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# Multi-Frequency Power Transfer in a Smart Transformer Based Distribution Grid

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**Abstract**—The smart transformer, a solid-state transformer with control and communication functionalities should provide services to the grid. This paper proposes to use a different frequency respect to the fundamental frequency, to provide such services to the distribution grid. The approach has the main benefit to transfer energy from point to point of the grid, exploiting the lower impedance path that multi-frequency converters offer. This paper describes the control strategy of the multi-frequency converters, and verifies their impact on distribution grid.

**Keywords**—Distributed generation, microgrids, power conditioning, power smoothing, power transmission, power transfer, smart transformer, solid state transformer.

## I. INTRODUCTION

Many changes in the past 15 years lead the distribution grids to new assets. The increasing penetration of distributed power generation (DPG) such as photovoltaics [1], [2], wind turbine systems [3] and combined heat and power (CHP) [4] systems has heavily affected the medium voltage (MV) and low voltage (LV) grids, impacting mostly on the grid management. In addition, new loads such as electric vehicle charging stations are introduced into the grid. As a result, voltage constraints [5]- [6] and line ampacity violations, in addition to a poor power quality (harmonics, flicker, voltage drops) [7], are increasingly present in the distribution grids. It is worth adding how the “fit and forget” policies for the DPG integration adopted in the last years have worsened the already difficult situation. The inadequate spread of DPG in the territory has brought to severe limitations of grid hosting capability. Particular attention is dedicated on the presence of harmonics in the grid: in case of massive penetration of DPG, the Total Harmonic Distortion (THD) limit imposed by the national regulatory frameworks is easily exceeded, and this represents a bottleneck in the amount of DPG that can be installed [8]. Mostly, the concerns of distribution system operators (DSO) are to build new infrastructure in order to meet the new loads and DPG requests and not violate the voltage and current limits. This represents a non cost-effective solution, both in economical and technical terms.

Many approaches have been proposed for solving the aforementioned issues, such as active demand or real-time management of distributed energy resources (DER). In this direction the smart metering plays a key role in the realization,

but it comes at a cost. Indeed, the number of appliances present in a LV or MV grid can be so large that monitoring all of them is not a simple task: the big data problem in the smart metering remains still one of the major challenge in the future smart grids [9].

The smart transformer (ST) solution [10] can deal with the integration of the DPGs and new loads, offering a good power quality at the same time. The ST is a solid-state transformer, already adopted in railway, harbor and data center applications. The use in the electric grid can lead to a great change, where the transformer is still a traditional component, without “smart” features. The ST can perform tasks a traditional transformer cannot achieve, as for example unbalanced control of voltage and power [11]. In order to provide services to the grid, a frequency different from the fundamental can be used.

In communication systems multiple frequencies are used to transmit information independently within a medium among several senders and receivers. Recently, multi-frequency approaches emerge to transfer power in the kilowatt range. In [12] a distributed power flow controller (DPFC) is proposed, which is based on the utilization of the 3rd harmonic to transfer power between shunt and series inverters through the line. Compared to the unified power flow controller (UPFC) it has the advantage of avoiding a common dc-link between shunt and series compensator, thus decreasing the cost of the system. Moreover, multiple single-phase inverters can be used as series compensator offering an additional redundancy in case of series inverter failures and further cost reduction due to lower ratings of the components. In [13], [14] it is proposed to use an additional frequency in multilevel modular converters (MMC) to implement nested secondary power loops in order to balance the voltages across the sub-module capacitors, independently of the main power loop. Another field of application is the inductive power transfer (IPT) by means of multiple frequencies [15], where single-frequency pick-ups can be tuned to different transmission frequencies receiving power simultaneously and independently.

This paper shows the possibility of multi-frequency power transfer (MF-PT) in presence of a ST in a distribution grid. Pulse width modulated voltage source inverters (PWM-VSI) have the capability to modulate more than one output frequency. Utilizing this potential a different frequency from the fundamental frequency can be used to send power from one

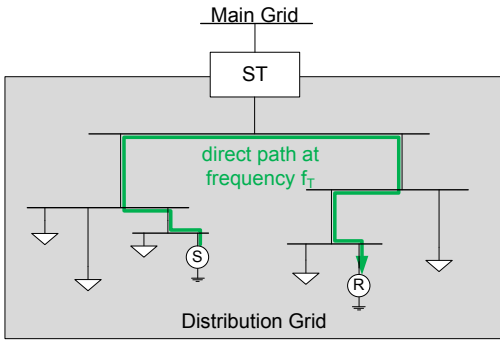


Fig. 1. Multi-frequency operation in a ST based distribution grid where S is the sender and R is the receiver

point to another part of the network. The focus of this work is to investigate the synchronization between the senders and receivers and to show the advantages and drawbacks of multi-frequency grid operations.

In Section II the potentials and limitations of MF-PT are discussed, followed by a description of a possible current-control scheme in Section III, which enables MF-PT for PWM-VSIs. Finally, simulation results are presented in Section IV, where the functionality of the proposed control scheme is verified. In addition, the impact of MF-PT in a distribution grid gets analyzed. Conclusions are finally drawn in Section V.

## II. MULTI-FREQUENCY POWER TRANSFER: POTENTIALS AND LIMITATIONS

As far as the general literature concerns, signal frequencies apart from the line frequency at 50/60 Hz have been treated as a disturbance in the grid or they have been used for communication purpose [16]. The impact of harmonics on the lifetime of the transformer [17]–[19], the increase of losses in the grid [20], and the limitation on the breaking capacity of the breakers [21] are well known. The voltage harmonics involve mostly the transformer level, affecting the flux. The current harmonics, instead, introduce higher heating losses, due to the rising of the Root Mean Square (RMS) value of the current [22]. In [18] the evaluation of the transformer loss of life due to the harmonics has been critically described. The harmonics affects also the rotating machine creating a pulsating torque, produced due to the interaction of the harmonics magnetic field and the fundamental one [21]. The presence of a large population of distributed generators in the grid cause high current harmonics that can introduce resonance problems. If one of the current harmonics corresponds to the resonance frequency of the grid, high voltage distortion occurs in the grid [23].

The proposed approach aims to use an additional transmission frequency  $f_T$  different from the fundamental frequency, to send power to a particular receiver located in another part of the grid. The concept is shown in Fig.1. It is based on the fact that the current flows through the lower impedance path, represented by the circuit between the sender and the receiver, without involving the local loads. The simulation results in Section IV describe how the current component of the frequency  $f_T$  does not affect the local loads, but only

the line linking the converters. The main advantage of this approach is the possibility to transmit energy from point to point in the grid. Through this capability, an energy storage system can be charged independently from the line frequency. This can be used for a power flow management to smooth the power variation at transformer level, for example. If the power suddenly decreases the storage system is discharged at line frequency, while it is still receiving power at the frequency  $f_T$ . Another possible application is islanding prevention. When the current capacity of the line at transformer level is reached, it is possible to send power from one part of the distribution grid to where it is required, not affecting the current congestion.

In this paper the third harmonic has been chosen as carrier frequency  $f_T$  for the above mentioned extra services, because this harmonic has the lowest limitations in grid standards [24]. Currents and voltages are supposed to be of direct sequence, in phase respectively with the 50 Hz currents and voltages. The reasoning behind this choice lies in the cross components of the power: indeed, applying a direct sequence for 150 Hz voltage and current instead of a zero-sequence, leads the system to have an oscillating power of 2nd harmonic instead one of 6th harmonic. The result is the avoidance of higher frequency oscillating power and the effect is the reduction of the losses and interferences with the grid communication system. Considering the aforementioned hypothesis, the voltage and current equations systems are implemented as follows:

$$\begin{aligned} v_a &= V_1 \sin(\omega t) + V_3 \sin(3\omega t) \\ v_b &= V_1 \sin(\omega t + 120^\circ) + V_3 \sin(3\omega t + 120^\circ) \\ v_c &= V_1 \sin(\omega t + 240^\circ) + V_3 \sin(3\omega t + 240^\circ) \end{aligned} \quad (1)$$

$$\begin{aligned} i_a &= I_1 \sin(\omega t + \varphi_1) + I_3 \sin(3\omega t + \varphi_3) \\ i_b &= I_1 \sin(\omega t + 120^\circ + \varphi_1) + I_3 \sin(3\omega t + 120^\circ + \varphi_3) \\ i_c &= I_1 \sin(\omega t + 240^\circ + \varphi_1) + I_3 \sin(3\omega t + 240^\circ + \varphi_3). \end{aligned} \quad (2)$$

Looking to the equations (1) and (2) the 50 Hz and 150 Hz voltage components are supposed to be in phase. The currents differ only for the angle  $\varphi$ . In order to compute the power flows and evaluate the impact of the 150 Hz components in the grid, the  $pq$  theory has been chosen. The real and imaginary power are defined as [25]:

$$p(t) = V_a * I_a + V_b * I_b + V_c * I_c \quad (3)$$

$$q(t) = \frac{1}{\sqrt{3}} [(V_b - V_c) * I_a + (V_c - V_a) * I_b + (V_a - V_b) * I_c]. \quad (4)$$

Carrying out the products between voltage and current equations, the instantaneous and imaginary power has been obtained:

$$\begin{aligned} p(t) &= \bar{p}(t) + \tilde{p}(t) = \frac{3}{2} [V_1 I_1 \cos(\varphi_1) + V_3 I_3 \cos(\varphi_3) \\ &+ V_1 I_3 \cos(2\omega t + \varphi_3) + V_3 I_1 \cos(-2\omega t + \varphi_1)]. \end{aligned} \quad (5)$$

$$\begin{aligned} q(t) &= \bar{q}(t) + \tilde{q}(t) = -\frac{3}{2} [V_1 I_1 \sin(\varphi_1) + V_3 I_3 \sin(\varphi_3) \\ &- V_3 I_1 \sin(2\omega t - \varphi_1) - V_1 I_3 \sin(-2\omega t - \varphi_3)]. \end{aligned} \quad (6)$$

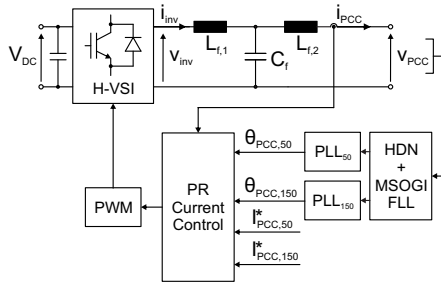


Fig. 2. Control scheme of single-phase H-bridge voltage source inverter (H-VSI) with LCL-filter

As can be observed from (5) and (6) four terms are present. The first two terms are the average values of the real and reactive power and in the classical representation of the power represent the 50 Hz and 150 Hz active power components; the remaining two terms are the oscillating terms  $\tilde{p}(t)$  and  $\tilde{q}(t)$ .  $\tilde{p}(t)$  represents the oscillating real power created by the interaction between the 50 Hz and 150 Hz components which produces a zero average value power.  $\tilde{q}(t)$  corresponds to the power exchanged among the phases, without any energy transferred to the loads.

### III. CONTROL OF PWM-VSI AS SENDERS AND RECEIVERS

To control the power transmission between the sender and receiver, different strategies are conceivable. In general, a PWM-VSI can be operated to act as a voltage or current source by applying a voltage control (VC) or current control (CC) scheme, respectively. An overview of the possible concepts in a ST based distribution grid is given in Table I. In the first approach, both the sender and receiver behave as current sources, while the ST regulates the voltage in the network, providing a 50 Hz and 150 Hz component. In the second and third concepts, either the sender or the receiver is operated as a voltage source, while the other represents a current source. The inverter with VC regulates the 150 Hz component of the voltage in the network, whereas the ST controls the 50 Hz voltage component. The fourth approach consists of two voltage sources as sender and receiver.

In this paper the first concept is discussed in order to show the functionality of multi-frequency grid operation and the impact on other loads in the network. A detailed comparison of the four approaches will be subject to future work. It is assumed that the control schemes of the sender and receiver are identical. The current control strategy of a PWM based single-phase H-bridge VSI with LCL-filter is shown in Fig.2.

Due to the ability of tracking high frequency sinusoidal references a P+Resonant (PR) controller with harmonic com-

TABLE I. CONTROL STRATEGIES IN ST BASED DISTRIBUTION GRID

Concept	Sender	Receiver
I	CC	CC
II	CC	VC
III	VC	CC
IV	VC	VC

pensator (HC) is chosen for current control [26], which are defined as:

$$G_{PR}(s) = K_P + K_I \frac{s}{s^2 + \omega_0^2} \quad (7)$$

$$G_{HC}(s) = \sum_{n=3,5,7,\dots} K_{I,n} \frac{s}{s^2 + (\omega_0 n)^2}. \quad (8)$$

Typically, the HC is tuned to compensate the current harmonics of the 3rd, 5th and 7th order as they are the most present harmonics of the grid current. In this scheme the capability to control harmonics is used to track the 150 Hz reference instead of compensation purposes.

For grid synchronization a synchronous reference frame based phase-locked loop (SRF-PLL) [27] is implemented for each frequency (50 Hz and 150 Hz). By applying two frequencies the voltage at the output of the LCL-filter is superimposed, naturally, for which reason filtering of the measured signal becomes inevitable. Therefore a frequency adaptive multiple second order generalized integrator frequency-locked loop scheme (MSOGI-FLL) [28] is added to the PLL. In combination with a harmonic decoupling network (HDN) the MSOGI-FLL is capable of detecting the fundamental frequency and its relevant harmonics under highly distorted grid conditions that makes it suitable for multi-frequency power transfer.

The  $V_{DC}$  is assumed to be constant, hence no  $V_{DC}$  controller has been implemented.

### IV. SIMULATION RESULTS

The aim of this section is to show the effectiveness of the power converter control strategies described in Section III to transfer power point-to-point and its impact on a low voltage distribution grid. Particular attention has been paid to the power quality at loads level, underlining the impact of the 150 Hz components in the grid. This section is divided into three subsections: the first subsection introduces the model of the tested distribution grid; the second subsection shows the results of the application of two current-controlled VSIs in parallel; the third subsection analyzes the impact of the 150 Hz component on the loads.

#### A. Model of the Tested Distribution Grid

Here a 8-bus LV grid is proposed, as show in Fig. 3. A ST has been chosen as interface with the main grid, acting like a slack bus. The sender is located at bus 4 and the receiver at bus 7, linked by line 6. Table II gives the lines configuration, with the resistance and inductance values.

Table III deploys the amount of load in the grid, assuming the load balanced. The composite loads have been modeled as suggested by [29], considering the loads voltage and frequency dependency. Both industrial, commercial and residential typologies have been chosen, in order to obtain a heterogeneous grid. The total amount of power requested by ST is 125 kW with an average  $\cos\varphi = 0.86$ .

#### B. MF-PT by Means of Two Current-Controlled Converters

The simulation setup to verify the control scheme presented in Section III is shown in Fig.4. Two VSIs are working in parallel as current sources, connected through the impedance

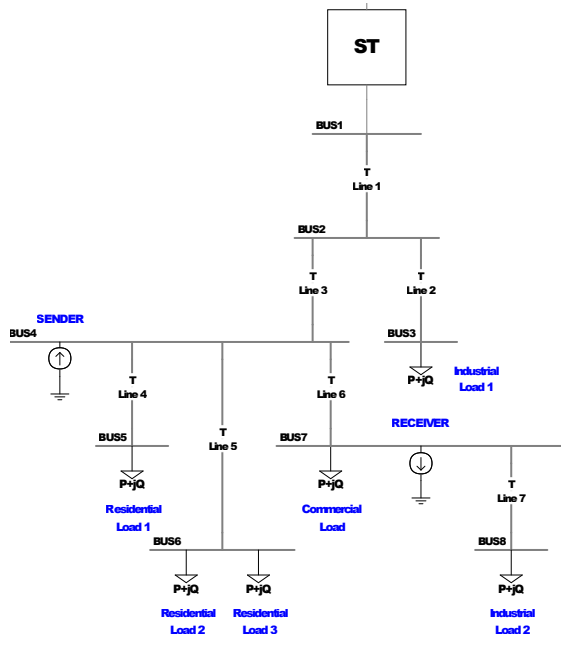


Fig. 3. 8-bus LV grid

TABLE II. LINE DATA

Line	From bus	To bus	Length (m)	Resistance ( $\Omega$ )	Inductance (mH)
1	1	2	10	0.0019	0.0024
2	2	3	50	0.0095	0.0119
3	2	4	15	0.0028	0.0036
4	4	5	25	0.0047	0.0059
5	4	6	75	0.0142	0.0179
6	4	7	50	0.0095	0.0119
7	7	8	25	0.0047	0.0059

TABLE III. LOAD DATA

Load	Active Power (kW)	$\cos\varphi$	$\partial P/\partial V$	$\partial Q/\partial V$	$\partial P/\partial F$	$\partial Q/\partial F$
Industrial 1	30	0.85	0.18	6.00	2.60	1.60
Residential 2	25	0.90	1.20	2.90	0.80	-2.20
Commercial	18	0.85	0.99	3.50	1.20	-1.60
Residential 2	25	0.90	1.20	2.90	0.80	-2.20
Industrial 2	18	0.85	0.18	6.00	2.60	1.60
Residential 3	30	0.90	1.20	2.90	0.80	-2.20

$Z_{line,6}$  (Table II, line 6). The ST is modeled as a constant voltage source with an amplitude of 325 V at 50 Hz and an amplitude of 5% of the fundamental value at 150 Hz, connected to the VSI through the impedance  $Z_g$  (Table II, line 1+3). The sender is controlled in such a way as it receives current at 50 Hz and sends current at 150 Hz into the grid. In contrast, the receiver receives current at 150 Hz and provides current at 50 Hz.

As it is shown in Fig. 5(a) the references of the 50 Hz currents are held constant. Moreover, all current references are in phase with the grid voltage, thus only active power flow is considered. The 150 Hz-power profile depicted in Fig. 5(b) can be split into two phases. In the first phase the sender

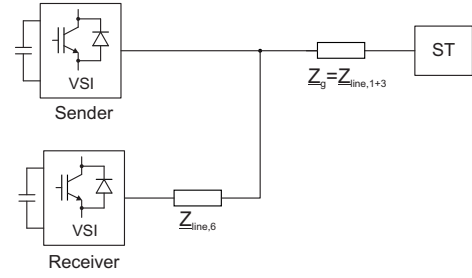


Fig. 4. Two VSIs in parallel as sender and receiver

and receiver are not synchronized, resulting in a distorted grid current  $i_g$  (see Fig. 6(a)). In the second phase the amplitudes of the 150 Hz current references are set equal. In consequence, the magnitudes of the 150 Hz power become equal, too, except for a small variation due to the losses in the line. As a result it can be seen in Fig. 6(b) that the grid current  $i_g$  has no component at 150 Hz and therefore it is nearly undistorted. The current behavior during the transition from phase I to phase II is shown in Fig. 7.

On the basis of this behavior it can be concluded that the sender and the receiver need to be well synchronized in order to avoid unwanted distortions of the grid current. The analysis and realization of an optimal communication between sender and receiver is subject of future work.

### C. Impact of MF-PT on the Grid

A steady state simulation has been performed, based on the grid described above. For the evaluation of the proposed approach we have considered the following hypothesis: 1) current injection and absorption are synchronized between the two converters in order to take in account the losses caused by the 150 Hz current, 2) there is no reactive power injected (sender) or absorbed (receiver) by the converters, 3) the lines are oversized, so they can manage the injection of the 150 Hz current component, and 4) the ST acts as slack bus imposing

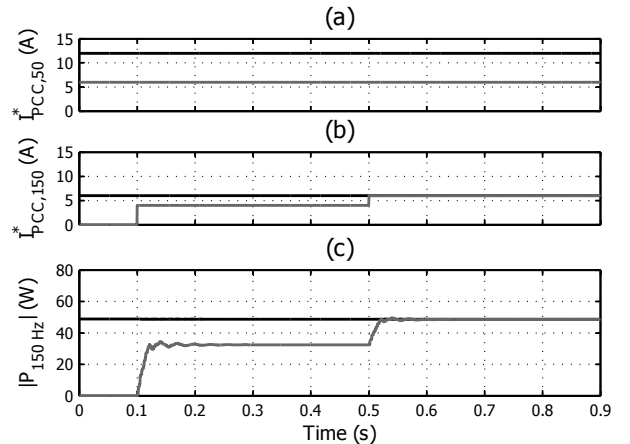


Fig. 5. (a) Amplitude of 50 Hz current reference. (b) Amplitude of 150 Hz current reference. (c) 150 Hz power profile: Phase I (0.1 s - 0.5 s), Phase II (0.5 s - 0.9 s); black: sender, grey: receiver

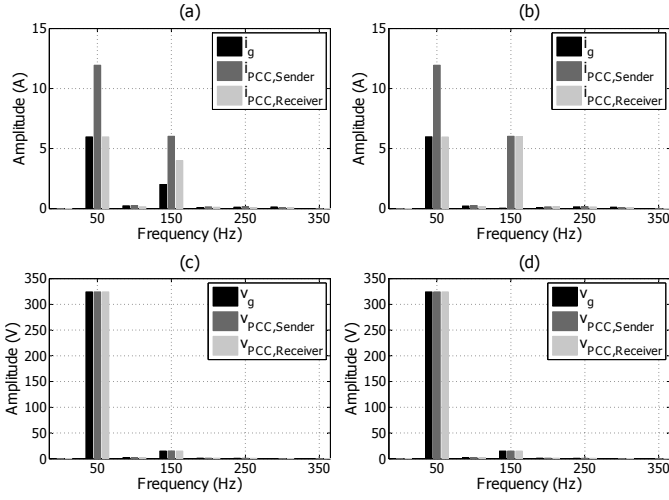


Fig. 6. Spectral analysis of the currents (Phase I: (a), Phase II: (b)) and of the voltages (Phase I: (c), Phase II: (d)) in the steady-state

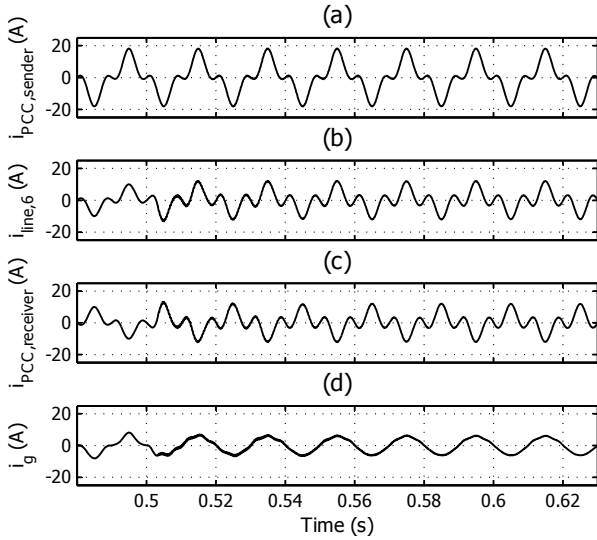


Fig. 7. Behavior at transition from phase I to phase II: (a) Sender current. (b) Line current. (c) Receiver current. (d) Grid current

a fixed 150 Hz voltage and taking in account the remaining losses. These hypotheses avoid the increase of the current and voltage THD, due to the reduction of 150 Hz current withdrawn from the grid. The 150 Hz active power generated from the sender is 9.18 kW, while the power absorbed by the receiver is 6.65 kW, and the ST supplies 0.21 kW the grid

If the overall efficiency of power transfer is defined as the receiver's absorbed power divided by the sum of the sender's generated power and the ST's supplied power, it stands around 70.8%. The remaining 29,2% represents the losses along the lines and the 150 Hz current absorbed by the loads. Table IV shows the voltage and current THD, after the application of the proposed approach. The voltage THD in the grid is in each point below 5%, being in agreement with the standard [24]. The current THD lies around 4%, avoiding great disturbances for the loads.

TABLE IV. HARMONIC DISTORTION OF THE GRID

Load	Voltage THD (%)	Current THD (%)
Industrial 1	4.90	4.24
Residential 1	4.76	4.44
Commercial	3.24	2.88
Residential 2	4.77	4.44
Industrial 2	3.24	2.88
Residential 3	4.77	4.47

Fig. 8 describes respectively the sender's and receiver's instantaneous power (Fig. 8 (a),(c)), the sender's and receiver's imaginary power (Fig. 8 (b),(d)) and the ST instantaneous and imaginary power (Fig. 8 (e)). Fig. 8 verify what can be inferred from the mathematical formulation: a 2nd harmonic component is present in the power profiles, creating oscillating powers. The oscillating component in the instantaneous power is relevant when referred to the two converters (Fig. 8 (a)-(d)), where the capacitors in the DC links works as a storage, but it becomes negligible when referred to the ST (Fig. 8 (e)). The imaginary power, being composed only by an oscillating component, represents only the imaginary power exchanged among the phases, and so it does not involve any power transferred in the grid.

Regarding the impact on the loads, Fig.9 shows the instantaneous and imaginary power profile of the Commercial Load (Fig.9 (a)) and the Residential Load 1 (Fig.9 (b)) placed respectively in bus 5 and 7. The Residential Load 1 has been chosen because its high current and voltage THD, instead the Commercial Load has been chosen because it takes place in the same bus as the receiver. As can be deduced Fig.9 active and reactive absorption of power are not affected by the 150 Hz power transmission. The instantaneous power of the Commercial Load shows how the oscillating power (2nd harmonic component) is far smaller than the active power (constant component). The same results valid for the reactive power absorption. This trend demonstrates how the loads are

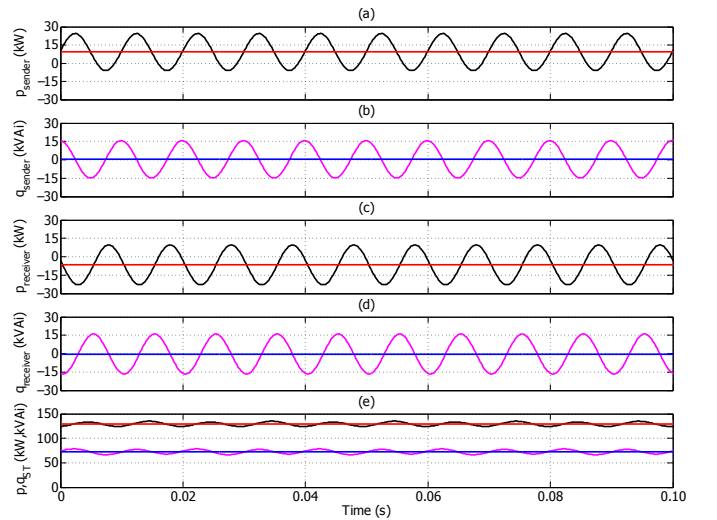


Fig. 8. (a) Three-phase sender's instantaneous and active power. (b) Sender's imaginary and reactive power. (c) Receiver's instantaneous and active power. (d) Receiver's imaginary and reactive power. (e) ST's power; black: instantaneous power, red: active power, magenta: imaginary power, blue: reactive power.

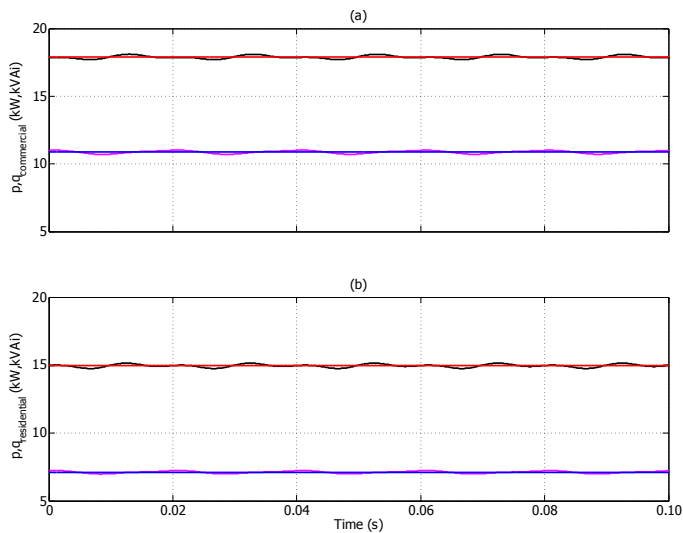


Fig. 9. (a) Three-phase power of Commercial Load. (b) Three-phase power of Residential Load 1; black: instantaneous power, red: active power, magenta: imaginary power, blue: reactive power

not involved in the 150 Hz power transfer, and the impact of the oscillating power is limited to less than 3% of the active and reactive power.

## V. CONCLUSION

This paper has investigated the possibility to manage power transfer at different frequencies in a smart transformer based distribution grid. The presented approach enables the power transfer point-to-point in the grid, exploiting the lower impedance path that the two converters offer to the energy. The resulting impact on the loads is still small in comparison with the power injected and can be reduced further if an optimal synchronization is adopted. This approach shows a promising way to provide service in the future smart grid remaining in compliance with the actual harmonics standards.

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