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Experimental Evaluation of Voltage Unbalance Compensation in an Islanded Microgrid

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Abstract—In this paper, a method for voltage unbalance compensation in an islanded microgrid based on the proper control of distributed generators (DGs) interface converter is proposed. In this method, active and reactive power control loops are considered to control the power sharing among the DGs. Also, a virtual impedance loop and voltage and current proportional-resonant controllers are included. Experimental results show the effectiveness of the proposed method for compensating voltage unbalance to an acceptable level.

I. INTRODUCTION

Distributed Generators (DGs) may be connected individually to the utility grid or be integrated to form a local grid which is called microgrid (MG). The MG can operate in grid-connected (connected to the utility grid) or islanded (isolated from the utility grid) modes [1].

DGs often consist of a prime mover connected through an interface converter (e.g. an inverter in case of dc-to-ac conversion) to the power distribution system (microgrid or utility grid). The main role of this inverter is to control voltage amplitude and phase angle in order to inject the active and reactive power. In addition, compensation of power quality problems, such as voltage unbalance, can be achieved through proper control strategies.

In [2]–[6], some approaches are presented to use the DG for power quality compensation purposes. The control method presented in [2] and [3] is based on using a two-inverter system connecting one in shunt and the other in series to the grid, like a series-parallel active power filter [4]. The main role of the shunt inverter is to control active and reactive power flow, while the series inverter balances the line currents and the voltages at sensitive load terminals, in spite of grid voltage unbalance. This is done by injecting negative sequence voltage. Thus, two inverters are necessary for the power injection and unbalance compensation.

Another method based on injecting negative sequence current by the DG to compensate voltage unbalance has been proposed in [5]. As a result, line currents become balanced in spite of the presence of unbalance loads. However, in the case of severe load unbalances (e.g. one-phase disconnection of a 3-phase load or connection of a single-phase load), the amplitude of the injected current can be very high. Thus, it

will use a large amount of the power and may limit the DG capability to supply active and reactive power.

The approach presented in [6] is based on controlling the DG as a negative sequence conductance in order to compensate the voltage unbalance. This is done by using the negative sequence reactive power to generate the reference conductance. Then, this conductance is multiplied by the negative sequence voltage to produce the compensation reference current. In this way, the effort of unbalance compensation can be shared between the DGs. The compensation reference is added to the output of the voltage control loop. However, such compensation is considered as a disturbance to be rejected by the voltage control loop. Hence, there is a trade-off between unbalance compensation and voltage regulation, which will limit the unbalance compensation capability.

To cope with this, the present paper proposes the direct change of voltage reference to compensate voltage unbalance in a microgrid. In this method, the overall control system is designed in stationary ($\alpha\beta$) reference frame. The control structure consists of the following loops:

- Voltage and current controllers
- Virtual impedance loop
- Active and reactive power controllers
- Voltage unbalance compensator

The details are provided in the next Section.

II. DG INVERTER CONTROL STRATEGY

Fig. 1 shows the power stage of an islanded MG with two DGs and also the proposed control strategy for the DGs inverters. This system consists of a DC prime mover, an inverter and a LC filter for each DG and also an inductor between each DG and load connection point which models the distribution line. Also, a single-phase load is connected between two phases to create voltage unbalance.

All the control loops of Fig. 1 are in $\alpha\beta$ reference frame. The Clarke transformation is used to transform the variables between abc and $\alpha\beta$ frames. The equations (1) and (2) are used for the transformation:

$$x_{\alpha\beta} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot x_{abc} \quad (1)$$

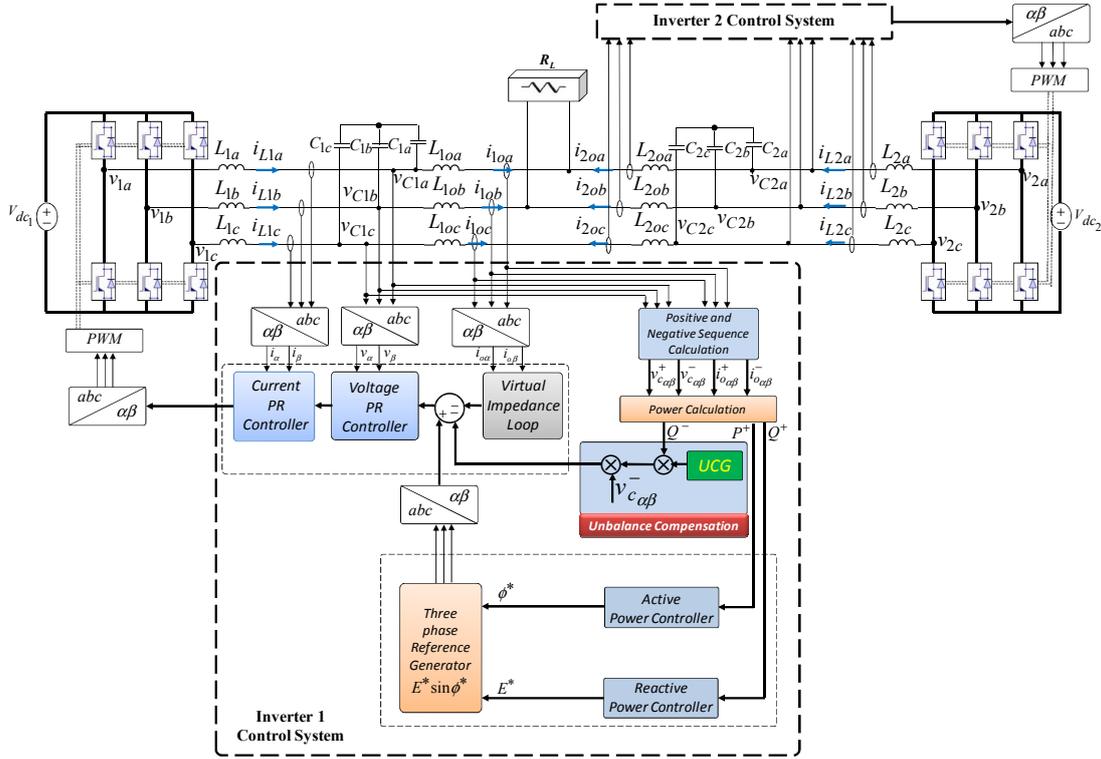


Fig. 1. Power stage and control system of an islanded MG

$$x_{abc} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} x_{\alpha\beta} \quad (2)$$

where x represents a control variable.

In the following Subsections, the details of the inverter control strategy are presented.

A. Active and Reactive Power Control

Considering a DG which is connected to the grid through the impedance $Z\angle\theta$, the active and reactive powers injected to the grid by the DG can be expressed as follows [7]:

$$P = \left(\frac{EV}{Z} \cos\phi - \frac{V^2}{Z} \right) \cos\theta + \frac{EV}{Z} \sin\phi \sin\theta \quad (3)$$

$$Q = \left(\frac{EV}{Z} \cos\phi - \frac{V^2}{Z} \right) \sin\theta - \frac{EV}{Z} \sin\phi \cos\theta \quad (4)$$

where E is the magnitude of the inverter output voltage, V is the grid bus voltage magnitude, ϕ is the load angle (the angle between E and V), and Z and θ are the magnitude and the phase of the impedance, respectively. Considering phase angle of the grid voltage to be zero, ϕ will be equal to inverter voltage phase angle.

Assuming mainly inductive electrical systems, ($Z \approx X$ and $\theta \approx 90$) the active and reactive powers can be expressed as the following equations:

$$P = \frac{EV}{X} \sin\phi \quad (5)$$

$$Q = \frac{EV \cos\phi - V^2}{X} \quad (6)$$

In practical applications, ϕ is normally small; thus, a P/Q decoupling approximation ($\cos\phi \approx 1$ and $\sin\phi \approx \phi$) can be considered as follows [7], [8]:

$$P = \frac{EV}{X} \phi \quad (7)$$

$$Q = \frac{V}{X} (E - V) \quad (8)$$

Thus, active and reactive powers can be controlled by the DG output voltage phase and amplitude, respectively. According to this, the following droop characteristics are considered for the positive sequence active and reactive power sharing between DGs in an islanded MG.

$$\phi^* = \phi_0 - m_P P^+ - m_I \int P^+ dt \quad (9)$$

$$E^* = E_0 - n_P Q^+ \quad (10)$$

where

- E_0 : rated voltage amplitude
- ϕ_0 : rated phase angle ($\int \omega_0 dt$)
- ω_0 : rated frequency
- P^+ : positive sequence active power
- Q^+ : positive sequence reactive power
- m_P : active power proportional coefficient

- m_I : active power integral coefficient
- n_P : reactive power proportional coefficient
- E^* : voltage amplitude reference
- ϕ^* : phase angle reference

In fact, equation (9) acts as a proportional-derivative controller for frequency. The derivative terms (m_p) helps to improve the dynamic behavior of the power control [7]. Also, as it can be seen in equation (10), no integral term is considered in reactive power droop characteristic. Because, in an islanded MG if the reactive power controllers try to share reactive power exactly (achieving zero steady-state error through integral term), voltage becomes unstable [9].

As it can be seen in Fig. 1, E^* and ϕ^* are used to generate the three phase reference voltages of the inverter. These voltages are positive-sequence components, thus positive sequence powers (P^+ and Q^+) are used in equations (9) and (10). As shown in Fig. 1, in order to calculate these powers, it is necessary to extract positive sequence of DG output voltage ($v_{c\alpha\beta}^+$) and current ($i_{o\alpha\beta}^+$). The details are as follows.

1. Positive and Negative Sequence Calculation

The detection of positive and negative sequence voltage and current is performed by using second-order generalized integrators (SOGIs). The details of design and implementation of SOGI is presented in [10]. The SOGI diagram shown in Fig. 2(a) can be expressed as follows

$$S(s) = \frac{y(s)}{x(s)} = \frac{\omega s}{s^2 + \omega^2} \quad (11)$$

where ω is the SOGI resonant frequency. In this way, SOGI acts as an ideal integrator at this frequency. So, a second-order bandpass filter (BPF) with the following transfer function can be achieved as shown in Fig. 2(b).

$$V(s) = \frac{v'_\alpha(s)}{v_\alpha(s)} = \frac{k\omega s}{s^2 + k\omega s + \omega^2} \quad (12)$$

where k is a constant which determines the damping factor of the BPF, chosen as $k = \sqrt{2}$.

Finally, the positive and negative sequences of the voltage and current can be extracted based on the block diagram of Fig. 3, as explained in [11].

2. Power Calculation

According to the instantaneous reactive power theory [12], the instantaneous values of positive sequence active and reactive powers and negative sequence reactive power are calculated by using the following equations:

$$p^+ = v_\alpha^+ i_\alpha^+ + v_\beta^+ i_\beta^+ \quad (13)$$

$$q^+ = v_\beta^+ i_\alpha^+ - v_\alpha^+ i_\beta^+ \quad (14)$$

$$q^- = v_\beta^- i_\alpha^- - v_\alpha^- i_\beta^- \quad (15)$$

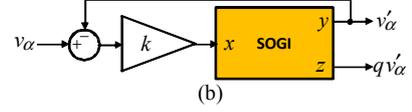
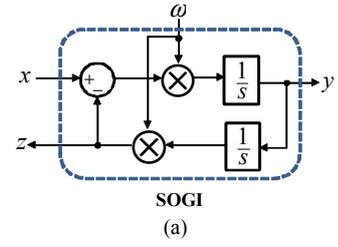


Fig. 2. (a) SOGI structure, (b) BPF block diagram

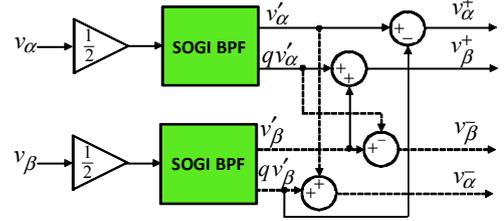


Fig. 3. Block diagram of positive and negative sequence calculation

where “+” and “-” superscripts indicate positive and negative sequence components, respectively.

Then, the dc components of p^+ , q^+ and q^- (P^+ , Q^+ and Q^-) are extracted by using three first-order low pass filters with the cut-off frequency of 0.2Hz.

B. Virtual Impedance Loop

It is known that the addition of virtual resistance control loop makes the oscillations of the system more damped without increasing the power losses [7]. Also, here virtual inductance component is considered to prevent the system impedance to be mainly resistive. In this way, active and reactive powers are pretty decoupled and dependent mainly on the load angle and voltage amplitude, respectively [13].

The virtual impedance in the stationary reference frame can be achieved as shown in Fig. 4, where R_v and L_v are the virtual resistance and inductance values, respectively [13].

As it can be seen in that Figure, the rated frequency (ω_0) is used in this loop, since it has very low difference with operating frequency. Also, a fixed value is preferable to avoid undesirable interactions with the control loops which could lead to instability.

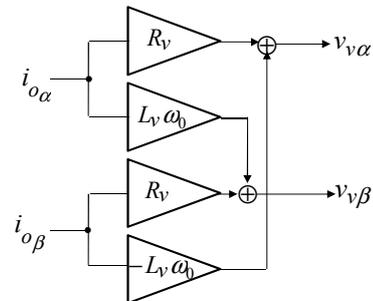


Fig. 4. Virtual impedance block diagram

C. Voltage and Current Proportional-Resonant (PR) Controllers

Due to the difficulties of using proportional-integral (PI) controllers to track non-dc variables, such as the voltage and current in stationary reference frame, proportional-resonant (PR) controllers are usually preferred [14]. In this paper, voltage and current PR controllers are as following:

$$G_V(s) = k_{pV} + \frac{2k_{rV}\omega_c s}{s^2 + 2\omega_c s + \omega_0^2} \quad (16)$$

$$G_I(s) = k_{pI} + \frac{k_{rI}s}{s^2 + \omega_0^2} \quad (17)$$

where

- k_{pV} : voltage proportional coefficient
- k_{rV} : voltage resonant coefficient
- k_{pI} : current proportional coefficient
- k_{rI} : current resonant coefficient
- ω_c : voltage central frequency

The resonant part of the voltage controller is considered as a non-ideal resonant. This structure provides more stability for practical implementation [2].

The Bode diagrams of voltage and current controllers using the parameters listed in Table II are depicted in Figs. 5(a) and 5(b), respectively.

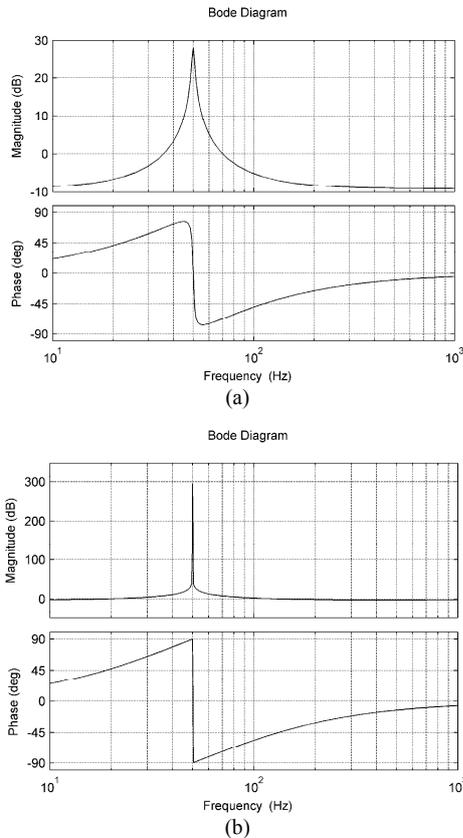


Fig. 5. Bode diagrams: (a) voltage controller, (b) current controller

As can be seen, non-ideal resonant provide a wider resonant peak, therefore is less sensitive to frequency fluctuations. The gain at resonant frequency is finite, however, still high enough to ensure a small tracking error.

As shown in Fig. 1, the voltage controller follows the references generated by virtual impedance, unbalance compensator and droop controllers and generates the current controller reference. The output of the current controller is transformed back to the abc frame to provide the reference voltages for the pulse width modulator (PWM) which controls the switching of the inverter based on this reference.

D. Voltage Unbalance Compensation

Compensation of voltage unbalance can be achieved through negative sequence voltage compensation. As shown in Fig. 1, the output of “Unbalance Compensation” block is injected as a reference for voltage controller. To generate the compensation reference, Q^- is multiplied by a constant (“UCG: Unbalance Compensation Gain”) and also by the negative sequence voltage ($v_{C_{\alpha\beta}}^-$). UCG controls the compensation effort of the DGs.

Since, with compensation of voltage unbalance (decrease of negative sequence voltage) Q^- will decrease, considering Q^- for generation of the compensation reference leads to proper sharing of compensation effort among the DGs.

Also, multiplying with $v_{C_{\alpha\beta}}^-$ ensures that the compensation reference will act in the opposite-phase of the negative sequence voltage (the voltage which should be compensated) considering the negative sign used for the reference injection.

III. EXPERIMENTAL RESULTS

The islanded MG shown in Fig. 1 is implemented for experimental evaluation of voltage unbalance compensation. Experimental setup is shown in Fig. 6.

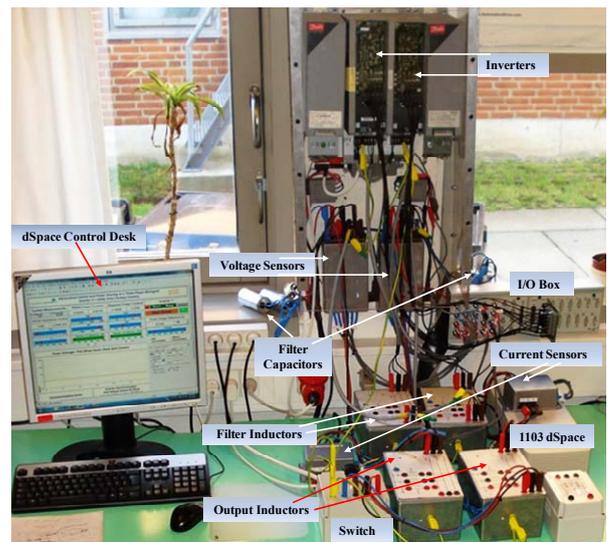


Fig. 6. Experimental Setup

The MG is controlled using an 1103 dSpace card. The switch shown in Fig. 6 is used to connect the DGs to form a MG. The switching frequency of the inverters is 10 kHz.

The power stage parameters of the MG are listed in Table I. In this Table the subscripts a, b and c are not shown, since all the system except the load is balanced. It should be noted that to simulate asymmetrical distribution lines, $L_{1o}=2L_o$ and $L_{2o}=L_o$. The other parameters of the DGs are the same.

Virtual resistance and inductance values were chosen as 1Ω and 8mH , respectively. The parameters of the voltage and current controllers are listed in Table II. UCG is set to 1.5 and the compensation is activated at $t=0.9\text{sec}$.

The results of P^+ , Q^+ , and Q^- sharing between two DGs are shown in Figs. 7-9. As can be seen, before compensation, in spite of asymmetrical output inductors, P^+ and Q^+ are well shared. Also, after the transient state caused by compensation activation, the powers are well shared.

Furthermore, Q^- is significantly decreased as a result of compensation. It shows the effectiveness of the proposed compensation method.

Also, voltage unbalance factor (VUF) of the DGs is shown in Fig. 10. VUF is defined as follows:

$$VUF = \frac{v_{o_{rms}}^-}{v_{o_{rms}}^+} * 100 \quad (18)$$

where $v_{o_{rms}}^-$ and $v_{o_{rms}}^+$ are the rms values of negative and positive sequences of the DG output voltage.

As shown in Fig. 10, as a result of compensation, VUF values are decreased, significantly. Considering the limit of 2% for voltage unbalance which is recommended by IEC [15], the resultant VUF values are satisfactory.

Finally, the waveforms of DGs output voltage, before and after compensation, are shown in Table III. It is obvious that the voltage unbalance is compensated, effectively.

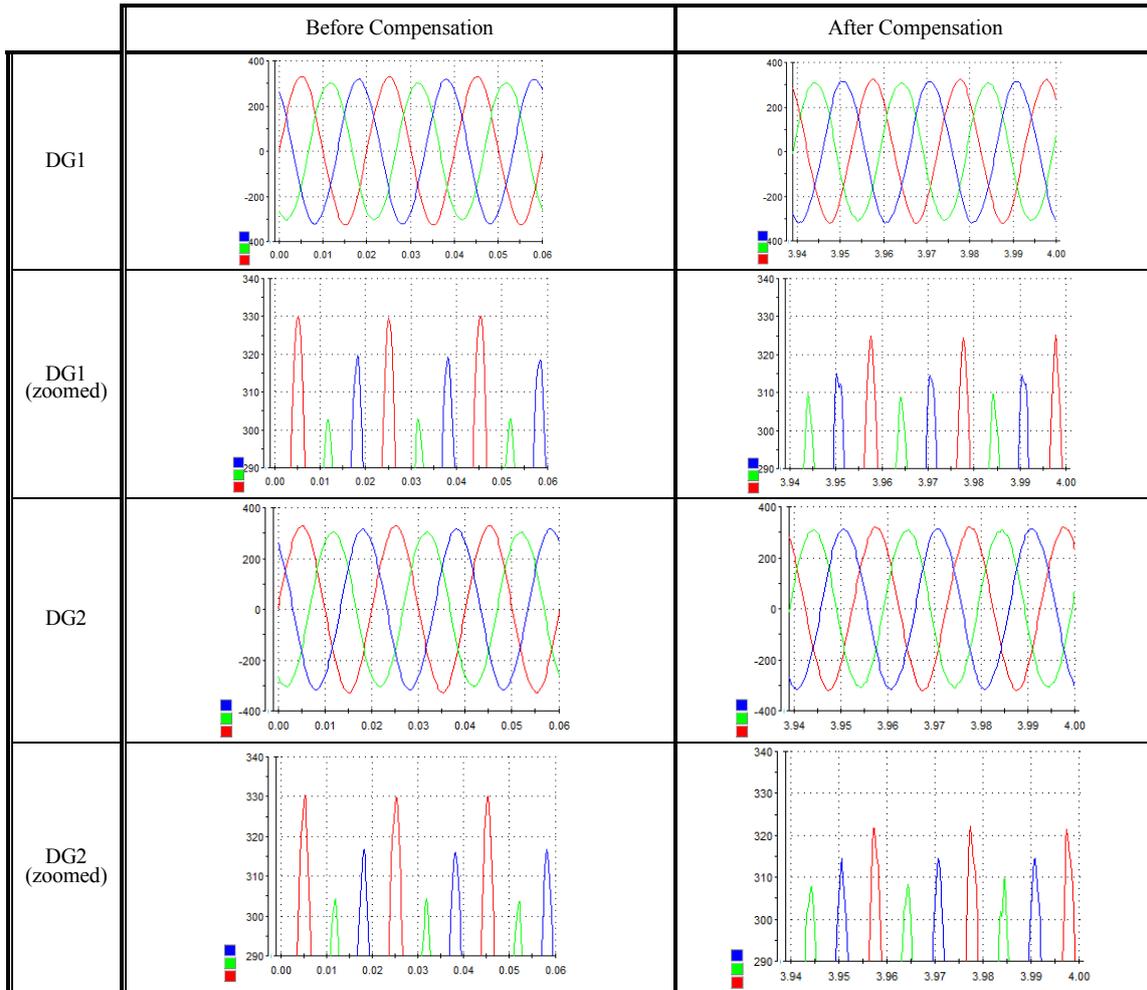
TABLE I. ELECTRICAL SYSTEM PARAMETERS

V_g (V)	L (mH)	C (μF)	L_o (mH)	R_l (Ω)
650	1.8	25	1.8	73

TABLE II. PR CONTROLLERS PARAMETERS

k_{pV}	k_{rV}	ω_c	k_{pI}	k_{rI}
0.35	25	4	0.7	500

TABLE III. DGs OUTPUT VOLTAGE WAVEFORM



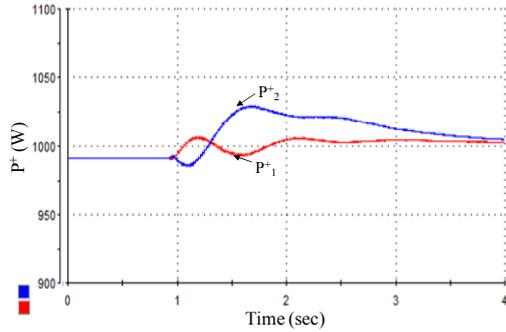


Fig. 7. Positive sequence active power sharing

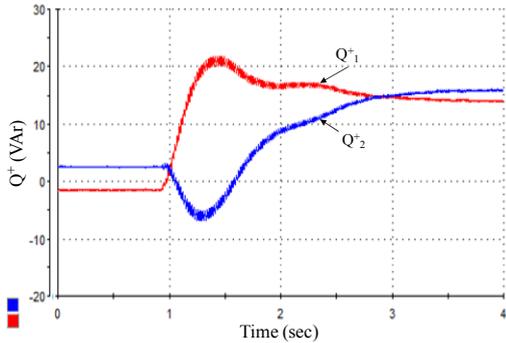


Fig. 8. Positive sequence reactive power sharing

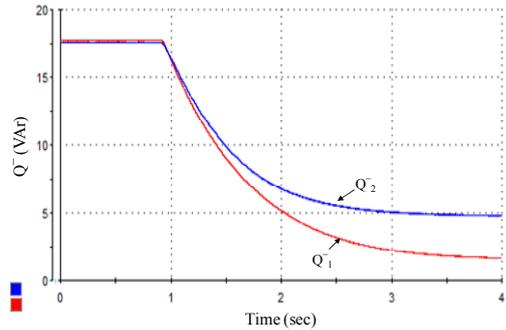


Fig. 9. Negative sequence reactive power sharing

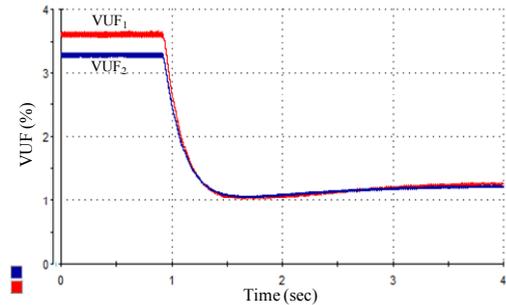


Fig. 10. Voltage unbalance factor

IV. CONCLUSIONS

In this paper a novel control approach to compensate voltage unbalance in a microgrid through proper control of DGs interface converter is proposed.

The method of extracting positive and negative sequence components of voltage and current is described. These values are used to calculate positive sequence active

and reactive powers and negative sequence reactive power. The positive sequence powers are used by the power controllers and negative sequence reactive power is applied for the generation of voltage unbalance compensation reference.

The experimental results show that by implementing this method voltage unbalance is well compensated and also the compensation effort is properly shared between the DGs.

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