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Selective Harmonic Virtual Impedance for Voltage Source Inverters with LCL filter in Microgrids

Mehdi Savaghebi[1], Juan C. Vasquez[2], Alireza Jalilian[1], Josep M. Guerrero[2], and Tzung-Lin Lee[3]
[1]Center of Excellence for Power System Automation and Operation, Iran University of Science and Technology
[2]Institute of Energy Technology, Aalborg University, Denmark
[3]Department of Electrical Engineering, National Sun Yat-sen University, Taiwan
savaghebi@iust.ac.ir, juq@et.aau.dk, jalilian@iust.ac.ir, joz@et.aau.dk, tzunglin.lee@gmail.com

***Abstract*—This paper presents a new control approach for voltage source inverters ended with *LCL* filters for microgrid applications. The control approach consists of voltage and current inner control loops in order to fix the filter capacitor voltage and a virtual impedance loop. The virtual impedance is added in order to mitigate the voltage distortion after the output inductor and improve the load sharing among parallel inverters. A general case with a combined voltage harmonic and unbalance distortion is considered. In such a case, voltage distortion is mitigated by inserting capacitive virtual impedance for negative sequence of fundamental component as well as positive and negative sequences of main harmonic components. Furthermore, resistive virtual impedances are added at these components in order to provide a proper load sharing and make the overall system more damped. Simulation results are presented to demonstrate the effectiveness of the proposed control approach.**

I. INTRODUCTION

RECENTLY, microgrids have been taken more attention in the power electronics research community due to their high potential of supporting the energy responsibility in certain areas [1]. The final approval of the IEEE 1547.4 standard in 2011 has been definitively a big impulse of microgrids. In such a standard, a microgrid is defined as a group of distributed generators and energy storage systems which could operate independently from the main grid. The standard defines the islanded operation of microgrids [2].

In many countries, the distributed generation (DG) equipment, normally connected to the grid, is not allowed to operate in islanded mode due to security reasons. However, new standards and grid codes allow microgrids to operate in either grid-connected or islanded modes. In the grid-connected operation of a microgrid, if the grid power quality is not good, the Microgrid Central Controller can decide to disconnect the microgrids and operate it autonomously. This mode of operation is also named as planned or intentional islanding [3]-[6].

In recent years, the use of *LCL* output filters to connect PWM inverters to the grid has been studied in detail [7]. Most of the works in this field apply grid-connected current-controlled inverters which export the maximum active power given by the prime mover, e.g. photovoltaic systems or wind turbine, by means of a maximum power point tracker (MPPT) algorithm. However, no reactive power and harmonics should be injected for such applications. However, few works have been done using voltage source inverters (VSI) with *LCL* filters for islanded applications, in which normally *LC* filters are used to fully control the voltage in the local bus. Nevertheless, when a number of VSIs are operating in parallel in a microgrid, *LCL* filters are preferred. In this sense, the droop control has been gaining popularity in microgrid applications together with virtual impedance loops, which ensures some impedance between voltage sources. This way, the current flow between inverters is reduced and output impedance magnitude and phase angle can be fixed [4].

Droop control with virtual impedance constitutes a framework for DG inverters control in a microgrid [1]. The virtual impedance is a current feedback loop that adjusts the voltage reference. The speed of this loop is limited by the voltage regulator [8]. Thus, to prevent fast current transients and to accommodate the voltage source to operate together with other voltage sources, such as other DG inverters or the grid, a real physical inductor is used. Thus, *LCL* filter can be used in two steps: an *LC* filter to generate the voltage at the capacitor like in an uninterruptible power supply (UPS) system, and an output *L* that connects the capacitor voltage to the microgrid [4]. This configuration works well when the microgrid supplies linear balanced loads; however, in presence of nonlinear and unbalanced loads, the current flowing through the output inductor (L_o) distorts the voltage at the output of the *LCL* filter.

Some virtual harmonic impedance methods have been proposed to share nonlinear loads between inverters terminated with *LC* filter [8]-[10] taking this idea from variable active-passive reactance (VAPAR) principle in large power systems [11]. However, no solution exists in the literature for three phase inverters with *LCL* filters. In addition, in microgrids with a number of *LCL* terminated inverters, resonance phenomena and whack-a-mole effects may appear when trying to eliminate the corresponding harmonics [12], [13]. The whack-a-mole effect is the phenomenon that appears when one inverter is trying to compensate the harmonics in its terminal, and those harmonics appear in another place of the microgrid or electrical distribution system.

In this paper, a selective virtual harmonic impedance loop is proposed for *LCL* terminated inverters. This loop contributes towards nonlinear load sharing while keeping the distortion of terminal voltage acceptable; thus, avoiding resonances and the whack-a-mole effects in the microgrid.

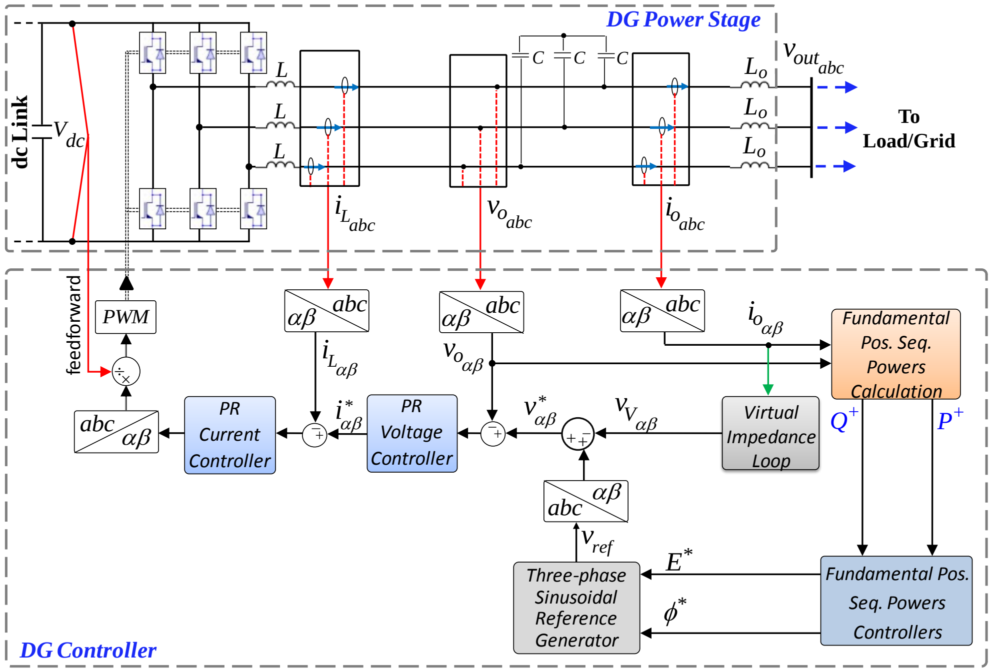


Fig. 1. DG power stage and control system.

II. Voltage Source Inverters with LCL Filters

Fig.1 shows the power stage and control system of a VSI consists of a three phase PWM inverter and an LCL filter. In a microgrid, the VSI can form the output stage of interface converter of a Distributed Generator (DG). The control system is designed in stationary ($\alpha\beta$) reference frame. Thus Clarke equations are applied to transform the voltages and currents between *abc* and $\alpha\beta$ frames.

As it can be seen in Fig. 1, a feedforward loop is included in order to consider small variations of dc link voltage (V_{dc}). The reference of the DG capacitor voltage ($v^*_{\alpha\beta}$) is provided by power controllers and virtual impedance loop. On the other hand, instantaneous capacitor (LC filter output) voltage ($v_{o_{abc}}$) is measured and transformed to $\alpha\beta$ frame ($v_{o_{\alpha\beta}}$). Then, according to $v^*_{\alpha\beta}$ and $v_{o_{\alpha\beta}}$, the reference current ($i^*_{\alpha\beta}$) is generated. Furthermore, LC filter inductor current is transformed to $\alpha\beta$ frame ($i_{L_{\alpha\beta}}$) and controlled by the current controller to generate the reference voltage for the PWM block. In this figure, $v_{out_{abc}}$ represents the output voltage of LCL filter.

By using the power droop controller, fundamental active and reactive powers can be shared properly among the VSI units of the microgrid [4]. However, the harmonic content is not taken into account by this control loop. As mentioned before, even if the voltage loop controls the capacitor voltage, properly; when supplying nonlinear and unbalanced loads, the current flowing through L_o creates voltage distortion at the output of the LCL filter. It is the main problem of VSI with LCL filters.

The virtual impedance is considered at fundamental frequency to enhance the performance of active and reactive power droop controllers [4]. Also, a selective harmonic virtual impedance loop is added to provide load sharing and mitigate output voltage distortion. Proportional-resonant (PR) controllers are applied as voltage and current inner control loops. The resonant terms are tuned at fundamental and main harmonics (3^{rd}, 5^{th} and 7^{th} orders). The details on structure and design of droop power controllers and voltage and current control loops are presented in [14]. The proposed virtual impedance loop is explained in Section III.

III. Selective Virtual Impedance

In the present paper, a general case in which some unbalanced nonlinear loads are supplied in the microgrid is considered. In such a situation, the load current contains fundamental positive and negative sequences as well as positive and negative sequences at harmonic frequencies. It is noteworthy that the normal mode for triplen harmonics is to be zero sequence; but, in unbalanced condition, these harmonics will have positive and negative sequence components [15]. The presence of such components in load current produces respective distortion in the output voltage of LCL filter ($v_{out_{abc}}$) which should be properly mitigated. On the other hand, these current components should be shared among VSIs. Here a selective virtual impedance scheme is presented in order to achieve these goals.

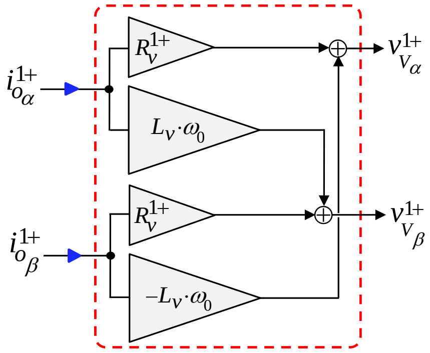


Fig. 2. Basic structure of virtual impedance.

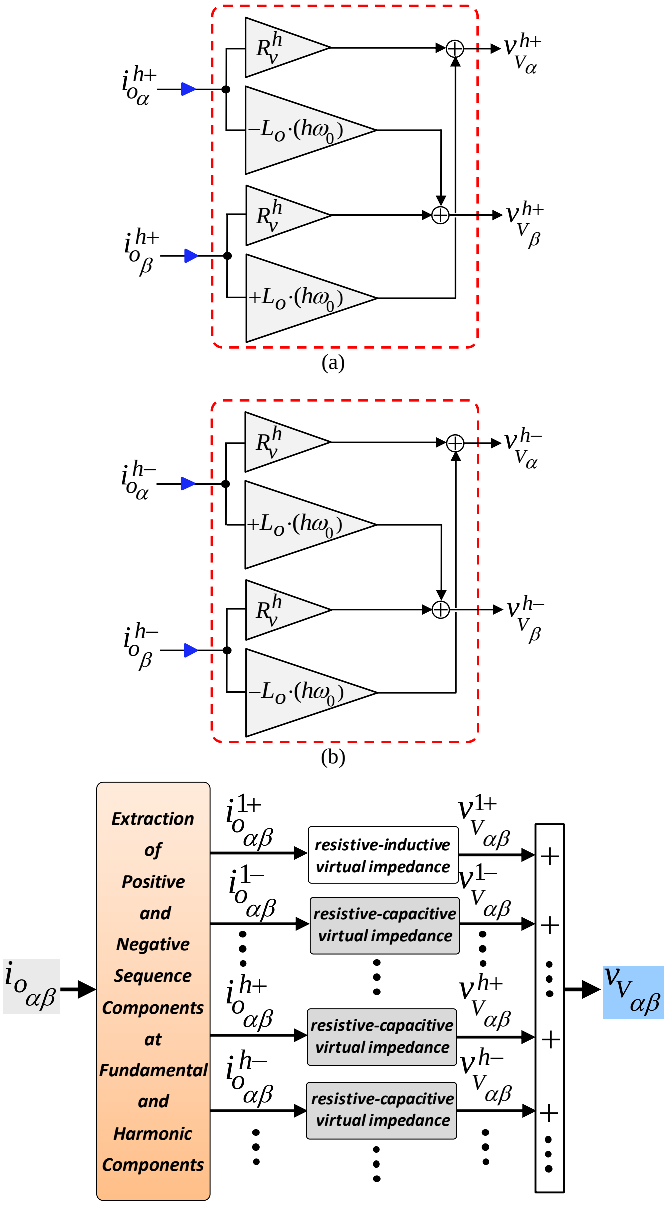


Fig. 3. Proposed virtual impedance scheme.
(a) positive-sequence resistive-capacitive virtual impedance.
(b) negative-sequence resistive-capacitive virtual impedance.
(c) total structure.

The basic structure of virtual impedance for stationary frame applications is depicted in Fig. 2 [16]. Here, this scheme is used for fundamental positive sequence of inverter output current ($i_{o_{\alpha\beta}}^{1+}$). In this figure, R_v^{1+} and L_v are the virtual resistance and inductance for fundamental positive sequence components and ω_0 represents the rated fundamental angular frequency. As mentioned before, fundamental positive sequence component of the load current is shared by droop controllers and this resistive-inductive virtual impedance is considered to enhance the performance of the droop controllers. In fact, the inductive part makes the system impedance inductive enough to have decoupled active and reactive power [9] and the resistive part increases the system damping [17].

Furthermore, in order to provide proper sharing of other current components (here, negative sequence of fundamental component and positive and negative sequences of main harmonic components) and to compensate LCL filter output voltage distortion, it is proposed to apply resistive-capacitive virtual impedances for all current components except fundamental positive sequence one. Considering the basic structure of Fig. 2, the proposed resistive-capacitive virtual impedance scheme for positive and negative sequences of h^{th} current harmonic are respectively shown in Figs. 3(a) and 3(b) where R_v^h is the virtual resistance at h^{th} harmonic. In comparison to the basic structure of Fig. 2, in order to provide capacitive behavior, L_v is replaced by $-L_o$ and in addition, $+h\omega_0$ and $-h\omega_0$ are used instead of ω_0 for positive and negative sequences, respectively. A structure similar to Fig. 3(b) should be used for negative sequence of fundamental component, but, $h\omega_0$ should be replaced with ω_0.

In addition, the total structure of virtual impedance which includes resistive-inductive virtual impedance for fundamental positive sequence component and resistive-capacitive virtual impedances for other components of inverter output current ($i_{o_{\alpha\beta}}$) is presented in Fig. 3(c). As it can be seen in this figure, at first, $i_{o_{\alpha\beta}}$ is fed to the virtual impedance block and its positive and negative sequences at fundamental and harmonic components are extracted. The current components are extracted according to [18]. Then, each current component is fed to respective virtual impedance block. In this figure superscripts "h+" and "h-" are used to indicate positive and negative sequence components of h^{th} harmonic.

In order to clarify the concept, the effect of resistive-capacitive virtual impedance on the output impedance at h^{th} harmonic of LCL terminated VSI is demonstrated in Fig. 4 where $v_o'^{\,h}$ and $Z_o'^{\,h}$ are the output voltage and output impedance of inverter with LC filter at h^{th} harmonic before adding the virtual impedance. These values are very low if voltage and current control loops are properly designed [14].

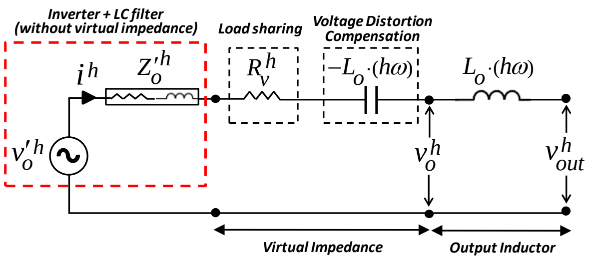


Fig. 4. Effect of resistive-capacitive virtual impedance on output impedance.

In addition, v_o^h, v_{out}^h, i^h and ω represent LC filter output voltage with virtual impedance, LCL filter output voltage, h^{th} harmonic of inverter output current and microgrid operating frequency, respectively. It can be seen in this figure that with negative virtual inductance (equal to virtual capacitance) the harmonic voltage drop on L_o can be compensated. However, addition of R_v^h can increase the distortion of v_{out}^h.

IV. Simulation Results

In order to evaluate the effect of capacitive virtual impedance on enhancement of LCL filter output voltage quality, a simulation study is performed using the islanded microgrid of Fig. 5. As can be observed, two DG units with LC+L_o filters are supplying an unbalanced nonlinear load (a three-phase diode rectifier). It is assumed that rated power of DG_1 interface converter is double of DG_2 respective value. The control and electrical systems parameters can be found in [14] and Table I, respectively.

Three simulation cases are considered:

- Case1 ($0 \le t < 1.5s$)

  Only resistive-inductive virtual impedances for fundamental positive sequence component are present.

- Case2 ($1.5 \le t < 3.5s$)

  Capacitive virtual impedances are added for negative sequence of fundamental component and positive and negative sequences of 3rd, 5th, and 7th harmonics, in order to improve the quality of v_{out_1} and v_{out_2}.

- Case3 ($3.5 \le t < 5s$)

  Resistive virtual impedances are added for negative sequence of fundamental component and positive and negative sequences of 3rd, 5th, and 7th harmonics, in order to improve the load sharing among DGs.

A. Case 1

Three-phase waveforms of $v_{o_1}, v_{o_2}, v_{out_1}$ and v_{out_2} in different simulation cases are presented in Table II. It can be seen that in case 1, v_{o_1} and v_{o_2} are approximately distortion-free due to proper performance of inner loop, but, v_{out_1} and v_{out_2} are noticeably distorted due to voltage drops on L_o.

Table III shows three-phase waveforms of DGs output current as well as phase-a of fundamental positive sequence and third harmonic negative sequence of these currents. Note that third harmonic waveforms are presented in shorter intervals. It can be observed that in this case, DG_2 supplies larger portion of third harmonic negative sequence current while its rating is half of DG_1. It is due to lower impedance between this DG and load bus. Positive and negative sequences of other current harmonic components as well as negative sequence of fundamental component are similarly shared between DGs; consequently, according to Table II, the distortion of v_{out_2} will be higher than v_{out_1}. But, as seen in Table III, fundamental positive sequence component of load current is properly shared by DG units due to good performance of droop controllers. However, the amplitudes of supplied three-phase currents are not in proportion with DGs rated powers.

B. Case 2

It can be seen in Table II that the waveform quality of v_{out_1} and v_{out_2} is noticeably improved by adding capacitive virtual impedances, but, this improvement is achieved at the expense of v_{o_1} and v_{o_2} distortion. This observation can be justified according to Fig. 4. As seen in this figure, voltage drop at h^{th} harmonic on capacitive impedance leads to increase of v_o^h distortion; however, v_{out}^h quality is improved due to compensation of harmonic voltage drop on L_o.

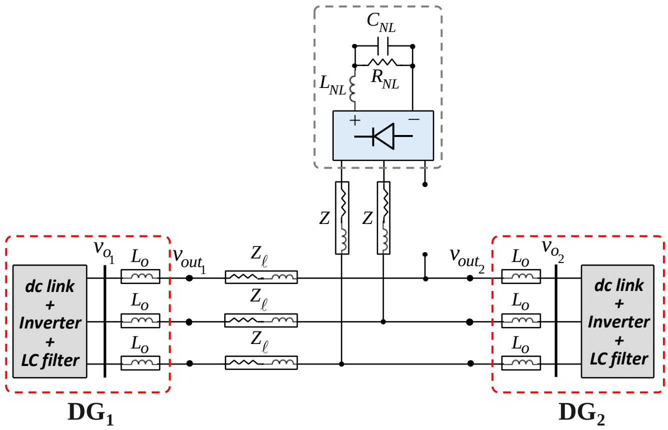


Fig. 5. Test system for simulation studies.

TABLE I
ELECTRICAL SYSTEM PARAMETERS

dc link voltage	LC Filter	Output Inductor	DG_1 / Nonlinear Load Tie Line	Nonlinear Load
V_{dc} (V)	L/C $(mH)/(\mu F)$	L_o (mH)	Z_ℓ / Z (Ω, mH)	C_{NL} / R_{NL} / L_{NL} $(\mu F)/(\Omega)/(mH)$
650	1.8/25	1.8	0.1, 1.8	235/50/0.084

TABLE II

VOLTAGE WAVEFORMS AT DIFFERENT SIMULATION CASES

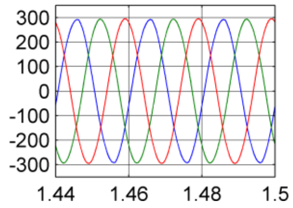
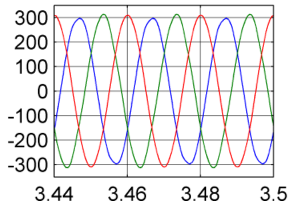
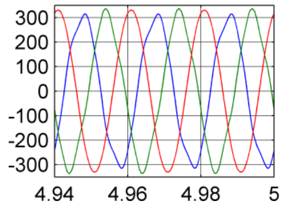
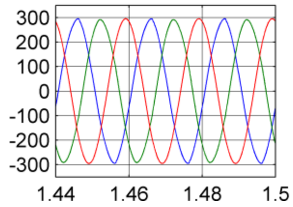
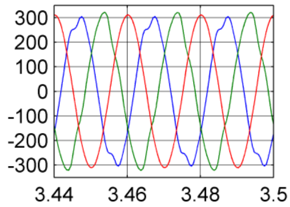
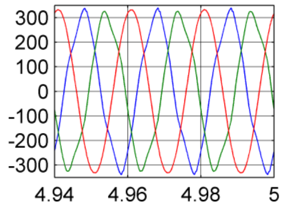
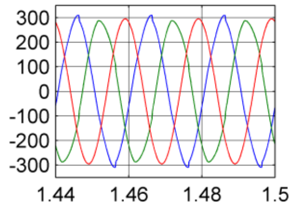
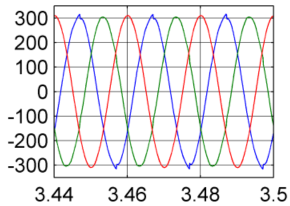
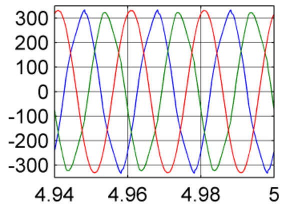
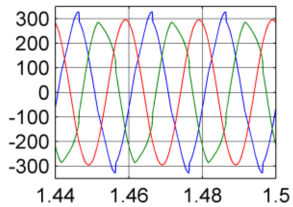
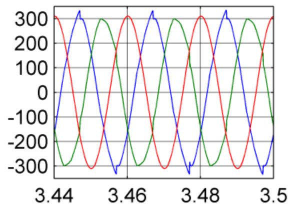
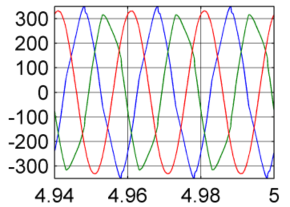
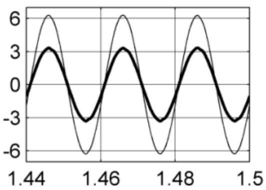
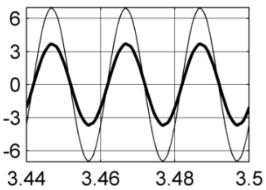
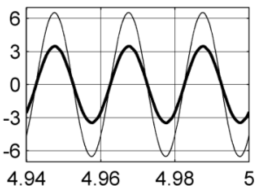
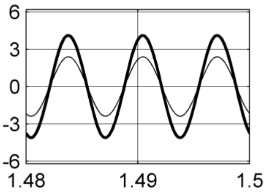
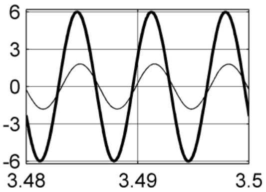
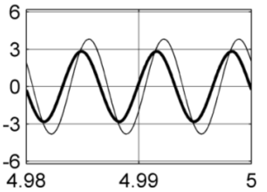
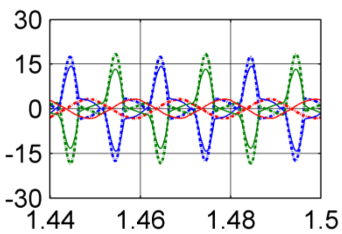
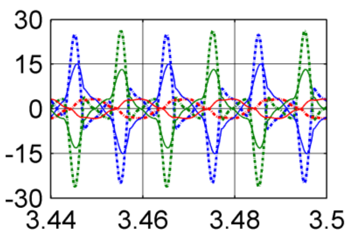
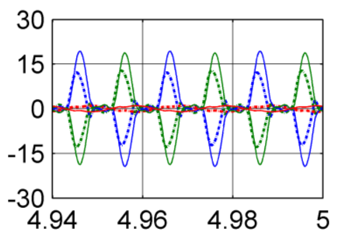
	Case 1	Case 2	Case 3
v_{o_1}			
v_{o_2}			
v_{out_1}			
v_{out_2}			

TABLE III

DGS CURRENT WAVEFORMS AT DIFFERENT SIMULATION CASES

	Case 1	Case 2	Case 3
fundamental pos. seq. components (DG_2: thick line)			
third harmonic neg. seq. components (DG_2: thick line)			
three-phase output currents (DG_2: dashed line)			

Moreover, it can be seen in Table III that as a results of L_o effect compensation (decrease of the impedance seen at negative sequence of fundamental component and positive and negative sequences of harmonics) DG_2 current increases, significantly, since there is no more impedances between this DG and load bus. Fundamental positive sequence components are a little changed. This change is originated from coupling between current components due to nonlinear nature of the load [14]. However, proper sharing of fundamental positive sequence components is maintained in this case.

C. Case 3

As expected, it can be seen in Table III that as a result of virtual resistance addition, the current sharing is improved noticeably. This improvement is achieved by decrease of DG_2 current components (excluding fundamental positive sequence one) and increase of DG_1 current respective components. This fact can be clearly seen about third harmonic components. In addition, fundamental positive sequence component of load current is still shared, properly. However, it can be seen in Table II that the current sharing improvement is achieved at the expense of increasing all voltage distortions.

V. CONCLUSIONS

A resistive-capacitive virtual impedance scheme has been presented for LCL-terminated voltage source inverters. The aim of this scheme is to compensate voltage distortion of LCL filter output voltage and improve the load sharing among DG units of a microgrid. The quality of LCL filter output voltage is important since the sensitive loads may be installed at LCL filter terminal or near to it. Enhancement of LCL filter output voltage quality is achieved at the expense of voltage distortion increase at filter capacitance, thus, in the cases that capacitor voltage quality is also important, a trade-off should be made between capacitor and output voltage quality.

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