# Control Scheme for Phase Balancing of Low-Voltage Distribution Grids

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***Abstract*—Low-voltage distribution grids face several challenges due to the high penetration of renewable energy sources, the increasing demand (electrification of thermal and transportation sector), and the limited observability (absence of smart metering infrastructure). These challenges impose problems regarding the integrity, stability, power quality and efficiency of distribution grids. Therefore, intelligent solutions are required in order to overcome these problems. This paper proposes a centralized control scheme for phase balancing of low-voltage distribution grids at the substation level. The proposed solution utilizes the advanced capabilities of the grid tied inverters of photovoltaics and storage systems to increase the utilization of distribution lines and to compensate the asymmetric loading conditions of the substation. The solution is based on only one smart meter installed at the distribution substation and utilizes available information and communication technology infrastructure to integrate the solution. The solution achieves significant benefits for the distribution grids, especially regarding their power quality and the effective utilization of their capacity.**

***Index Terms*—ancillary services, asymmetric loading, low-voltage distribution grids, phase balancing, power quality, photovoltaics.**

## I. Introduction

### A. Motivation and Background

Contemporary Low-Voltage Distribution Grids (LVDGs) face major challenges such as the massive penetration of variable Renewable Energy Sources (RES), the increasing demand due to the electrification of transportation (i.e., electric vehicles) and the thermal sector (i.e., air-conditioners and heat-pumps), and the limited observability of distribution grids due to the absence of smart metering infrastructure. As a result, the stability, integrity and power quality of LVDGs may be threatened.

Towards the evolution of LVDGs within the framework of smart grids, the following key technologies need to be fully exploited: (a) advanced capabilities of grid tied inverters, (b) flexibilities of storage devices, (c) smart metering infrastructure, and (d) the Information and Communication Technology (ICT). In line with this framework, this paper proposes a novel control solution for compensating the asymmetric loading conditions of a distribution feeder by utilizing advanced operational capabilities of grid tied inverters of photovoltaic (PV) and battery storage systems (BSS). The motivation of the proposed solution is to improve the power quality of distribution grids and maximize their utilization.

### B. Relevant Literature

In the literature, several approaches can be found that facilitate the active management of LVDGs. A quasi real-time monitoring scheme is developed in [1] to enable the awareness of distribution grid operating conditions. According to the monitoring scheme output, appropriate control actions [2]-[3] can be taken for regulating distributed generators to ensure the operation of the LVDG within the proper voltage and thermal limits. Controllers based on optimization schemes are proposed in [4]-[5] for distribution grids where the active and reactive power of distributed generators are regulated to minimize network losses and voltage variations. In a similar approach, model predictive control schemes are developed in [6]-[7] for regulating voltage deviation within the feeder by regulating RES and BSS operation. In [2]-[7], the focus of LVDG management techniques is to regulate the active and reactive power of distributed generation in a symmetrical way in order to ensure proper operating conditions. However, the asymmetrical loading conditions of the feeder have not been considered.

The asymmetrical loading conditions or phase unbalances in LVDG are usually intense since the majority of loads in residential or commercial buildings are single-phase [8]. The asymmetrical currents cause higher losses, reduce the effective utilization of distribution line capacity, and exacerbate voltage asymmetries. Further, power quality standards limit the voltage asymmetries to 2% for 10 min intervals and 4% maximum instantaneous according to EN50160 [9]. The limits for voltage asymmetries should be ensured, since voltage unbalance can degrade the performance of transformers and power electronic based RESs, can reduce the lifetime expectancy of three-phase devices and can impose further asymmetrical currents. It should be noted that 1% phase unbalance in voltage can cause 6-10% current asymmetries according to [8], which then can derate the effective utilization of distribution grids. Thus, symmetrizing the loading conditions of LVDGs can have a significant impact on the overall operation of a distribution and transmission grids

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benefiting their power quality, utilization, and efficiency. This is also depicted by the fact that the phase balancing is considered as an ancillary service in micro-grids according to international standards [10]. Therefore, cost-effective techniques to ensure the phase balancing of LVDGs are of high interest for Distribution System Operators (DSO) and can enable the effective coordination and utilization of low-voltage feeders.

A few works can be found in the literature dealing with phase-balancing of LVDGs. The installation of shunt active filters [11] in several locations of the distribution grid can compensate the asymmetric loading conditions and the harmonic distortion. However, such a solution comes with a significant cost for the operator. In [12], the use of a dedicated hardware device is proposed to switch online the connection of a single-phase PV system to a different phase according to the loading conditions of the feeder. Such a solution imposes an additional cost for the interconnection hardware and requires three-phase connectivity in single-phase connected buildings. The installation of an Energy Storage System (ESS) with advanced operational capabilities is proposed in [13], where the ESS is utilized to regulate the power exchange between the low- and the medium-voltage distribution grid and to compensate the asymmetric loading. This solution imposes a high cost capital investment by the DSO or the grid owner. Another approach to achieve phase balancing and harmonic compensation is proposed in [14]-[16], where the grid tied inverter of a PV system is enhanced with advanced functionalities in order to compensate the prosumer asymmetric loading conditions at the building level. The deployment of these solutions requires additional current sensors to locally measure the building loading conditions and it is only effective for buildings that are equipped with PVs or a BSS. An unbalanced current sharing control is proposed in [17] where measurements from every building are required for compensating the asymmetric loading within a microgrid. This approach requires intense communication traffic to collect measurements from every building. A voltage unbalance compensation scheme is proposed in [18], where local voltage asymmetries are considered to symmetrize the operation of a microgrid. Since voltage asymmetries are quite limited in an LVDG, this solution can be affected by the voltage measurement noise. This approach is more effective in islanded microgrid applications where the grid impedance is higher and thus the asymmetric currents cause higher impact on voltage unbalance.

### C. *Contributions and organization*

This paper proposes a cost-effective Low-Voltage Distribution Feeder (LVDF) controller for phase balancing distribution feeders at the substation level. The solution requires only one smart meter installed at the substation (minimum capital investment for the DSO) and utilizes advanced functionalities of three-phase PV and BSS inverters already installed within the feeder. The solution requires that the inverters will be Internet of Things (IoT) ready devices to be able to exchange coordination signals with the centralized LVDF controller. Note that the majority of commercial inverters are already IoT ready devices. Further, the grid tied inverter must be enhanced with advanced functionalities according to [14], [19], [20] to be able to intentionally inject asymmetrical currents while delivering the PV or storage power into the grid. Thus, a novel inverter controller is developed with enhanced functional capabilities. The solution is integrated based on ICT technology which is used for concentrating measurements from one smart meter at the distribution transformer and for sending the coordination signals to PV/BSS inverters for phase balancing the LVDG operation at the substation level. The proposed solution is based on existing ICT infrastructure and requires minimum data exchange through communication. The operational cost for communication and additional maintenance cost for the inverter that may arise since its mission profile is changing can be considered as a compensation tariff through a business plan that will enable the provision of this new ancillary service. It should be highlighted that the proposed method is more adequate for LVDG where the majority of buildings and PV systems are already three-phase connected. The benefits of the proposed LVDF controller are significant for the distribution grid (both at medium and low voltage level) regarding its power quality, efficiency and stability and can maximize the utilization of its capacity.

The rest of the paper is organized as follows. The controller for the inverter to enable the new functional mode is demonstrated in Section II. Section III presents the proposed centralized controller for phase balancing the LVDG. Section IV demonstrates simulation results to validate the effectiveness of the solution, while the paper concludes in Section V.

## II. Advanced Controller for Grid Tied Interters

The proposed phase balancing control scheme for LVDGs is based on grid tied inverters with advanced operational functionalities and IoT readiness capabilities. Therefore, it is important to develop first a novel inverter controller for enabling three-phase PV and BSS inverters to inject on purpose unbalanced currents in order to compensate loading asymmetries of the feeder. In contrast to the current practice regarding the inverters where a symmetrical current injection is required, the new inverter should be able to deliver the produced PV power into the grid by injecting intentionally asymmetrical currents. Hence, for enabling such operational mode for an inverter, an enhanced controller for an inverter is developed here based on: an advanced synchronization method, a new current controller, and an enhanced PQ controller as shown in Fig. 1. The reference current for asymmetrical current injection $(\mathbf{i}_{inv-k}^{-1*})$, where $k$ is the number of PV or BSS inverter participating in the phase balancing scheme, is sent through Modbus TCP/IP protocol to each inverter over the network. For such an advanced grid tied inverter, an advanced

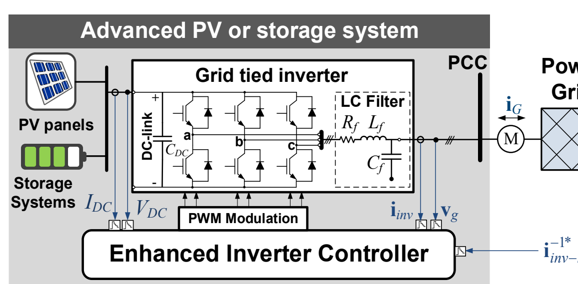


Fig. 1. Overall structure of an advanced grid tied inverter with capabilities of injecting intentionally asymmetric currents into the grid.

synchronization scheme is required to estimate the positive $(\mathbf{v}_{dq}^{+1})$ and negative $(\mathbf{v}_{dq}^{-1})$ sequence of grid voltage ($\mathbf{v}_g$) and the phase angle ($\theta^+$) of its positive sequence under any grid conditions. The DNαβ-PLL [19] is implemented in this study as a synchronization unit to extract the positive and negative sequence voltage. The positive sequence voltage is used to track the voltage angle for synchronization purposes, while the negative sequence voltage is utilized by the advanced current controller as a feed-forward vector, as shown in Fig. 2(a).

The injection of on-purpose unbalanced currents requires an advanced current controller. Therefore, a current controller that can effectively regulate simultaneously the positive and negative sequence of currents is utilized according to the method that has been recently developed in [14]. More specifically, the current controller is designed in two synchronous reference frames, rotating at positive ($dq^{+1}$) and negative ($dq^{-1}$) fundamental speed and is based on Proportional Integral (PI) controllers. It should be mentioned that the new current controller requires to dynamically analyze the injected current by the inverter ($\mathbf{i}_{inv}$) into its positive ($\mathbf{i}_{dq}^{+1}$) and negative ($\mathbf{i}_{dq}^{-1}$) sequence components to allow the independent control of each sequence. For this purpose, a cross coupling decoupling network is used based on the multiple use of (1) for $n$=+1, -1.

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

In (1), $\mathbf{i}_{dq}^{n*}$ and $\mathbf{i}_{\alpha\beta}^{n*}$ represent the dynamic estimation of the positive or negative sequence of inverter current in synchronous ($dq$) or stationary frame ($\alpha\beta$), $\mathbf{i}_{\alpha\beta}$ is the inverter current expressed in $\alpha\beta$-frame, $[T_{dq^n}]$ represents the 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 [19]. The cross-coupling structure of the decoupling network is demonstrated in Fig. 2(b). It should be noted that the specific decoupling network is used for the implementation of the new current controller due to the very fast dynamic response regarding the decomposition of the current vector to its corresponding symmetrical components. This fast response and the limited delays introduced by this decoupling network allows the stable operation of the current controller to intentionally inject asymmetrical currents.

Furthermore, a PQ controller is used to estimate the reference currents required by the current controller. The main objective of the PQ controller is to inject the produced PV power into the grid and allow to manage active and reactive power independently. Hence, a maximum power point tracking (MPPT) algorithm is used to extract the maximum available energy from the PV system. Occasionally, the system operator can demand active power curtailment in order to reduce the peak generation. In addition, the provision of reactive power is adjusted according to the grid voltage or the produced active power. Furthermore, the PQ controller considers the limitation of negative current injection in cases where the provision of this ancillary service causes violation on the inverter rating currents to ensure the integrity of the inverter. Thus, the PQ controller calculates the maximum allowable limit for negative current injection $\hat{\mathbf{i}}_{inv-k}^{-1}(t)$ by the inverter as defined in (2),

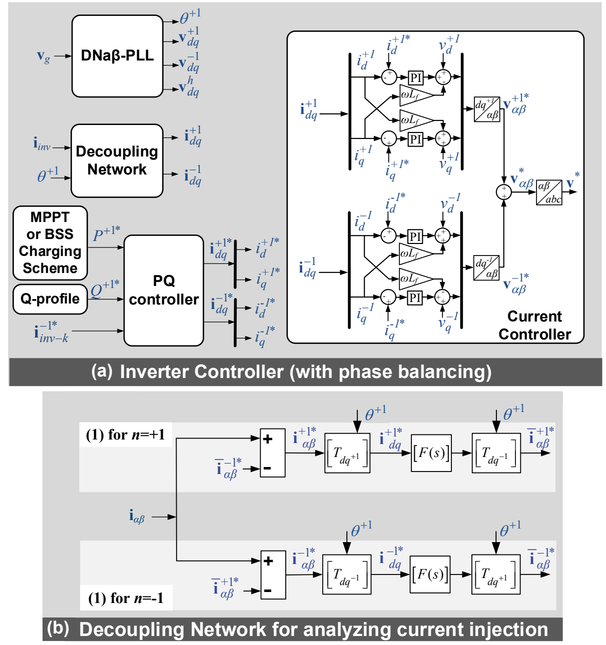


Fig. 2. (a) The structure of the proposed inverter controller to intentionally inject asymmetrical currents, (b) the decoupling network to dynamically decompose the inverter current sequences.

$$\hat{\mathbf{i}}_{inv-k}^{-1}(t) = \sqrt{\widehat{I_k}^2 - \left(\mathbf{i}_{inv-k}(t)\right)^2} \quad (2)$$

where $\widehat{I_k}$ is the rating currents of inverter $k$ and $\mathbf{i}_{inv-k}(t)$ is the instant injected current vector by the corresponding inverter. It is observed that the availability for provisioning phase balancing service is highly related to the inverter operating conditions. As a result, at noon during a sunny day, the PV inverters are expected to have very limited availability for providing phase balancing services, which is one of the main limitation of the proposed method. It should be noted that in case of a BSS inverter, a very similar inverter controller is used, with some slight differences regarding the provision for bidirectional operation and the replacement of the MPPT method with a charging scheme (Fig. 2(a)).

The injection of negative sequence current of each inverter $k$ is regulated by a coordination signal ($\mathbf{i}_{inv-k}^{-1*}$) send by the Low-Voltage Distribution Feeder (LVDF) controller (Section III) through Modbus TCP/IP protocol in order to compensate the loading asymmetries at the substation level.

## III. DISTRIBUTION GRID CONTROLLER

A building level approach for phase balancing the distribution grid was proposed recently in [14]. In this case, the control scheme is developed for each prosumer building, where the rooftop PV installation compensates the asymmetries imposed by the corresponding prosumer loads. In this approach, the asymmetric loading compensation utilizes only local measurements (for prosumer loads) without requiring any particular communication layer. In this approach [14], a complete elimination of asymmetric loading conditions of the LVDG can only be achieved if all the buildings of the feeder are three-phase connected and are equipped with an inverter with phase balancing capabilities. However, this scenario is not realistic. This paper proposes a simple and more realistic approach (feeder level approach), in which the available PVs and BSSs installed within a LVDG can contribute towards the complete phase balancing of the feeder at the substation level by compensating the overall asymmetries imposed by all the consumers/loads connected to this feeder, as shown in Fig. 3.

In this paper, the provision of phase balancing is regulated by the LVDF controller for compensating loading asymmetries at the substation. The LVDF controller receives measurements from a smart meter installed at the MV/LV transformer and calculates the negative sequence reference set-points for each PV or BSS inverter $(\mathbf{i}_{inv-k}^{-1*})$, where $k$ is the number of the PV or BSS inverter participating in this service, as demonstrated in Fig. 3. For the stable operation of the LVDF controller, the availability (maximum allowable limit) for negative sequence current injection $(\hat{\mathbf{i}}_{inv-k}^{-1})$ by each inverter is required in each control loop of the LVDF controller. This information is calculated within the inverter controller according to (2) and sent to the LVDF controller through Modbus TCP/IP. In the proposed cost-effective solution, only one smart meter is required to measure the grid current $\mathbf{i}_{grid}$ (at the low-voltage side of the transformer). A fast reporting smart meter (reporting rate of 200-500 ms) that supports a Modbus TCP/IP communication protocol can be used to obtain measurements from the substation over a local area network. For this work, a Janitza UMG 604E smart meter has been considered to be installed at the substation and a 200 ms control period is used for the LVDF controller. The specific meter has also power quality analyzer capabilities and thus, the negative sequence grid current $\left(\mathbf{i}_{grid}^{-1}\right)$ of the feeder can directly be derived. If the meter does not provide power quality analysis, the symmetrical components theory for analyzing the three-phase currents (a, b and c) to their positive, negative and zero sequence components (+, -, 0) can be used to identify the negative sequence of the grid current.

As soon as the negative sequence grid current $\left(\mathbf{i}_{grid}^{-1}\right)$ and the availability of each inverter for phase balancing support $(\hat{\mathbf{i}}_{inv-k}^{-1})$ are available in the LVDF centralized controller, then a simple control structure is developed to compensate the asymmetric loading conditions at the substation level. Since the delta-wye configuration of the distribution transformer eliminates the zero sequence currents, the compensation of loading asymmetries can be achieved by forcing the negative sequence of the grid current at the substation $\mathbf{i}_{grid}^{-1}$ to zero through the manipulation of the negative current injection by the available PV and BSS installations. To achieve this, the measured negative sequence current is transformed in the synchronous reference frame rotating at negative fundamental speed, where the negative sequence current is represented as a non-oscillating term and thus, a typical PI controller can be effective to achieve the phase balancing objective. For tuning the PI controllers, the following parameters have been selected ($k_P$=0.2 and $k_I$=2). The PI controllers are equipped with anti-windup limiter to bound their output to the total availability for negative sequence current injection by all the inverter $(\sum \hat{\mathbf{i}}_{inv-k}^{-1})$ and thus, to ensure the stable operation of the scheme. Thereafter, the PI controllers generate the total negative sequence reference current $\left(\mathbf{i}_{tot}^{-1*} = \left[\mathbf{i}_{tot-d}^{-1*} \quad \mathbf{i}_{tot-q}^{-1*}\right]^T\right)$ that needs to be injected by the inverters participating in the scheme to completely eliminate the asymmetric loading conditions at the substation level. Then, the total asymmetrical current injection is allocated to the inverters according to their availability for phase balancing services provisioning (using adaptive weights $\hat{\mathbf{i}}_{inv-k}^{-1}/\sum \hat{\mathbf{i}}_{inv-k}^{-1}$ based on their operating conditions), as shown in Fig. 3. Finally, the controller sends the reference coordination set-points to each inverter through the Modbus TCP/IP communication protocol. The applicability of the solution requires that commercial and certified inverters to be enhanced with capabilities to inject asymmetrical current upon request (as explained in Section II).

Summarizing, the proposed controller is a cost-effective solution for phase balancing the LVDG at the substation level. The solution requires only one fast reporting smart meter and it is integrated through ICT technology. The advanced functional capabilities of the proposed inverter enable the utilization of the PV and storage inverters as flexible actuators in order to compensate the substation loading asymmetries.

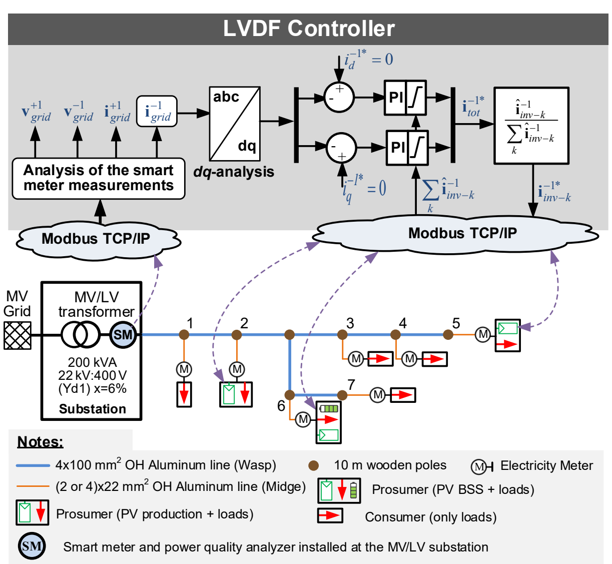

Fig. 3. The structure of the proposed LVDF controller for phase balancing the asymmetric loading conditions of a low-voltage distribution feeder.

## IV. Simulation Based Case Study

In this section, a simulation-based case study is demonstrated to prove the effectiveness of the proposed LVDF controller. The LVDF controller exploits the advanced functionalities of grid tied inverters and the available ICT infrastructure to completely eliminate the loading asymmetries at the secondary distribution substation. The investigation is enabled by developing a discrete-time electromagnetic transient model for an LVDG in MATLAB/Simulink. A realistic low-voltage feeder is modeled as shown in Fig. 3. The feeder serves seven consumers, three of which are prosumers equipped with PV systems, and one of the prosumer is also equipped with a BSS. A 5 kW peak three-phase PV installation is considered for each prosumer, where it is assumed that the grid tied inverter that integrates the PVs into the grid is enhanced with the advanced operational capabilities according to Section II. A 5 kW – 5 kWh BSS is integrated in prosumer 6 through an advanced inverter with phase balancing capabilities. The main distribution line of the feeder is developed based on 4x100 mm$^2$ overhead aluminum lines (Wasp), while the connection of the main feeder with each building is accomplished using 2 or 4 overhead aluminum wires (for single or three phase consumers respectively) with a 22 mm$^2$ cross section area. The structure of the LVDG is demonstrated in Fig. 3. It should be noted that the low voltage network is realistic considering the structure and the line types of a sub-part of an LVDG in Cyprus. In this feeder, three PVs and one BSS are randomly allocated on three-phase consumers. The load consumption of each building is selected in a way to present a total 9-10% asymmetric loading condition at the substation (regarding the ratio between negative and positive sequence of grid current). During this case study, the PVs generate 2 kW each and the battery discharges with 1 kW. For $t < 5$ s, the total consumption by all building is 66 kW which can be considered as 9% penetration of PVs (since 6 kW are generated by PVs). For $t > 5$ s, a 24 kW load change occurs leading to a 6.6% penetration of PVs during the rest of the simulation.

For this case study, a fast reporting smart meter has been installed at the substation and the LVDF controller is using a sampling period of 200 ms. The steady state performance of the proposed solution for phase balancing and the transient operation of the LVDF controller are demonstrated.

### A. *Steady State Performance*

The steady state performance of the LVDF controller is shown in Fig. 4. The test scenario incudes two cases where: (a) the LVDF controller is deactivated and (b) the LVDF is activated. In both cases of Fig. 4, the consumers' loads within the feeder are constant and absorb unbalanced currents and create asymmetric loading conditions for the LVDG.

When the LVDF controller is deactivated (Fig. 4(a)), the injected currents by inverters ($\mathbf{i}_{inv\text{-}k}$) are symmetrical according to the conventional operation. Since the loads within the feeder absorb unbalanced currents, the resulted grid current ($\mathbf{i}_{grid}$), measured at the substation transformer, is highly asymmetric as shown in Fig. 4(a). Such asymmetric loading conditions, reduce the utilization of the feeder and transformer capacity (i.e., the most loaded current requires a capacity of 142 A peak), can negatively affect the power quality of the LVDG (intense double frequency power oscillations and asymmetric voltage conditions) and increases the energy losses within the distribution grid. These double frequency power oscillations are a result of the coupling effect between the positive sequence of the grid voltage and the negative sequence of the grid current.

When the LVDF controller is activated, the LVDF manipulates the grid tied inverters of PV and storage systems to intentionally inject asymmetrical currents for phase balancing the distribution grid operation. Therefore, the inverter current injection is intentionally asymmetrical. However, the grid current at the substation is purely symmetrical as demonstrated in Fig. 4(b). As a result, a complete elimination of the loading asymmetries is achieved at the substation level with great benefits for the operation of distribution grids. The phase balancing of the distribution grid can: improve the power quality and minimize the voltage asymmetries of the feeder, reduce the losses in the distribution grid, and maximize the utilization of the feeder capacity by compensating the loading asymmetries of the distribution transformer. The effective utilization of the feeder capacity in case of phase balancing is demonstrated by the fact that a peak of 130 A maximum capacity is required for the feeder in Fig. 4(b) compared to the 142 A peak capacity required in Fig. 4(a).

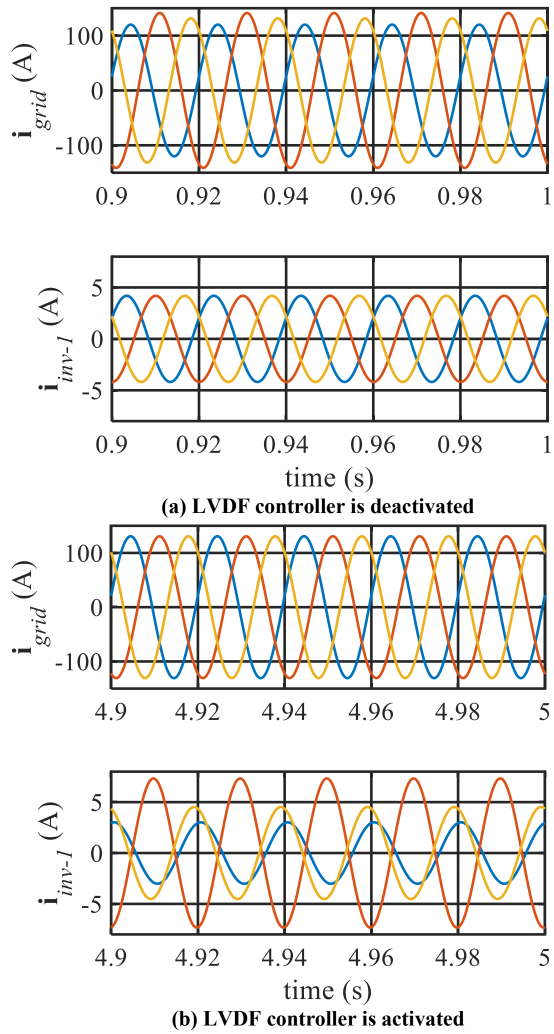


Fig. 4. The steady state performance of the LVDF control scheme when (a) the LVDF controller is deactivated, and (b) when the LVDF controller is activated. In each plot, the grid current at the ssubstation and a current injection by inverter 1 connected at bus 2 is demonstrated.

### B. *Transient Behavior of the Distribution Feeder*

The transient behavior of the LVDF controller is investigated here. In this case study, the smart meter is used to read the measurements every 200 ms and calculate the negative sequence grid current. Then, the LVDF controller generates the phase balancing coordination signals for each PV system to compensate the asymmetric loading conditions of the feeder. The scenario considers that the grid current initially contains asymmetrical component due to the loading conditions of the feeder and the LVDF controller is deactivated. The LVDF controller is activated at $t$=1 s, and the inverters are disconnected at $t$=9 s. A load change event occurs at $t$=5 s where both positive and negative sequence demand currents are changed. The results are demonstrated in Fig. 5.

In the beginning of the case study (Fig. 5), the LVDF controller is deactivated and the grid current is highly

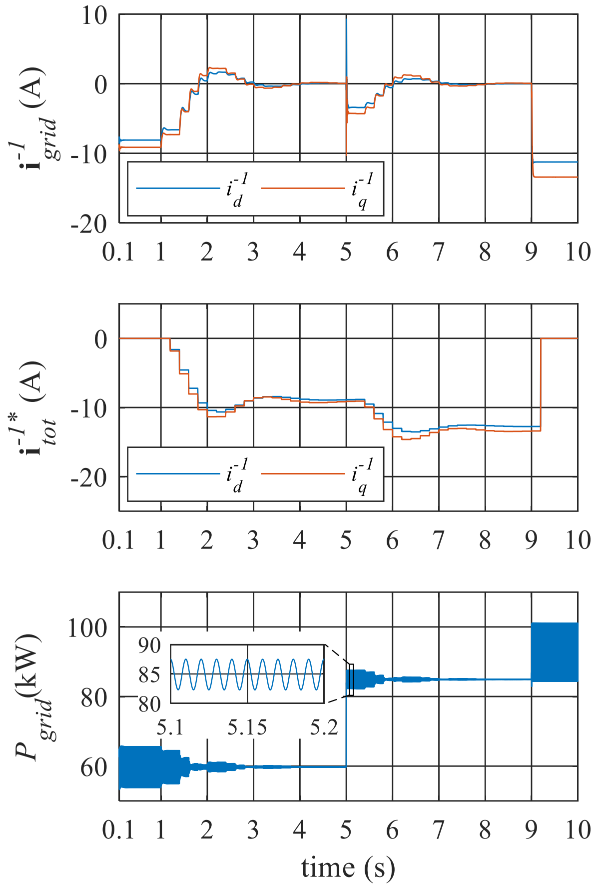


Fig. 5. The transient operation of the LVDG according to the LVDF controller. The LVDF controller is activated at $t$=1 s and deactivated at $t$=9 s. A load change is applied at $t$=5 s in some consumers loads.

asymmetrical. Initially, the negative sequence grid current is equal to $\mathbf{i}_{grid}^{-1} = \left[\mathbf{i}_{grid-d}^{-1}\ \ \mathbf{i}_{grid-q}^{-1}\right]^T = [-8.1\,A\ \ -9.1\,A]^T$ at the substation, while the inverters are injecting symmetrical currents according to the conventional operating mode. It can be observed that the active power at the substation suffers from intense double frequency oscillations due to asymmetrical loading conditions. Similar double frequency oscillations also occur on the reactive power of the substation. At $t$=1 s the LVDF controller is activated and generates the coordination reference signals for PV and BSS inverters ($\mathbf{i}_{tot}^{-1*}$) for enabling the phase balancing mode. It is observed in Fig. 5 that the LVDF controller can eliminate the loading asymmetries and thus, the power oscillations are compensated and the negative sequence of grid current at the substation level becomes zero within approximately 2 seconds $\left(\mathbf{i}_{grid}^{-1} \approx [0\,A\ \ \ 0\,A]^T\right)$. Then, a load is changed at $t$=5 s varying the feeder loading conditions. In this case, the LVDF controller reacts fast and compensate the asymmetries within 1 second. Finally, at $t$=9 s, the inverters are disconnected which increases the mean value of the active power fed by the substation (due to the loss of distributed generation) and intense oscillations occurs due to loading asymmetries. This case study demonstrates the effectiveness of the proposed centralized LVDF controller to dynamically compensate asymmetric loading conditions at the substation level by utilizing advanced capabilities of grid tied inverters.

## V. Conclusions

A novel control scheme is proposed for phase balancing the LVDG operation at the substation level. The proposed solution considers advanced operational capabilities by inverters and utilizes existing ICT infrastructure. The performed investigation demonstrates the effectiveness of the proposed low-cost solution to eliminate the asymmetric loading conditions at the substation level. Hence, the distribution grid operation is beneficially affected regarding the power quality, efficiency and effective utilization of its capacity.

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