Diversifying the role of distributed generation grid side converters for improving the power quality of distribution networks using advanced control techniques

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Abstract—Diversifying the role of grid side converters (GSC) associated with distributed generation (DG) may have a technical and economic impact. The increasing number of residential photovoltaic rooftop systems can be exploited by distribution network (DN) operators in order to support and improve the power quality of the grid without considerable further investment. GSC can support the grid during abnormal conditions but may also be used to improve the power quality by balancing out asymmetries and alleviating the grid from unwanted harmonics. The proposed advanced control technique and associated sophisticated controllers demonstrate through simulation and experimental results that the role of GSC can be upgraded to improve the power quality of the grid. Furthermore, the proposed controller and advanced control scheme is validated on a realistic low-voltage DN using data from Cyprus Electricity Authority. Consequently, conventional practices by DN operators can be re-assessed as the necessary electronic hardware for mitigating grid problems are already present within the GSCs of DG systems.

Keywords—Prosumers, harmonic and asymmetries compensation, current controller, distribution network, rooftop PV systems, power quality.

I. INTRODUCTION

The number of residential rooftop photovoltaic (PV) systems has always been increasing and will be increasing for various reasons. One reason is the cost of PV for example, which has considerably decreased over the past few years and it might decrease even further. The fact that a lot of research is underway for improving the efficiency of PVs is also an indication that PVs will dominate distributed generation (DG) in coming years. Targets set for reducing CO_2 emissions and for gradually becoming independent of conventional forms of energy and fossil fuels (for which there is a lot debate in relation to the reserves) have also played a huge role. Furthermore, consumers are realizing that they benefit from residential rooftop PV systems as they see their electricity bills dramatically being reduced (in countries where the net-metering system has been adopted for example). Despite the many problems distribution network (DN) operators have had and perhaps still face with DG, research is now shifting towards investigating how all these rooftop PV systems can be exploited to favor and support the grid. The contribution of renewable energy systems during unwanted events occurring on the grid such as the presence of harmonics, phase unbalance, faults, voltage sags etc., as well as the requirement for optimum interaction with microgrids and smart grids, are some of the areas where research is headed. This can be achieved by the grid side converter (GSC) which is an inherent component of PV rooftop systems. The electronics necessary for engaging in operations necessary for any of the above-mentioned grid modes/functionalities are already installed in the GSC and this provides great flexibility since advanced features can be incorporated. The additional installation of power electronics equipment (such as active power filters [1]) is not necessary reducing therefore the cost to DN operators when they have to deal with such problems. Hence, it is more cost-effective and economical to use the existing GSC for delivering desired active/reactive power and in addition, to perform the function of mitigating the asymmetries and harmonics caused by loads. Advanced grid functionalities of GSC such as harmonic injection and asymmetry (unbalance) compensation can be performed through the control scheme and modifications to the current controller which are discussed later.

PV systems installed on rooftops of residences transform passive consumers to active consumers, commonly referred to as prosumers (the ones who can consume as well as deliver the excess power back to the electrical grid). The “brain behind the energy traffic control is the GSC, normally a three-phase inverter for systems over 4 kW. As the majority of three-phase commercial or residential loads cannot be balanced, problems are very often encountered [2] related to: increased power losses in the DN, asymmetric and harmonically distorted currents and voltages resulting in lower power quality, lower power factor, the distribution capacity of (cables, transformers, and lines) is decreased, the performance of machines is jeopardized with possible torque oscillations and overheating etc.

Exploiting GSCs towards the benefit of the grid has been discussed in literature [2-5] but with limitations and restrictions. In particular, the harmonic distortion caused by non-linear loads is mitigated by a single phase GSC based PV system, but the configuration proposed does not allow the symmetrization of prosumer’s loads [4, 5]. A method for mitigating the asymmetries of DN voltage by injecting both positive and negative sequence of currents was published in [2]. Although it is not necessary to measure the prosumer’s loads, information

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about grid impedance at point of common coupling (PCC) is necessary for implementation, which in most of the cases is not available. An innovative scheme in which GSC is used for mitigating prosumer's asymmetries and selective harmonics is discussed in [3], where the current references are generated by using the delayed signal cancellation method and thereby a modified deadbeat current controller is employed to inject commanded reference currents. Interesting methods of reference generation in accordance with prosumer's loads are respectively presented in [6] and [7] based on conservative power theory and physical components analysis. Implementing this method however with current GSC technology will impose computational problems due to its complexity and slow response.

This paper proposes a GSC with an innovative control technique consisting additional advanced features for regulating the power quality of grid by mitigation of asymmetries and harmonics caused by connected prosumer's loads. The proposed technique involves three main components: the synchronization unit for obtaining grid voltage phase angle under normal and abnormal grid scenarios, a decoupling network for estimating the asymmetric current component and harmonics (used for reference current generation) and an advanced current controller.

The proposed innovative control technique requires an advanced current controller with improved and fast dynamic response, less oscillations/overshoot at the time of fault and/or reference variation. In addition, an important element for real time implementation of GSC controller is the computational complexity. The controller must be as less complex as possible in order to be easily implemented in low-sized Digital Signal Processors (DSP). So far, many current controllers have been proposed in the literature dealing with variety of power system issues. The simplest SRF based conventional current controller [8] generates the voltage reference for PWM by utilizing positive SRF (dq^{+1}) and two PI controllers. The main drawback of conventional SRF controller is that it cannot perform accurately under unbalance grid voltage due to the presence of coupled double frequency (2ω) oscillation on the transformed dq^{+1} voltage and current component caused by negative sequence voltage component. These oscillations are directly affecting the performance of PI controller, designed to track the DC reference, according to Internal Model Principle (IMP). The problem caused by 2ω oscillations are mitigated in [9] by the introduction of dual SRF (DSRF) controllers (one for positive sequence and one for negative sequence) and some filtering techniques. The DSRF current controller is developed by combining two conventional SRF controllers, respectively operating in fundamental positive and negative rotating reference frames. The DSRF is also equipped with two additional notch filters in each SRF frame for eliminating the undesired $\pm 2\omega$ oscillations. The additional filter however increases the computational cost and results in slower dynamic response. The problem of slower dynamic response is mitigated by an Enhanced Decoupled DSRF (EDDSRF) current controller [10]. The EDDSRF employs a more intelligent and accurate method for the elimination of undesired 2ω oscillations and allows simultaneous injection of both positive and negative sequence of current. The oscillations appearing on corresponding positive and negative transformed current vectors are accurately estimated and removed through a cross-decoupling network. The EDDSRF current controller is however computationally very complex and requires large computational resources due to significant number of Park's transformations. The computational complexity, however, is a critical parameter for the real time implementation of the algorithm in limited sized digital signal processors. In addition, the necessary voltage feedforward terms are not used in EDDSRF controller, thereby increasing the control effort of PI controllers.

An equivalent of conventional SRF controller in stationary $\alpha\beta$ frame is proposed in [11], where the PI controller is replaced by Proportional Resonant (PR) controller, but it cannot perform satisfactorily under abnormal grid conditions. Furthermore, a combination of I and PR controllers are developed in [12, 13] for mitigating the effect of unbalanced grid faults and to achieve accurate injection of current. The use of voltage feedforward is not allowed by PR controller, which ultimately results in higher control effort of the controller [14]. An interesting technique is proposed [15], where a combination of R and PI controller is used for the accurate injection of positive sequence current, but this controller cannot perform accurately under unbalanced grid conditions and in addition, it is unable to inject the negative sequence of current. A current controller mitigating the effect of unbalance faults is proposed in [16]. It can inject both sequences of currents separately, but doesn't allow simultaneous injection. All the current controllers mentioned above cannot inject both the sequences of current simultaneously except the DSRF and EDDSRF current controllers. The simultaneous injection in some cases may be required because positive sequence current supports grid in terms of voltage and frequency, whereas the negative sequence current is used to minimize the effect of unbalances caused by grid faults.

An advanced current controller is therefore proposed in this digest that offers fast dynamic response with low oscillations/overshoot and all this is done with very low computational cost compared to the above mentioned current controllers. The reason behind the fast dynamic response of proposed current controller is the absence of a filter in the control path (unlike DRSF controller [9]) and the unnecessary decoupling network for eliminating the oscillations as in the case of EDDSRF current controller [10]. Hence, the proposed current controller presents significant advantages over its predecessors and contributes to the grid code regulations imposed by DN to RES in many respects. The new current controller is discussed in section II where the advanced GSC control technique is presented. The simulation and experimental results validating the performance of the new current controller and of the overall control technique for mitigating the prosumer's loads asymmetries and harmonics are presented in section III. The impact of the proposed current controller and advanced control technique is demonstrated using a realistic distribution system in section IV.

II. ANALYSIS OF PROPOSED CONTROL TECHNIQUE

The proposed control technique consists of three parts: the synchronization unit (for the purpose of this paper the DNαβPLL [17] is used, because it can work under unbalances and harmonically distorted grid voltages), an advanced current controller and a new PQ controller (proposed in this work).

A. Advanced Current Controller

As mentioned earlier, the only controller that allows simultaneous injection is EDDSRF current controller, but is computationally very complex and furthermore, a higher control effort is required by PI controller because the necessary voltage feedforward terms are not used. According to [17], when a measured signal (containing asymmetric and harmonic components) is transformed with a specific SRF speed (for instance, $+\omega$), oscillations are observed on transformed current vectors due to the presence of other frequencies (such as, $-\omega$, $\pm 5\omega, etc.$). All current controllers mentioned, transform the measured signal to dq^{+1} or dq^{-1} frames which are subsequently subtracted from the reference current and provided to the PI controller. This is the main reason why oscillations are observed and decoupling networks are hence needed for their elimination. In contrast, if the error signal is acquired before frame transformation and the error is subsequently transformed with corresponding speed, no oscillations are observed on the transformed vectors. This theoretical idea (feeding the error signals before frame transformation), motivated the development of a new current controller. The new current controller is developed by modifying the dual SRF controller, details/characteristics of which are:

1. The controller is designed using two SRF frames with two PI controllers, one for positive sequence rotating with $+\omega$ speed and other for negative sequence rotating with $-\omega$ speed, as shown in Fig. 1.
2. For both the SRFs, the error signals are fed before frame transformation to ensure zero oscillations. This completely eliminates the use of filters and/or decoupling network as in [9, 10].
3. The only problem in feeding the SRF with error is how to implement the cross-coupling terms necessary for control implementation, since the cross coupling requires the measured currents instead of the error signal. The measured signals are calculated by a mathematical approach where the current error signal is subtracted from the reference current, as shown in Fig. 1.
4. The feedforward terms are used in order to minimize the higher effort imposed by PI controller. These feedforward terms are obtained from DNαβPLL [17].

The new Type D current controller reduces the computational complexity to a significant level and this is due to complete elimination of decoupling networks (which require large number of Park's transformations) and filters as opposed to ones employed in [9] and [10]. In addition, Type D current controller offers improved performance with fast dynamic response and lower overshoots. Hence, the proposed Type D current controller enables accurate injection of positive and negative sequence of currents with improved performance and lower computational resources. It is worth mentioning that the dq^{+1} is regulating positive sequence of current whereas the dq^{-1} frame is employed to inject negative sequence 'on purpose' for enabling the mitigation of asymmetries. The proposed current controller can also be extended to include the "on purpose" injection of "harmonic components" in order to compensate the harmonic distortion caused by prosumer's non-linear loads. The extended version of Type D current controller referred as ETD is shown in Fig. 1, where the replication of modular SRF controller is replicated for whatever number of harmonics are required to be injected. The ETD controller is being employed in the proposed advanced control technique for mitigating the asymmetries and harmonics caused by unbalanced loading and non-linear prosumer's loads.

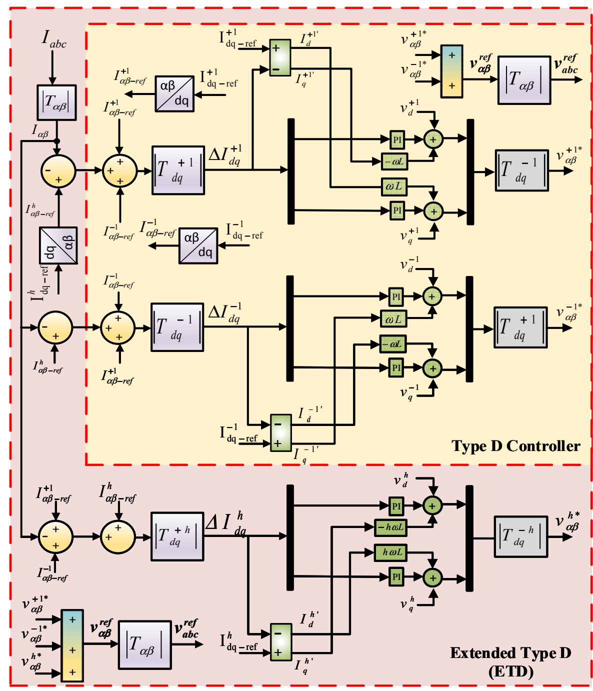

Fig. 1: Proposed advanced current for asymmetries and harmonic current injection.

B. New Advanced PQ Controller

The *PQ* controller generates the reference currents necessary for the real (*P*) and reactive (*Q*) power penetration, and in addition, the mitigation of asymmetries and harmonics (in case of proposed control technique). The *PQ* controller in the proposed advanced control technique is divided in two modules, Fig. 2. The first one is the conventional *PQ* controller responsible for generating the reference currents $\left(I_{dq}^{+1*}\right)$ for positive sequence current controller in order to ensure that the total generated power by PV is delivered to the grid. The second module is an advanced *PQ* module where a decoupling network is used to analyze the prosumer's loads and estimates the accurate amount of required negative sequence and harmonic currents for effective compensation of these abnormalities. The prosumer's load currents are dynamically decoupled by the multiple use of (1) for $n = +1, -1, +3, -3 \ldots$, which is a mathematical realization for decoupling network. The decoupling network therefore accurately estimates the positive sequence $\left(I_{dq-L}^{+1}\right)$, negative sequence $\left(I_{dq-L}^{-1}\right)$ and harmonic $\left(I_{dq-L}^{h}\right)$ components of load current. From this estimation the negative and harmonic currents can be directly used as a reference for current controller of GSC, that is $I_{dq}^{-1*} = I_{dq-L}^{-1}$ and $I_{dq}^{h*} = I_{dq-L}^{h}$. The GSC thereafter locally injects the required amount of asymmetrical and harmonically distorted current to the loads for mitigating the adverse effect of these prosumer loads on the power quality of current drawn from the utility grid. Hence the exchange of power between utility grid $\left(\mathrm{i}_g\right)$ and that of prosumer loads becomes symmetrical and free of harmonic distortion.

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

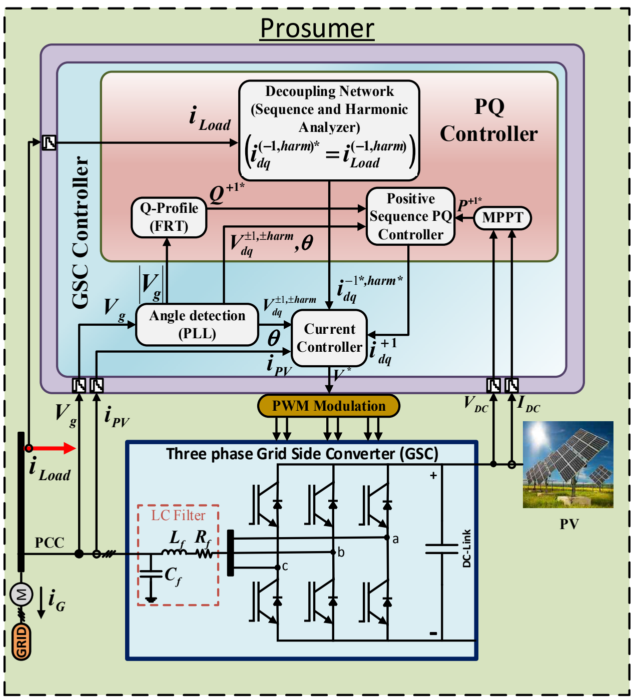

Fig. 2: An advanced innovative control technique for the GSC of PV systems.

For some cases, when the asymmetries and harmonic distortions are intense, there is a possibility to violate the converter's maximum current limit. In such cases, the magnitude of positive sequence current is maintained at its reference value, whereas the magnitude of negative sequence and harmonic components are reduced to avoid violating the assigned GSC max current limit i_{ml}. The maximum value of negative sequence and harmonic currents are determined as $\left|I_{dq}^{-1*} + I_{dq}^{h*}\right|_{max} = \mathrm{i}_{ml} - I_{dq}^{+1*}$. Therefore, $\left(I_{dq}^{-1*} + I_{dq}^{h*}\right) < \left|I_{dq}^{-1*} + I_{dq}^{h*}\right|_{max}$ and in case when $I_{dq}^{-1*} + I_{dq}^{h*}$ is exceeded beyond the maximum allowed value, it must be reduced by $I_{dq}^{-1*} + I_{dq}^{h*} / \left|I_{dq}^{-1*} + I_{dq}^{h*}\right|_{max}$ in order for ensuring the safe and reliable operation of GSC without crossing the safety limits.

The proposed innovative control technique (Fig. 2) enables the accurate mitigation of asymmetries and harmonic distortion locally by accurate injection of required prosumer's load currents (negative sequence and/or harmonic currents) through the existing GSC of the PV system. Consequently, the flow of current between prosumer and grid is totally symmetric and free of any undesired harmonic frequency components. The flexible unbalance and harmonic control allows the accurate mitigation of prosumers load without risking the deliverance of produced PV power and without compromising the integrity of GSC.

III. VALIDATION OF PROPOSED CURRENT CONTROLLER AND ADVANCED CONTROL TECHNIQUE

This section validates the performance of the proposed current controller and of the innovative control technique (new current and PQ controller). The simulation and experimental validation is carried with a sampling rate of 5 kHz for digitally implemented controller. The maximum order of harmonic that can be injected by the proposed ETD controller is equal to 1/10 of the sampling rate. Hence, for 5 kHz rate, 9th ($\cong \frac{1}{10} \cdot 5kHz$) harmonic is the maximum order that can be injected. For experimental verifications, the proposed GSC control strategy is implemented in dSPACE DS1104 together with MATLAB real time interface, a SEMITECH (B6U+E1CIF+B6CI) for the grid side inverter and a Delta Elektronika power supply (SM 600-10) used as DC source, as shown in Fig. 3.

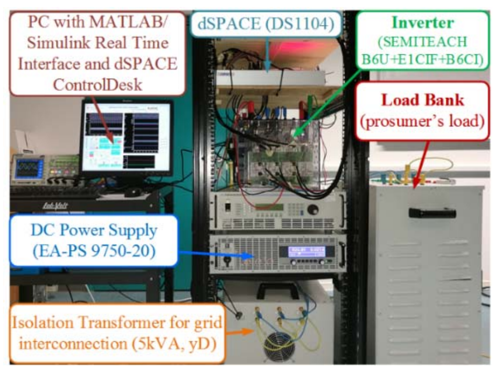

Fig. 3: Experimental laboratory setup employed.

A. Simulation Results

a. Proposed Current Controller

With zero initial value, I_{dq}^{+1} is subjected to a step change of 3 A and 2 A, respectively at 0.4 s. Following this an unbalance fault occurs at 0.6 s. Similarly, the reference values for I_d^{-1} and I_q^{-1} are changed from zero to 2 A and 1.5 A respectively at 0.8 s. The new technique (ETD shown in Fig. 1) improves the quality of injected current by improving the controller's response (reduced oscillations/overshoot and smooth transitions). Following this, 5th and -5th harmonics are injected. The magnitude of I_{dq}^{+5} and I_{dq}^{-5} is set to 0.5 A and are respectively injected at 1 s and 1.15 s. The results are demonstrated in Fig. 4, representing the more accurate injection with minimal oscillations at the time of current injection/fault. However, the computational complexity of Type D controller (able to inject positive and negative current) is less due to complete elimination of decoupling cells as opposed to [10]. According to computational complexity analysis (number of mathematical computations), the proposed current controller is 45 % less complex compared to [10].

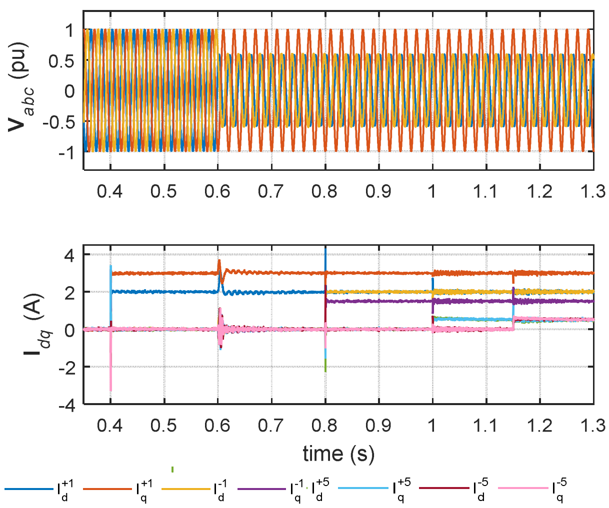

Fig. 4: Fundamental positive, negative and harmonic current injection using ETD Current Controller.

b. Operation under Innovative Control Technique (Advanced PQ controller)

The operation of GSC under the proposed control technique is demonstrated in Fig. 5 and 6. In Fig. 5, until 0.4 s, all the three phases are symmetrical, hence the current drawn from grid is also symmetrical. However, at t=0.4 s a step change of 1 kW is applied to phase b and c (causing asymmetry). Consequently, the current demanded by load becomes asymmetric. Until 0.5 s, the advanced control technique is not activated, hence the negative sequence component of current is drawn from grid (as can be seen from Fig. 5). At t=0.5 s, the control technique is activated and the negative sequence current is locally generated by GSC of PV, thereby making the grid current symmetrical by delivering the required amount of negative current.

Furthermore, a step change of 0.9 kW is again applied to phase b and c at 0.6 s. In this case, a small amount of asymmetric current is drawn from grid because the GSC maximum current limit is reached (severe asymmetry) and the injection of negative current is limited for safety of GSC switches. After 0.7 s, the control technique is again deactivated and all the asymmetric current is drawn from grid. The result in Fig. 5 verifies the effectiveness of proposed control scheme for mitigating the undesired asymmetric effects of prosumer's load.

Likewise, the technique is also effective for the mitigation of harmonic generated by prosumer's non-linear load (as shown in Fig. 6). The load requires 5th harmonic with magnitude of 0.3 A and until 0.5 s the proposed control technique for harmonic mitigation is deactivated, so the harmonic current is drawn from grid. However, after 0.5 s when the control technique is activated and harmonic current is injected locally via GSC, the grid current becomes free of harmonic distortion.

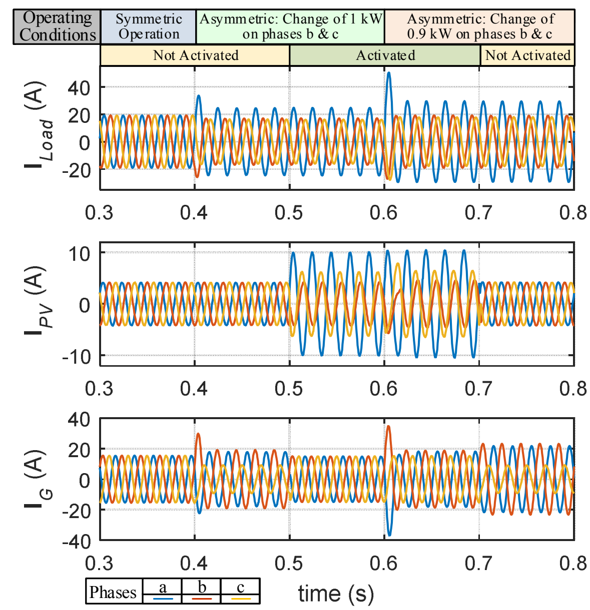

Fig. 5: Mitigation of prosumer's asymmetries using proposed control scheme.

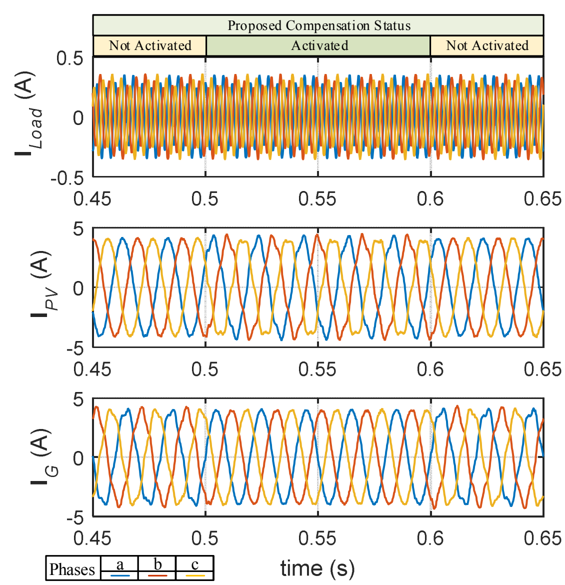

Fig. 6: Mitigation of prosumer's harmonics using proposed control technique.

B. Experimental Results

a. Proposed Current Controller

The new current controller is investigated for three case studies. In all the three cases, the d and q axis positive sequence currents are respectively injected according to 1200 W active and 0 VAr reactive power. The first case validates the injection of negative sequence current together with the positive sequence, as shown in Fig. 7. With zero initial value, i_{d-ref}^{-1} is subjected to a step change of 1 A at 158.34 s. Consequently, the current controller continues to inject balanced sinusoidal currents until 158.34 s, and thereafter the injected current becomes asymmetrical.

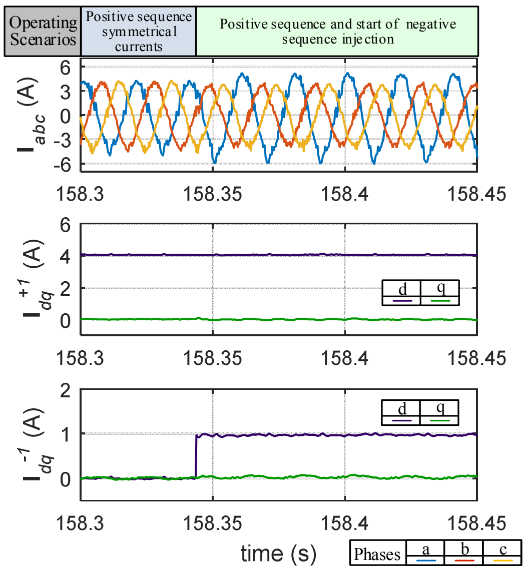

Fig. 7: Experimental results validating the simultaneous injection of fundamental positive and negative current sequences.

The performance of ETD controller is further validated through the injection of harmonic current component, as shown in Fig. 8(a). The initial value of i_{q-ref}^{-5} is set zero and later on it is subjected to step change of 1 A at the point marked with the red arrow. At this instant, the ETD controller enables fast and accurate injection of harmonic current with almost zero oscillations and no overshoot.

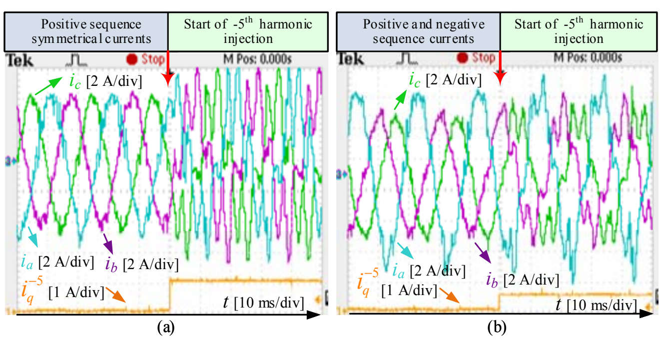

Fig. 8: Experimental results validating the simultaneous injection of fundamental positive and negative current sequences.

The third case study analyzes the performance of ETD when all the three components, that is, fundamental positive sequence, negative sequence and -5th harmonic are injected simultaneously, Fig. 8(b). The ETD controller continues to injected positive sequence (4 A), negative sequence (1 A) and at point marked with red arrow the q-component of -5th harmonic is injected with a magnitude of 0.5 A. The grid current is asymmetrical from start and later on it becomes "on purpose" harmonically distorted. The fast and accurate performance of ETD is verified from all the three case studies presented. It is worth mentioning that the proposed ETD is the most flexible controller compared to the others one discussed above, since in addition to unbalance currents it allows the injection of harmonic currents as well.

b. Operation under Innovative Control Technique (Advanced PQ controller)

The significance of the proposed scheme is experimentally demonstrated by an interaction between the prosumer's three-phase load current I_{Load}, the PV injected current I_{PV} and the current exchanged between the prosumer and the grid I_G. In this case study, the proposed innovative control scheme is always activated and the prosumer's load changes at $t = 0.185$ s. In particular, the RMS load currents of the prosumer are $[i_{a-rms}\ \ i_{b-rms}\ \ i_{c-rms}]$= [0.66 A 2.05 A 2.05 A] for $t < 0.185$ s, and at 0.185 s they are modified to $[i_{a-rms}\ \ i_{b-rms}\ \ i_{c-rms}]$= [0.66 A 0.95 A 0.66 A] including an injection of required 1% -5th harmonic as well, as demonstrated in Fig. 9. The innovative control scheme can instantly sense the prosumer load change and react accordingly in order to regulate the current injection by the PV to compensate the asymmetries imposed by the new load within 30 ms. Therefore, the current exchanged between the prosumer and the grid I_G becomes symmetrical and the power quality of the distribution grid is ensured.

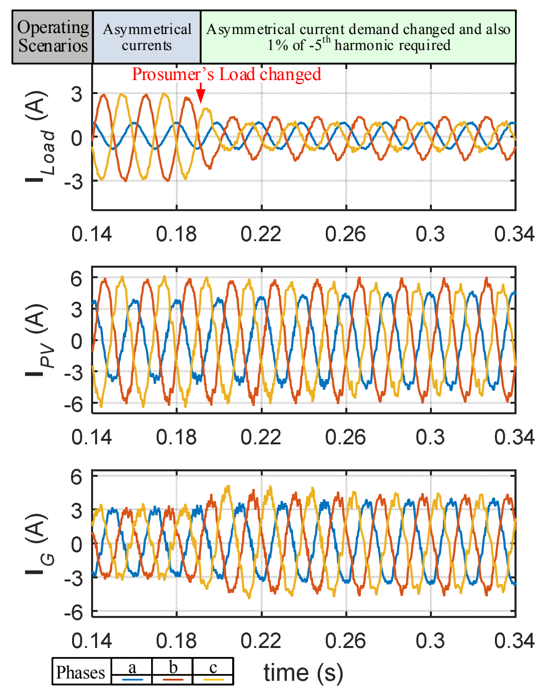

Fig. 9: Experimental results validating the significance of proposed innovative control scheme for effective mitigation of prosumers abnormalities.

IV. IMPACT OF ADVANCED GSC CONTROL TECHNIQUE ON DISTRIBUTION NETWORK

The mitigation of asymmetry and elimination of harmonics significantly reduces the power losses, may optimize the usage of grid capacity and improves the power quality of distribution network (DN). The significance of proposed advanced control technique is further validated by implementing it on the realistic low-voltage DN data. The distribution grid data is obtained from Cyprus Electricity Authority for enabling the validation of proposed study. Consequently, a small portion of low-voltage

DN is modelled in MATLAB SimPowerSystem/Simulink. For the purpose of analysis, the DN consists of 6 buses in total with some buses consisting of normal consumer's load and others containing prosumers loads, as shown in Fig. 10. The consumers single and three-phase load are connected at bus 1 and 4, whereas for enabling the existence of prosumers in the DN, buses 2, 3, 5 and 6 consist of three-phase PV rooftop systems. Bus 6 consists of a 5^{th} harmonic absorption load, added intentionally to justify the compensation of harmonics and to demonstrate the impact to the power quality. To examine and demonstrate the impact to the DN, the control system of all the installed PV systems are equipped with the proposed ETD current controller and advanced control scheme. The ETD current controller is used at all times, whereas the advanced innovative control technique will be activated and deactivated to justify its significance and contribution.

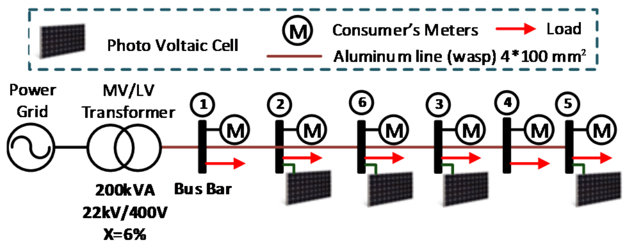

Fig. 10: One-line diagram for realistic distribution grid of Cyprus

The impact of the proposed Innovative Control Technique (referred to as ICT) on distribution network is investigated under different operating conditions. The operating conditions include, (i) The PV rooftops injecting symmetrical currents (with ICT deactivated), (ii) PV injection enabled using proposed ICT, and (iii) operation of DN when PV rooftops are completely disconnected. The performance enhancement resulting by employing proposed innovative control technique is analyzed by observing the three-phase current ($\mathbf{I}_{abc}$), the active (P) and reactive (Q) powers drawn from Low Voltage (LV) side of distribution grid MV/LV transformer, as shown in Fig. 11. Furthermore, one of the bus (no. 6) measured quantities are presented in Fig. 12 to reflect the clear improvement of power drawn from grid using the proposed ICT.

Examining the results in Fig. 11, when all the PV rooftop systems are injecting symmetrical currents between 0.25 s to 0.35 s, the current drawn from the grid is harmonically distorted and highly asymmetrical due to the presence of asymmetrical, harmonically distorted prosumer and consumer loads. The current from grid is asymmetrical and distorted because the proposed ICT is not activated. Considering the second operating condition between 0.35 s to 0.45 s, the proposed ICT is activated and corresponding improvement in the grid currents are clearly seen. The current drawn from the grid is harmonic free and almost symmetrical. It cannot be completely symmetrical because at buses 1 and 4, there are no PVs and hence the ICT asymmetric compensation cannot be installed. The corresponding active and reactive power oscillations which occurred as a result of the negative sequence and harmonic current initially required from the grid are also reduced due to ICT activation (these currents are now provided by the PV systems). Furthermore, when the PVs are disconnected, the grid currents become again asymmetrical and distorted. In addition, the amount of active power drawn, and the oscillations in active and reactive power are also observed to increase.

Similar conclusions are obtained from Fig. 12 showing the results for the 6^{th} bus of DN. When operated without ICT, the current drawn by bus 6 from grid is asymmetrical and harmonically distorted. However, at 0.35 s when ICT is activated the grid currents become harmonic free and symmetrical. The corresponding active and reactive power oscillations are completely eliminated. During 0.35 to 0.45, all the distorted and asymmetric currents required by the loads are provided by the PV system, as can be seen from Fig. 12.

A detailed analysis of the proposed ICT on the power quality of distribution network is presented in Table I. The analysis presents the power loses and power quality at the LV side of the MV/LV transformer. The power quality is assessed by calculating the ratio between the negative sequence and harmonic component magnitude to the magnitude of positive sequence, that is, for current $(|\mathbf{i}^-|+|\mathbf{i}^h|)/|\mathbf{i}^+|$ and for voltage $(|\mathbf{v}^-|+|\mathbf{v}^h|)/|\mathbf{v}^+|$. These indices determine the level of asymmetries and harmonics in the grid quantities. For cases (i) and (iii), the performance indices have the highest values, representing the lower power quality of DN. The largest values observed in case (i) are due to the reason that PV is injecting some part of the symmetric current ($\mathbf{i}^+$), whereas the asymmetric ($\mathbf{i}^-$) and harmonic ($\mathbf{i}^h$) currents are completely drawn from the grid MV/LV transformer. However, examining case (ii), both of these indices result in very low values, indicating the significant improvement in the power quality of DN. All the asymmetric and harmonic current delivered by PV in case (ii) is the reason for improved power quality.

The DN power losses are highest under PV disconnection and are significantly reduced under the scenario (i) when PVs are integrated, resulting in 28.8% less power losses. These losses are further decreased by 5.5%, when the PVs are operated with the proposed ICT. The calculation of losses considers only the LV network. Taking into consideration of the presence of RES systems on MV networks, the contribution of this control scheme can be more significant. The effect on the capacity of DN transformers and lines is also presented in Table I. It can be seen that the presence of distributed PVs reduces the required grid capacity by 18.3%. The capacity is further reduced by 16.8% when PV injection is operated with the proposed innovative control technique compared to scenario of (i). The lower power losses, improved power quality and optimized grid capacity shows the substantial impact and contribution of proposed innovative control scheme on the operation of DN.

TABLE I. POWER QUALITY ANALYSIS OF THE DISTRIBUTION GRID

Operating Conditions	**DN power losses (W)**	**Required DN capacity (A)**	**Power quality at MV/LV transformer**	
			$(\lvert\mathbf{v}^-\rvert+\lvert\mathbf{v}^h\rvert)/\lvert\mathbf{v}^+\rvert$	$(\lvert\mathbf{i}^-\rvert+\lvert\mathbf{i}^-\rvert)/\lvert\mathbf{i}^+\rvert$
(i) PV injecting symmetrical currents	452	89.1	0.64	10.59
(ii) PV operating as per ICT	**427**	**74.5**	**0.077**	**1.50**
(ii) PV disconnected	635	104.2	0.55	8.83

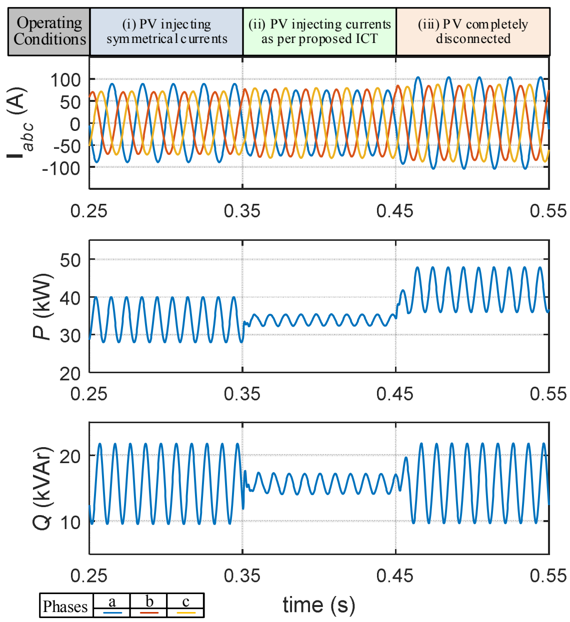

Fig. 11: Impact of proposed innovative control scheme on the power drawn from distribution grid.

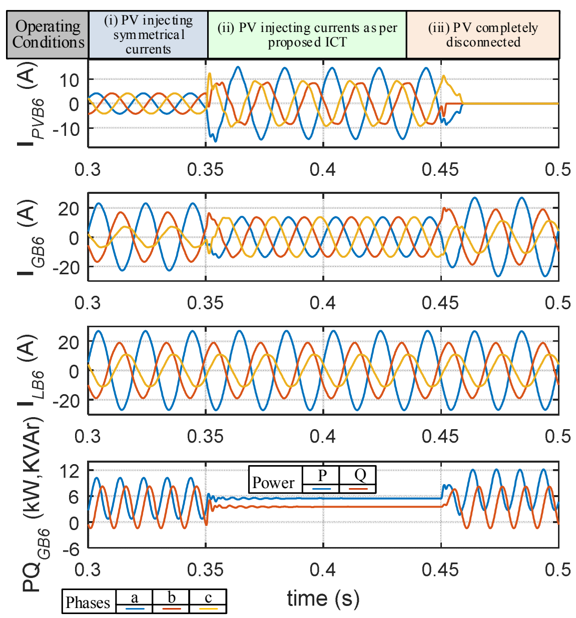

Fig. 12: Impact of proposed innovative control technique on DN (specifically for bus 6, containing both asymmetric and harmonic loads). GB6 (grid current of bus 6), LB6 (load current at bus 6), PVB6 (PV current injected at bus 6).

V. CONCLUSION

This paper proposes a new current controller for fast and accurate injection of “on purpose” unbalance and harmonic currents. Furthermore, an innovative control scheme for a diversified and flexible operation of the PV inverters is proposed that mitigates the asymmetries and harmonics caused by non-linear prosumer’s loads. The control system of existing installed PV systems is modified to incorporate the injection of “on purpose” unbalance and harmonic currents in order to improve the power quality of DN as presented through the simulation and experimental results. The impact of the proposed control technique is demonstrated on a realistic low-voltage distribution network. The results indicate significant improvement in power losses, reduced network capacity and improved grid power quality, verifying the significant contribution and impact of the work.

VI. REFERENCES

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