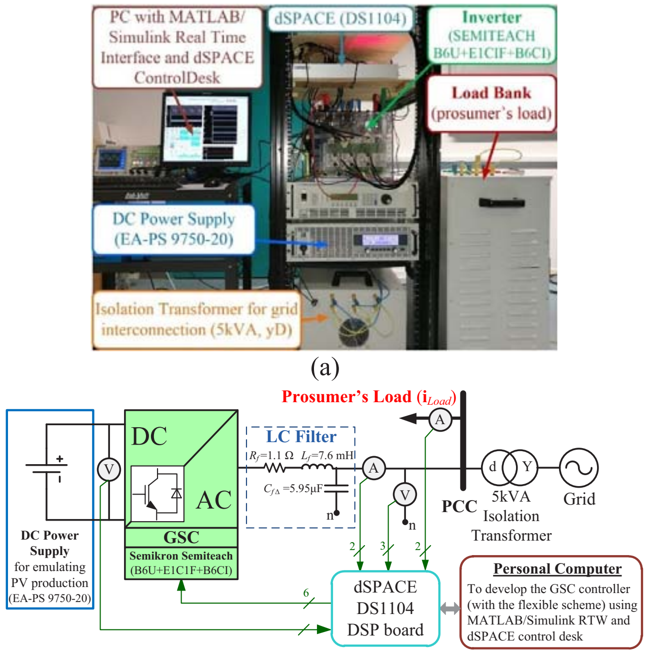

Fig. 3. (a) A photo and (b) a schematic of the experimental setup.

Hence, the proposed FPCS enables the GSC to compensate the asymmetric load of the prosumer by locally producing the negative sequence of currents that are needed by the prosumer. As a result, the overall current exchange between the prosumer and the grid is symmetrized, improving the DN operation. The flexible unbalanced current compensation of the prosumer provided by the GSC of PVs is achieved without reducing the PV produced power and without risking the GSC integrity.

III. Evaluation of the Proposed Scheme

In this section, the operation of the GSC based on the FPCS is presented. The performance of the proposed FPCS is validated through tests on both simulation and experimental setups. Note that the simulation and the experimental setup are similar however, there are a few differences between the two setups. More particularly, the simulation model (developed in MATLAB/Simulink) considers a voltage at the PCC (v_{PCC}) equal to 230 V and a 5 kVA three-phase inverter, which has as current limits $\hat{I}_{nom} = 10.25\ A$. For the experimental setup v_{PCC}=132.8 V (for isolation purposes due to the Y-d isolation transformer of Fig. 3) and a three-phase 1.8 kVA inverter has been used, where $\hat{I}_{nom} = 6.5\ A$. Fig. 3 presents a photo and a schematic of the experimental setup used to evaluate the proposed scheme. The experimental setup is configured according to a grid tied inverter (SEMIKRON Semiteach B6U+E1C1F+B6CI), a DC power supply (EA-PS 9750-20) for emulating the injected power by a PV system into the dc-link, and a dSPACE (DS 1104) controller board where the GSC controller with the proposed flexible control scheme have been developed by using the MATLAB/Simulink Real Time Interface. It is worth mentioning that both simulation and experimental setups use a 5 kHz sampling and switching rate.

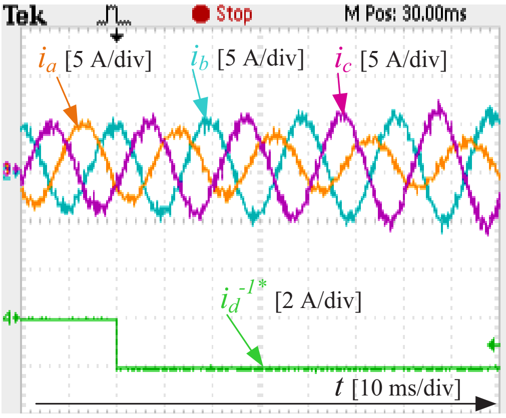

Fig. 4. Experimental results for the GSC operation according to the modified current controller for injecting symmetric and assymmetric currents.

A. Experimental operation of the proposed current controller

The objective of this subsection is to experimentally evaluate the behavior of the proposed current controller under asymmetric current injection. The ability of the GSC to inject "on purpose" asymmetric currents is essential for the operation of the GSC based on the FPCS. According to the experimental results of Fig. 4, one can note that as long the reference of the negative sequence current is $\mathbf{i}_{dq}^{-1*} = [0\ 0]^T$, the inverter injects balanced sinusoidal currents. The injection of symmetrical currents is achieved even when the grid voltage presents some unbalances, due to the capability of the proposed controller to compensate the effect of voltage variations. This is the case until the reference of the negative sequence current is changed to a non-zero value. As it is demonstrated in Fig. 4, when the reference signal i_d^{-1*} shifts from 0 A to -2 A, the GSC operation is switched from a symmetric to an asymmetric current injection. It is noted that the current controller can track the new references in less than 30 ms.

B. GSC operaton according to the FPCS

1) Simulation tests - GSC operation with the FPCS

The simulation results presented in Fig. 5 validate the contribution of the proposed method for symmetrizing the asymmetric loads of the prosumer in a flexible way. The evaluation of the FPCS is done by comparing: the currents absorbed by the prosumer's load ($\mathbf{i}_{Load}$), the currents generated by the PV ($\mathbf{i}_{PV}$), and the currents exchanged between the prosumer and the grid ($\mathbf{i}_G$), as presented in Fig. 5. At the beginning of the simulation (t=0.2-0.3 s) the prosumer's load is considered as an ideal symmetric load. At t=0.3 s, an asymmetric change of 1 kW is applied on the phases b and c, resulting to the appearance of an asymmetric prosumer's load. Note that for t=0.3-0.4 s (PV conventional operation), the proposed FPCS is disabled resulting to the appearance of an asymmetric grid current. This is the case until t=0.4 s, where the FPCS is activated. Its activation introduces "on purpose" asymmetric PV currents in order to improve the prosumer's interaction with the grid and thus, the $\mathbf{i}_G$ is total symmetric.

Furthermore, at t=0.5 s the load has an additional increase of 0.9 kW on phases b and c. Although the FPCS is activated, the grid currents $\mathbf{i}_G$ tend to be, but they are not purely symmetrical. The reason behind this behavior is that the required negative current injection by the GSC for symmetrizing the grid current can cause the violation of GSC ratings (current limits) as described in Section II.B. As a result, the negative current injection by the GSC is reduced in order to maintain the currents within the GSC limits. It is noted, that during this case, only the negative current is reduced while the positive current (that delivers the PV power production) remains unaffected. The impact of the proposed scheme is more evident in this case, when the FPCS is deactivated, leading to the asymmetric grid current presented at t=0.6-0.7 s.

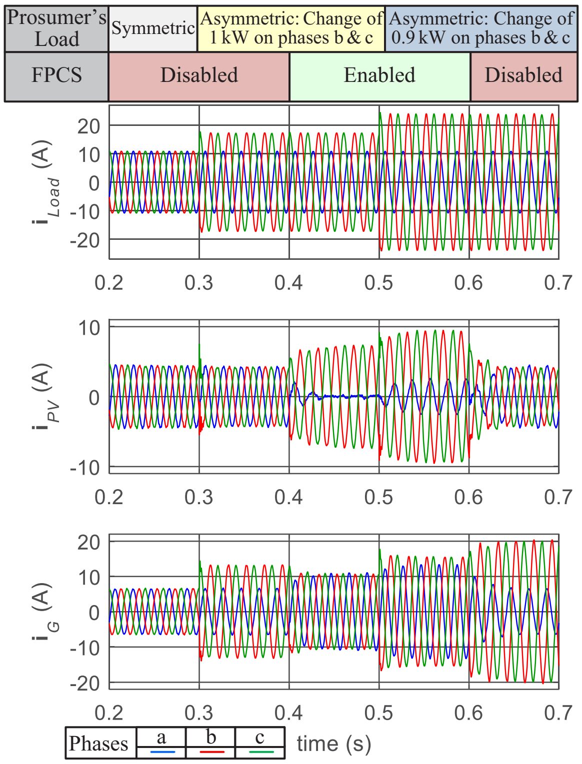

Fig. 5. Simulation results for evaluating the proposed FPCS of the grid tied PV inverter under several scenarios.

2) Experimental validation - GSC operation with the FPCS

The developed FPCS for the GSC aims to improve the interaction between the prosumer and the grid. The experimental setup of Fig. 3 enables the experimental validation of the proposed flexible control scheme under real conditions. The GSC controller equipped with the FPCS has been digitally developed within the dSPACE ds1104 control board for enabling the GSC to operate according to the proposed scheme.

The experimental results are presented in Fig. 6, where the $\mathbf{i}_{Load}$, $\mathbf{i}_{PV}$ and $\mathbf{i}_G$ are shown, when the flexible control scheme is activated or deactivated. More specifically, initially the FPCS is deactivated and the PV is injecting symmetrical currents (conventional case), therefore the unbalanced loads of the prosumer are directly affecting the currents exchanged between the prosumer and the grid $\mathbf{i}_G$. It is noted that during this period (t<0.185 s), the $\mathbf{i}_G$ is highly unbalanced and thus, the power quality of the distribution grid is negatively affected. This is the case until t=0.185 s, where the flexible control scheme is activated. It can be seen that by activating the proposed controller, the injected $\mathbf{i}_{PV}$ currents are changed from

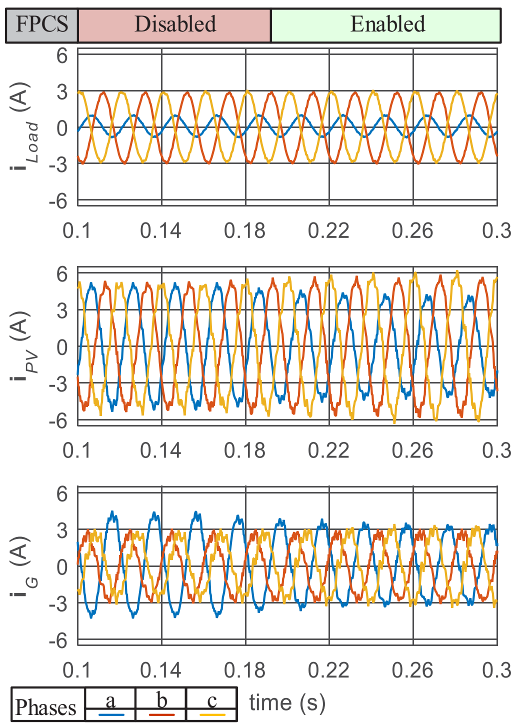

Fig. 6. Experimental results for evaluating the operation of the GSC when the proposed FPCS is activated.

symmetrical to asymmetrical in order to directly and locally compensate the unbalanced currents absorbed by the prosumer's load ($\mathbf{i}_{Load}$). Hence, the current exchanged between the prosumer and the grid $\mathbf{i}_G$ becomes symmetrical and the power quality of the distribution grid is enhanced. It is worth mentioning that the proposed control scheme requires less than 40 ms to compensate the prosumer's load.

IV. Impact of the Proposed Scheme on Distribution Grid

The objective of this section is to present and investigate the impact of the proposed methodology on the overall operation of the DN. To achieve this, a realistic DN is modeled in MATLAB/Simulink according to a small sub-part of the low-voltage distribution grid in Cyprus, as shown in Fig. 7. The Electricity Authority of Cyprus has provided the distribution grid data to enable this study. In this investigation, the installation of three-phase rooftop PV systems is considered at buses 2, 3, 5 and 6 in order to enable the presence of prosumers in the DN. Furthermore, single- and three-phase consumers are considered at buses 1, 4, and 7. In all the installed PVs, the GSC controller is modified with the proposed FPCS for investigating its impact on the DN.

The performance of the proposed FPCS is evaluated by simulating various operating scenarios. These include scenario (a) where the FPCS is deactivated and the PVs are injecting symmetrical currents in the distribution grid, scenario (b) in which the FPCS is activated, and scenario (c) where the PVs are disconnected. To observe the effect of utilizing the proposed FPCS in the distribution grid, Fig. 8 presents the voltage ($\mathbf{v}_{abc}$), current ($\mathbf{i}_{abc}$), active (P) and reactive (Q) power of the MV/LV distribution transformer on the low-voltage (LV) side.

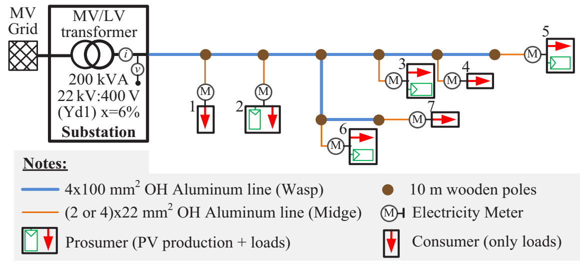

Fig. 7. Realistic distribution grid configuration for investigating the impact of the proposed flexible control scheme on the overall operation of the DN.

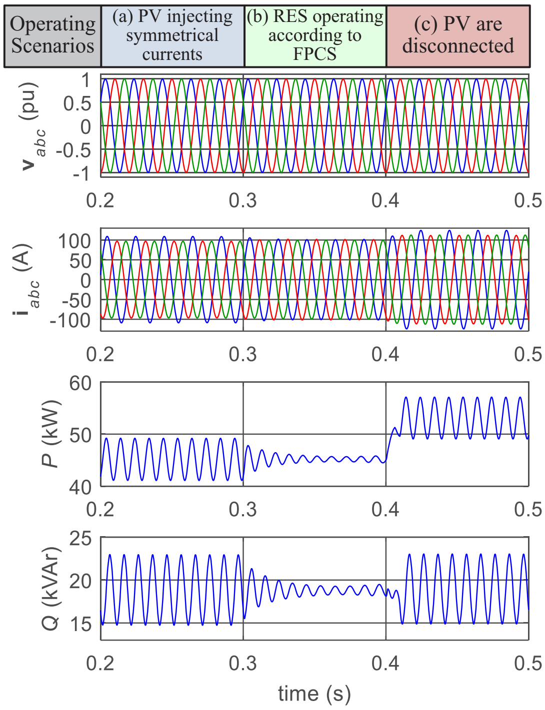

Fig. 8. Simulation results to demonstrate the operation of the distribution grid (at the MV/LV transformer) under different PV operational scenarios.

In the case of scenario (a) of Fig. 8 (t=0.2-0.3 s), the current at the feeder is intensively asymmetrical due to the existence of asymmetrical consumer's and prosumer's loads and due to the fact that the proposed FPCS is deactivated. This result is considerably improved at scenario (b) of Fig. 8, where the FPCS is activated and as shown the transformer's current is almost symmetrical (t=0.3-0.4 s). The current is not completely symmetrical due to the presence of consumers in the network (where there are no PVs in order to apply the proposed FPCS on the corresponding GSC) and due to the current limitation of the GSC, as it was described in Section II.B. Furthermore, it is worth to mention that when the FPCS is activated, the oscillations on the active and reactive power on the low-voltage feeder have been significantly decreased. To illustrate the impact of not including PVs in the distribution grid, scenario (c) is presented for t=0.4-0.5 s in Fig. 9. In this case, the transformer's current gets worsen and as expected the active power coming from the grid increases, along with the power oscillations.

Table I presents additional results regarding the aforementioned operating scenarios. More specifically, it shows

TABLE I. OPERATION ANALYSIS OF THE DISTRIBUTION GRID

Operating Scenarios	Total DN power losses (W)	Minimim capacity for the DN (A)	Power quality analysis at the MV/LV transformer	
			$\|\mathbf{v}^-\|/\|\mathbf{v}^+\|$	$\|\mathbf{i}^-\|/\|\mathbf{i}^+\|$
(a) PVs injecting symmetrical currents	747	109.3	0.13	8.34
(b) PVs operating according to FPCS	**727**	**101.5**	**0.025**	**1.2**
(c) PVs are disconnected	995	124.5	0.12	7.17

the power quality and power losses from the LV side of the MV/LV transformer. The former is estimated by utilizing the transformer's voltage $|\mathbf{v}^-|/|\mathbf{v}^+|$ and current $|\mathbf{i}^-|/|\mathbf{i}^+|$ ratios between the magnitudes of the negative and positive sequences. These indices are actually representing the asymmetric to symmetric voltage and current ratio of the grid operation. By comparing scenario (a) with scenario (c), it can be seen that both ratios ($|\mathbf{v}^-|/|\mathbf{v}^+|$, $|\mathbf{i}^-|/|\mathbf{i}^+|$) increase when PVs are integrated which means that the power quality of the DN deteriorates. This can be explained since the PVs inject symmetric currents and thus they reduce the symmetric power delivered by the MV/LV transformer (through $\mathbf{i}^+$), while the asymmetric part of the load is still completely satisfied by the MV/LV transformer (and thus $\mathbf{i}$- remains unchanged). In the case of scenario (b), one can note that both indices ($|\mathbf{v}^-|/|\mathbf{v}^+|$, $|\mathbf{i}^-|/|\mathbf{i}^+|$) reduce drastically compared to the other scenarios, indicating that way the considerable power quality improvement due to the activation of the FPCS. The symmetrizing of the prosumers currents can directly affect the DN voltage as well, since the asymmetrical voltage drop on the DN lines is also minimized.

Furthermore, it is evident from Table I that the power losses of the DN are significantly lower when PVs are integrated (25% less power losses), and these losses are further decreased when the FPCS is applied (2.7% further reduction) due to the symmetrizing of the DN operation. Note that these losses are considered only up to the LV feeder, as shown in Fig. 7. The losses of the remaining distribution and transmission grid are not included and thus further improvement is expected since more Renewable Energy Sources (RESs) are installed on the low and medium voltage. In addition, in Fig. 8 and Table I, the required capacity of DN lines and transformers is demonstrated. It is obvious that the penetration of PVs according to scenario (a) can reduce the required DN capacity (12.2% less required capacity compared to scenario (c) with no PVs) due to the presence of distributed generation in the DN. Furthermore, the proposed FPCS can symmetrize the DN currents and as a result a further 7.1% reduction of the required DN capacity can be achieved compared to scenario (a) (where PVs are operating according to the conventional scheme). The combination of power losses, required grid capacity and power quality indicates that the proposed scheme has a beneficial impact on the overall operation of the DN.

V. CONCLUSION AND FUTURE WORK

This paper proposes a methodology for symmetrizing the prosumer's load utilizing the flexible capabilities of the PV inverters. In this way, the installed PV systems are modified into flexible PVs (with software control modification) which can be used to compensate asymmetric loads of the DN, leading to more symmetric grid currents and thus better power quality for the distribution grid. Simulation and experimental results are used to evaluate the performance of the proposed power control scheme on the prosumer's level, where the FPCS is tested in the presence of asymmetric prosumer's loads in order to ensure its effectiveness. In addition, an investigation took place regarding the impact of the FPCS, on a realistic low-voltage DN. The results from this investigation indicate that the massive deployment of the proposed FPCS in grid tied inverters of PVs can reduce the power losses of the grid, minimize the required network capacity, and improve the power quality of the distribution grid.

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