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***Abstract*—Most of the large scale photovoltaic power plants (LS-PVPP) count on power converters with a central configuration. Advantages such as robustness, low maintenance and installation cost makes this configuration the preferred specially suitable in large scale systems. However, important drawbacks like the low efficiency level make necessary to develop new solutions for future power plants. In this paper a power station for large scale PV systems is proposed, which consists of power inverters synchronized with an interleaving modulation and connected to a multi-winding transformer. The main principles that support this proposal, as well as, simulation results are presented to validate the effectiveness of the proposed configuration.**

***Index Terms*—Interleaving modulation, Large scale photovoltaic power plants, Multi-Winding transformer.**

I. INTRODUCTION

During the last years the photovoltaic (PV) energy has grown drastically, becoming one of the most promising renewable energies worldwide [1]. The environmental awareness, economic incentives from the government and cost reduction of PV panels are the main reasons behind the huge increase in the PV power installed. In fact, by 2015 some countries began to consider the PV energy as a grid parity regarding to conventional energy sources. In 2016 the cumulative photovoltaic energy was 304 GW with a power installed of 75 GW [2], being China, Japan and the US the top three biggest producers [2]. The European Photovoltaic Industry Association (EPIA) predicts that the PV energy will continue increasing and could reach more than 800 GW of generation by 2030.

PV grid connected systems are still the 99% of the overall power installed, if compared to stand alone systems. Grid connected systems are divided in three main configurations: small scale, medium scale and large scale [3]. Commonly, small scale systems generate less than 100 kW and are located in industrial and residential areas. Likewise, medium scale systems are less than 1 MW and they represent small PV farms. Finally, large scale systems reach power levels higher than 1 MW and they represent more than 90% of grid connected systems, being characterized by large PV plants installed at the countryside and desert areas. Commonly, small and medium scale systems use power inverters with string or multi-string configurations. The string configuration has several PV panels connected in series to one DC-AC inverter. Therefore, as the power increase, it is necessary to connect several strings in parallel to reach the power level required. On the other hand, multi-string configurations have two stage of conversion, which includes one or more DC-DC stages. The DC-DC converters provide an independent maximum power point tracking (MPPT) to each PV string and they are able to boost the DC voltage and provide high frequency isolation [4].

Large scale PV systems require thousands of PV panels to generate high power levels. Although, string and multi-string are possible structures to be used in these systems, their high implementation cost give rise to central configurations, that have shown to be the most suitable alternative. Advantages such as: high robustness and low maintenance make the central configuration the preferred solution in most of the cases [5]. However, high mismatching, high DC voltage variation and few MPPT's [5], motivate the search of new solutions to improve the current systems. A commercial central inverter operates power levels up to 1 MW. Therefore, in order to generate a higher power, several central inverters are connected. Usually, the central inverter is formed by a two level voltage source inverter (2L-VSI) connected to several PV strings at the DC side and one low frequency transformer to step up the output voltage at the AC side. Due to the fact that the inverter operates with low switching frequency, a high AC filter is required to eliminate the current harmonic content.

Considering the characteristics of large scale PV plants, a novel configuration formed by classical central inverters is proposed. The proposal, called power station, has several central inverters connected to one multi-winding transformer, where all inverters, called modules, are synchronized in order to reduce the harmonic content in the current injected into the grid. According to the interleaving modulation used in DC-DC converters, the synchronization signal shift the modulation carrier of each inverter so that the current harmonic decrease as the number of inverters connected increase. By doing this, it is possible to reduce the filter size and the large number of low frequency transformers. However, it is required a multi-winding transformer to provide isolation to each inverter and boost the AC voltage.

In this paper the aforementioned power station for PV power plants (PS-PVPP) and the interleaving modulation is presented. The paper is organized as follow: In section 2 is

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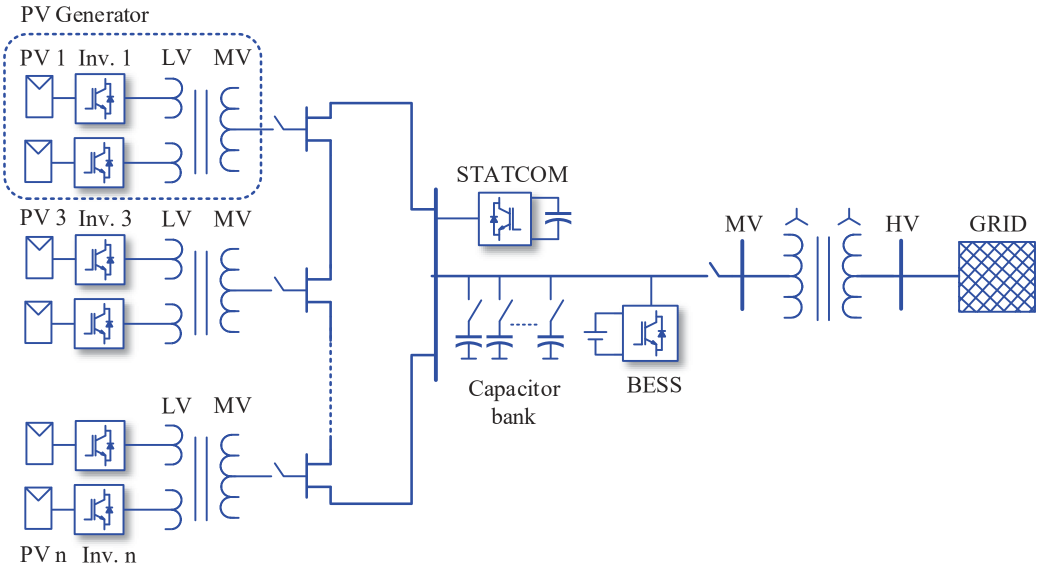

Fig. 1. General PV large scale power plant

described the PV large scale configuration used in most of the PV plants. In section 3 is described the power station proposed and the filter analysis is discussed. In section 4 is validated the configuration by means of simulation analysis. Finally, in section 5 the paper is concluded.

II. PV LARGE SCALE CONFIGURATION

A general configuration for PV plants is shown in Fig.1. The configuration comprises all possible elements to provide frequency and voltage support to the grid and store the overproduction power coming from the PV panels [6]. The DC side of one central inverter is connected to a PV array, which consist of hundreds of parallel PV strings that are necessary to reach the generation power levels. Due to the variable irradiation, the DC voltage level fluctuates between 650 V and 1000 V. Therefore a three phase transformer is required to boost the output voltage from low (LV) to medium voltage (MV) levels and provide low frequency isolation. Commonly, a commercial PV generator has two central inverters connected to one transformer with two winding in the low voltage side and one winding in the medium voltage side, which is connected to an internal PV collector with a radial, ring or star configuration [7]. The radial collector consists of several central inverters connected to one common bus bar (feeder) being the cheapest and the simplest configuration. However, the radial collector shows a low reliability, that makes this option less interesting. On the other hand, the ring collector is based on a radial design, but it has one feeder more to increase the reliability of the system. Therefore, when one feeder is disconnected, the collector can still supply the power generated to the system through the second feeder. Finally, in the star collector all the PV generators are connected to the main collector, which is commonly placed in the middle of the PV plant to have similar power losses in all the PV generators.

In order to provide grid support functionalities (frequency and voltage amplitude regulation) [8], PV plants include ancillary elements such as: capacitor banks, FACTS and batteries connected to the internal PV collector. The reactive power regulates the voltage amplitude according to the voltage droop curve defined by the transmission system operator (TSO). This reactive power is supplied by the central inverters, capacitor banks and facts. Indeed, the capacitor banks deliver the major part of reactive power, while the fine regulation is performed by facts and central inverters [6]. On the other hand, the grid frequency regulation is controlled by the active power, which depends on the operation point and the available energy stored in the PV plant. Therefore, an absence of power reserve limits the regulation capability when the grid frequency drops below its reference.

In a large scale system a second three phase transformer is implemented to boost the voltage from the internal collector and consequently connect the PV plant to the high voltage transmission line. When the power levels increase, more than one internal collector is used. All of them are linked to the same medium voltage bar, which is connected to the MV side of the second transformer.

III. POWER STATION FOR LS-PVPP

As it was previously mentioned, a PV plant is formed by one or more collectors with several PV generators connected to one feeder. The power station proposed takes advantage of this configuration and it connects all central inverters of one collector to one multi-winding transformer. Like in a classical PV plant, each central inverter receives a specific power

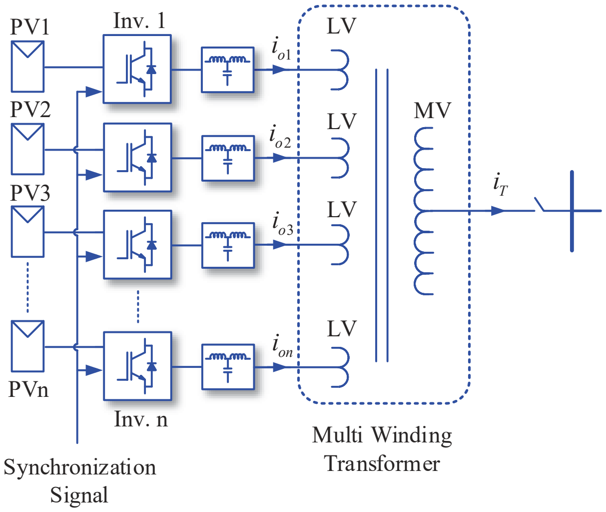

Fig. 2. Power Station proposed for LS-PVPP

reference given by the TSO. However, all their modulation carrier signals are synchronized through an external signal with the purpose of introducing a phase shifted in the AC output voltage, and thus, reducing the output current harmonic. The strategy is based on the interleaving modulation used in DC-DC converters, where the carrier modulation of two or more converters connected in parallel are shifted to increase the apparent switching frequency in order to reduce the DC current ripple.

In Fig.2 the structure of the proposed power station is shown. In this diagram N central inverters are connected to N low voltage winding of the multi-winding transformer. The transformer used in the classical PV generator is removed and the AC filter of each central inverter is connected directly to the new transformer. This is an important point, as keeping an acceptable harmonic distortion in the grid current with small AC filters through the interleaving configuration is one of the contributions of this proposal.

Moreover, due to the fact that all central inverters are gathered together, one MV switchgear is required by each internal PV collector. On the contrary, in the classical configuration each PV generator requires a MV switchgear. Therefore, the installation and maintenance cost of the LS-PVPP is considerably reduced.

The shunt connection of LV windings makes the total current increase in the MV winding, as the number of central inverters increase. This current can be written as:

$$i_T = \frac{N_p}{N_s}\left(\sum_{i=1}^{N} i_{o,i}\right) \tag{1}$$

Where $i_{o,i}$ is the output current of each inverter in the LV side and N_p/N_s represents the turns ratio between the primary and the secondary winding. It is assumed that all LV windings have the same number of conductor turns.

A. Interleaving modulation

By means of synchronizing all central inverters connected to the low voltage side in the multi-winding transformer and performing a proper phase shifting of their carrier modulations, it is possible to eliminate some current harmonic contents in the total current. In general, N identical inverters operating at the same switching frequency f_c, can provide an apparent frequency N times higher in the total current as a consequence of the harmonic elimination [9]. This effect helps to reduce the filter size of each inverter, since the current ripple is reduced as the number of central inverters connected increases. As it was mentioned before, the interleaving strategy used to phase shift the carrier signal in inverters connected in parallel is mainly used in DC-DC converters [9]. This effect can be studied in the frequency domain by using the analysis of the Cascade H-bridge (CHB) inverter presented in [10], where the carrier modulation is shifted in order to increase the number of voltage levels through the series connection of modules. The analysis presented in [9] defines the total output voltage in the CHB as:

$$v_o = N\frac{V_{dc}}{2}M cos(\omega_o t) + \frac{2V_{dc}}{\pi}\sum_{m=1}^{\infty}\sum_{n=-\infty}^{\infty}\frac{1}{m}J_n(\frac{m\pi}{2}M)$$
$$sin\left[(m+n)\frac{\pi}{2}\right] * \sum_{i=1}^{N} cos(n\omega_o t + m\omega_c t + m\theta_i) \tag{2}$$

Where N is the number of inverters connected, V_{dc} is the dc-link voltage of each inverter, M is the modulation amplitude, ω_o is the fundamental frequency of the grid, m and n are the carrier and modulating signal harmonics, J_n is the Bessel function of order n, ω_c is the switching frequency and θ_i is the shifted angle of the inverter i. In order to obtain sideband harmonic components centered around the N carrier multiples, it is necessary to accomplish the expression (3).

$$\sum_{i=1}^{N} cos(n\omega_o t + m\omega_c t + m\theta_i) = 0 \tag{3}$$

Theoretically, the voltage will increase the number of levels and the frequency will be Nf_c. In order to accomplish with the previous expression, for all $m \neq kN$ and $k = 1, 2, 3, ...$ the shifted angle requires the next definition.

$$\theta_i = \frac{2(i-1)\pi}{N} \tag{4}$$

Where N is the number of inverters connected in the power station and i is the central inverter. From these expressions it can be concluded that the first inverter has a phase shifted equal to zero, while the second inverter has a phase shifted equal to $2\pi/N$ and so on. For instance, with three central inverters the carrier modulation would be shifted 120° in

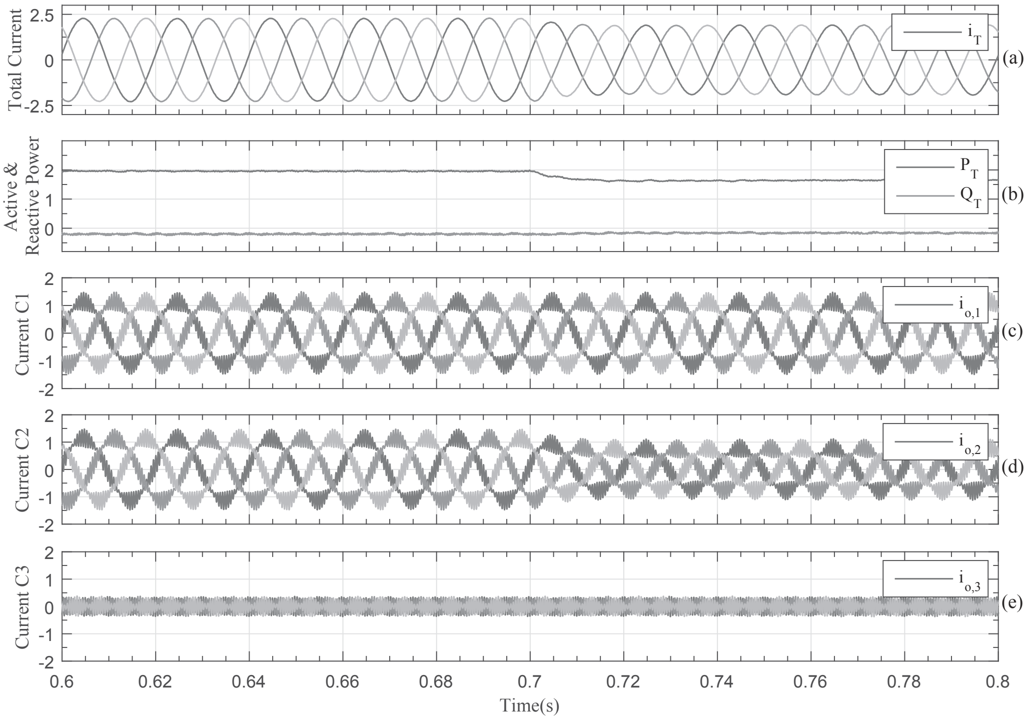

Fig. 3. Power station under different power variation. (a) Output current in the secondary side of the transformer, (b) Active and Reactive power injected into the grid, (c) Output current of the central inverter 1 after the LCL filter, (d) Output current of the central inverter 2 after the LCL filter, (e) Output current of the central inverter 3 after the LCL filter .

each inverter and the harmonic cancellations up to sidebands multiples of $3f_c$ will be achieved in the total current.

B. AC Filter Analysis

AC filters reduce the current ripple and minimize the amount of current distortion injected to the grid, as a result of the switching voltage. LCL filters are the most attractive configurations to achieve the total harmonic distortion (THD) required by grid codes and also to reduce the electromagnetic interference (EMI). In order to choose the optimal LCL filter parameters, several criteria are considered to limit the size of reactive elements which affect the power factor and reduce the power losses due to passive damping requirements. In [11] and [12] some strategies to obtain the filter parameters are presented. In these works the inverter side elements LC are chosen to limit the current ripple in the inverter side, while the grid inductance is evaluated in terms of harmonics rather than ripple amplitude [11].

The filter should be properly designed to avoid saturation effects and achieve an appropriate current ripple. The correct design of the LCL filter is based on achieving a good trade-off between ripple reduction and inductor cost, since a high value of inductance reduces the current ripple, but it increases the cost. On the other hand, a high current ripple may lead to saturation problems in the inductor core and high power losses. In the literature, a current ripple attenuation of 20% in the inverter side is considered acceptable, while the grid current should have a THD lower than 3% [11]. Moreover, passive damping is required to avoid resonances due to LC elements.

The interleaving modulation used in the power station provides the capability of reducing the filter size as the number of central inverters increase. However, saturation effects limit the minimum value of the inductor filter as a result of the current ripple in the inverter side. For this reason, the inductance is defined by several requirements to obtain the optimal filter and switching frequency. Since, a detailed analysis to find the optimal filter parameters and switching frequency is out of the scope, as a first instance, the configuration proposed is validated with a filter size (per central inverter) that reduces the current ripple of the converter side in 40% and after the filter a THD of 20% is achieved.

IV. POWER STATION MODEL

Based on the same control structure of a classical PV plant [4], central inverters have a local control which is responsible for managing the power provided from the PV arrays. The TSO distributes the total power dispatched among all the PV generators, therefore each central inverter receives its own power reference. The control used operates the central inverters as a current source, where an inner current control loop is used to control the current set point provided by an external control loop. In order to simplify the model, the influence of the capacitor and the damping resistance in the LCL filter is neglected, therefore the dynamic model of the power station is given by:

$$[v_{c,i}] = [L_f]\frac{d[i_{o,i}]}{dt} + [R_f][i_{o,i}] + [v_{s,i}] \tag{5}$$

Where $[L_f]$ and $[R_f]$ are the equivalent series inductance and resistance of the LCL filter, $[v_{c,i}]$ is the inverter voltage, $[v_{s,i}]$ is the grid voltage reflected to the low voltage side of the transformer and $[i_{o,i}]$ is the output current of the central inverter i.

V. SIMULATIONS RESULTS

This section presents the effectiveness of the proposed power station through simulation results. The configuration evaluated has three PV generators connected to one multi-winding transformer with a power rating of 3 MW and a voltage of 400V / 13.5kV. The MV-HV transformed is omitted and the grid is modeled as a voltage source of 13.5 kV / 50Hz with a SCR of 15. More parameters are detailed in table I.

Each central inverter has a nominal power of 1 MW, and their filters have been designed according to [11]. However, in order to validate the advantages of the power station, the filter parameters have been designed to have a current ripple of 40% in the inverter side, and a THD of 20% in the current after the filter. All results are presented in per unit (pu).

The accuracy of the system is tested under two scenarios. In the first case, all central inverters operate with different power levels and the ability to control all of them independently is evaluated. In the second case, the current distortion is analyzed when all central inverters inject their nominal power. Fig.3 shows the current flowing after the LCL filter in each central inverter, the total current in the secondary winding and the power injected into the grid. During the time scale presented, the central inverter 1 operates at its maximum power point, while the central inverter 2 decreases its power from the nominal level until its 70% at 0.7s as shown in Fig.4.c and Fig.4.d respectively. This variation is also appreciated in the active power of Fig.4.b. On the other hand, the central inverter 3 does not generate any power, but it keeps connected to inject the current harmonic required to reduce the current ripple as a result of the interleaving modulation. Despite, having a high current distortion in central inverters, the output current in the secondary side of the transformer (Fig.4.a) has an almost neglected current ripple. This low distortion is also visible in the active and reactive power of Fig.3.b.

TABLE I
SIMULATION PARAMETERS

Parameters	Symbol	Value
Nominal power	P_o	3MW
Grid voltage	v_s	13.5kV
Grid frequency	f_s	50Hz
Number of central inverters	N	3
Nominal power of one inverter	P_{inv}	1MW
Switching frequency	f_c	2000kHz
Low voltage side of transformer	v_{TL}	400V
Medium voltage side of transformer	v_{TM}	13.5kV
Inductance inverter side	L_p	0.037pu
Inductance transformer side	L_s	0.0342pu
Capacitor LCL filter	C_f	0.0671pu
Base power	P_B	3MW
Base voltage	v_B	400

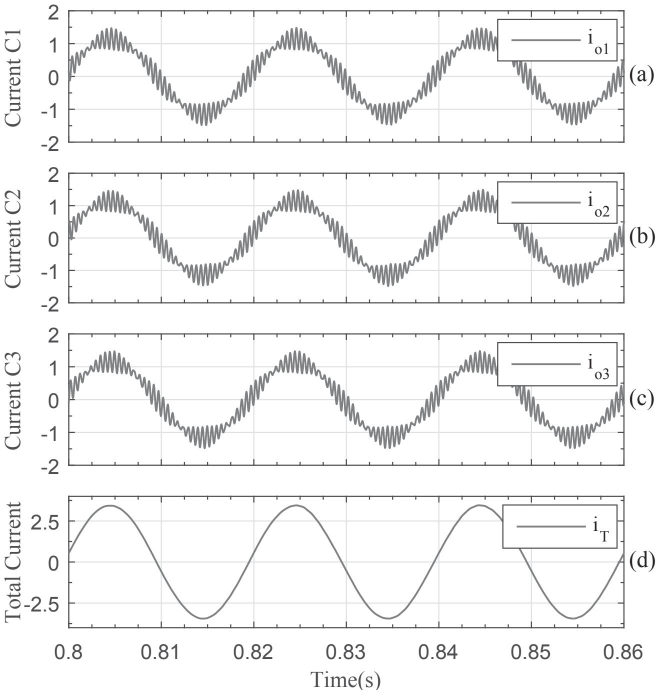

Fig. 4. Output current after the LCL filter, (a) central inverter 1, (b) central inverter 2, (c) central inverter 3, (d) current injected into the grid.

The output current of the inverters operating at nominal power are presented in Fig.4. Since the filters have been designed to have a 40% of current ripple in the inverter side, the current after the LCL filters have a high current distortion. These results can be evaluated in the FFT response, where it can be appreciated a 21% of THD (Fig.5.a , 5.b and 5.c). However, the total current in the secondary side of the transformer decrease considerably and its current reaches a THD of 0.3%.

VI. CONCLUSION

In this paper a power station for LS-PVPP based on classical PV generators is presented. The objective of maintaining a low THD in the current injected into the grid by decreasing the AC filters and reducing the switching frequency is tested. Moreover, gathering together the central inverters in one multi-winding transformer, the medium voltage breakers decrease and thus, the implementation cost of the PV plant is reduced. In simulation results the accurate of the power station by using the interleaving modulation is analyzed and a low harmonic content in the output current is obtained. This harmonic reduction take place despite the fact that small AC filters are used in central inverters.

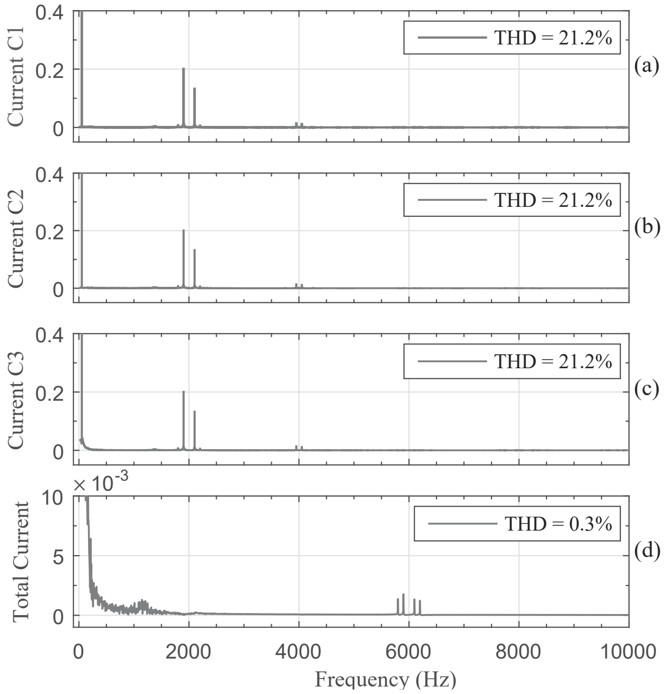

Fig. 5. FFT of the output current after the LCL filter, (a) central inverter 1, (b) central inverter 2, (c) central inverter 3, (d) current injected into the grid.

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