International Journal of Innovative Technologies
WWW.IJITECH.ORG
ISSN 2321-8665
Volume.06, Issue.01,
January-June, 2018,
Pages:0384-0389

Harmonic Analysis of Distribution System in Grid-Connected and Islanding Microgrids

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Abstract: To achieve better operation of grid-connected and islanding microgrids, the paper considers a simple harmonic propagation model in which the microgrid is placed at the receiving end of the feeder. the impacts of voltage-controlled and current-controlled distributed generation (DG) units to microgrid resonance propagation are compared. It can be seen that a conventional voltage-controlled DG unit with an LC filter has a short-circuit feature at the selected harmonic frequencies, while a current-controlled DG unit presents an open-circuit characteristic. To mitigate the feeder harmonic distortions, a modified virtual impedance-based active damping method that consists of a virtual resistor and a virtual nonlinear capacitor is also proposed. The virtual capacitor eliminates the impacts of *LCL* filter grid-side inductor and the virtual resistor is interfaced to the receiving end of the feeder to provide active damping service. Due to different behaviors at harmonic frequencies, specific harmonic mitigation methods shall be developed for current controlled and voltage-controlled DG units, respectively. This paper also focuses on developing a voltage-controlled DG unit-based active harmonic damping method for grid-connected and islanding microgrid systems. Simulated results have been obtained from a single-phase low voltage microgrid.

Keywords: Active Power Filter, Distributed Power Generation, Droop Control, Grid-Connected Converter, Microgrid, Power Quality, Renewable Energy System, Resonance Propagation, Virtual Impedance.

I. INTRODUCTION

The microgrid paradigm is emerging as an attractive way to future smart distribution grids, thanks to its capability to operate in both grid-connected and islanded modes. The dynamic islanding operations bring more flexibility on the integration of Distributed Generation (DG) units, and also provide a more reliable electricity service. On the other hand, during the islanded operations, the microgrid usually becomes much weaker and more sensitive to power quality disturbances. Thus, the harmonic distortion tends to be more apparent in an islanded microgrid. Furthermore, since the use of LCL-filters is gaining a wide acceptance in grid connected converters, the aggregated shunt capacitance for a number of LCL-filters may lead to harmonic resonance with the line inductance, and the consequent harmonic voltage amplification on a distribution feeder. Hence, stringent demands are being imposed on the ancillary services of inverter-interfaced DG units, such as the mitigation of circulating harmonic current in multiple DG units, harmonic voltage reduction and harmonic resonance damping. To avoid the adoption of passive damping equipment, various types of active damping methods have been developed. Among them, the resistive active power filter (R-APF) is often considered as a promising way to realize better performance. Conventionally, the principle of R-APF is to emulate the behavior of passive damping resistors by applying a closed-loop current-controlled method (CCM) to power electronics converters.

In this control category, the R-APF can be simply modeled as a virtual harmonic resistor if it is viewed at the distribution system level. Additionally, a few modified R-APF concepts were also developed in the recent literature. In the discrete tuning method was proposed to adjust damping resistances at different harmonic orders. Accordingly, the R-APF essentially works as a nonlinear resistor. In the operation of multiple R-APFs was also considered, where an interesting droop control was designed to offer autonomous harmonic power sharing ability among parallel R-APFs. The idea of Resistive-Active Power Filter (R-APF) is implemented based on a high-bandwidth current controller, where DG inverters are controlled to behave as resistors at harmonic frequencies, such that harmonic resonances and voltage distortions can be damped. To autonomously share harmonic currents, a droop relationship between the distorted power of a DG inverter and the controlled harmonic resistance is built. However, it has been shown that only the output voltage of a DG unit is regulated in this method, whereas the voltage at the Point of Connection (PoC) tends to be undamped in the presence of grid-side inductance. Another popular scheme is based on the virtual output impedance concept, where a load current feed forward loop is introduced together with a high bandwidth output voltage controller. Thus, either the virtual inductance or the virtual resistance can be synthesized at the harmonic frequencies.

It is essentially a frequency-dependent voltage droop with the output harmonic currents. As a consequence, the additional harmonic voltage distortions are inevitably increased, and even become more severe when a large virtual inductance is needed to attenuate the differences among the grid-side inductances of DG units. To alleviate the adverse effect of the grid-side inductance, a PoC voltage feed forward control scheme is developed recently. With a positive gain G in the PoC voltage feed forward loop, the harmonic impedance seen from the PoC of a DG inverter can be scaled down by 1/(1+G). Nevertheless, the performance of this scheme is limited on the harmonic resonance damping due to the absence of additional harmonic resistance. To achieve better operation of grid-connected and islanding microgrids, the paper considers a simple harmonic propagation model in which the microgrid is placed at the receiving end of the feeder. To mitigate the feeder harmonic distortions, a modified virtual impedance-based active damping method that consists of a virtual resistor and a virtual nonlinear capacitor is also proposed. The virtual capacitor eliminates the impacts of LCL filter grid-side inductor and the virtual resistor is interfaced to the receiving end of the feeder to provide active damping service. Simulated results are provided to confirm the validity of the proposed method.

II. SYSTEM MODELING

During the islanded operation, microgrid voltages usually becomes more sensitive to harmonic currents produced from the nonlinear loads, due to the limited power capacity of DG units and the low short-circuit ratio. Moreover, the presence of shunt capacitors tends to result in harmonic resonance and propagation throughout the microgrid. As a consequence, the mitigation of circulating harmonic current among all the DG units is needed to prevent overloading of some DG inverters, and meanwhile, proper resonance damping measures are also important to suppress harmonic voltage amplifications. Fig. 1 illustrates an example of a low-voltage microgrid dominated by multiple inverter-interfaced DG units. A static switch is used to dynamically disconnect the microgrid from the upstream distribution system during abnormal conditions.

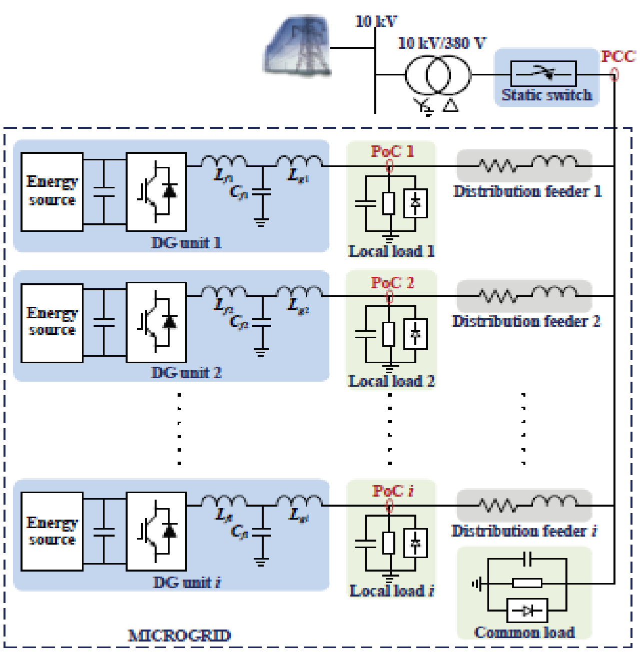


Fig.1. A sample low-voltage microgrid dominated with multiple inverter interfaced DG units.

For the local and common loads, the diode rectifiers are used to denote the nonlinear loads, whereas the shunt capacitors represent the aggregated effect of capacitive loads and the capacitors in the LCL-filters of the grid-connected converters like battery chargers and active front-end rectifiers. For the sake of simplicity, this paper only adopts a simple microgrid configuration to demonstrate how the microgrid power quality is affected by resonancepropagation. In addition, this paper also assumes that shunt capacitor banks and parasitic feeder capacitances are evenly distributed in the feeder. Fig. 2 illustrates the configuration of a single-phase microgrid system, where a few DG units are interconnected to the point of common coupling (PCC) through a long underground feeder. Note that the static transfer switch (STS) controls the operation mode of the microgrid. When the main grid is disconnected from the microgrid, the PCC nonlinear loads shall be supplied by the standalone DG units.

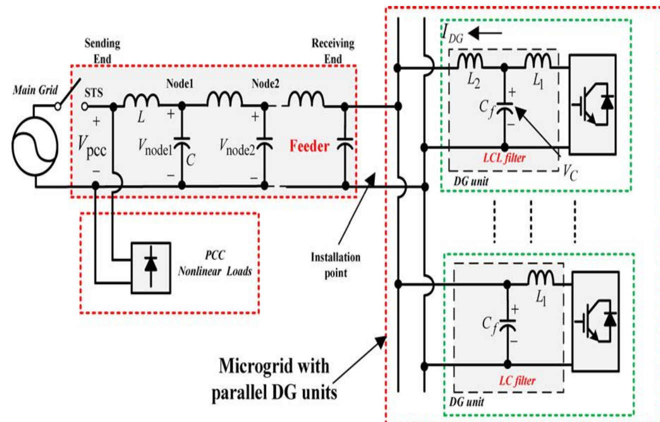


Fig.2. Simplified one-line diagram of a single-phase microgrid.

For a long feeder, as illustrated in Fig2, lumped parameter model is not able to describe its resonance propagation characteristics. Alternatively, the distributed parameter model was discussed, where the voltage distortions at PCC induce a harmonic voltage standing wave along the feeders. To make the discussion more straightforward, we assume that the microgrid in the feeder receiving end only consists of one DG interfacing converter. In the next section, the modeling of resonances in multiple DG-unit-based microgrid is discussed. The previous section focuses on the analysis of grid-tied DG units. For an islanding microgrid system, the VCM operation of DG units is needed for direct voltage support. To the best of the authors' knowledge, the quantitative analysis of islanding microgrid harmonic propagation is not available. By further utilizing the resonant controllers to avoid the derivative operation, the paper proposes a nonlinear virtual capacitor control method instead of the use of negative virtual inductor. This is because the impedance of a capacitor also has 90° lagging phase angle, which is the same as that in a negative inductor. However, for a capacitor with fix capacitance, its impedance magnitude is in inverse proportion to harmonic orders.

This feature is in contrast to the characteristics of a virtual inductor. With this modified outer loop controller, the DG unit fundamental voltage tracking and harmonic virtual impedance regulation can be realized separately. The detailed DG controller with the control of virtual nonlinear capacitor can be seen that the derivative operator in Fig. 3. In the revised controller, the harmonic voltage references associated with virtual resistor and virtual capacitor are only regulated by the harmonic resonant controllers.

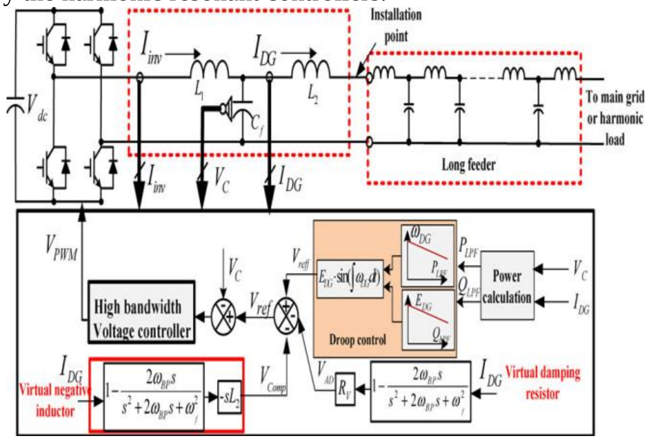


Fig3. Mitigation of distribution feeder harmonic propagation using virtual resistor and virtual negative inductor.

In this paper, a small proportional gain is selected to ensure that there is no noticeable coupling between the fundamental and the harmonic DG voltage tracking. With aforementioned efforts, the derivative operation is successfully avoided by using the proposed virtual nonlinear capacitor.

III. SIMULATION RESULTS

Simulated results have been obtained from a single-phase low voltage microgrid as shown in Figs.4 to 14. To emulate the behavior of six kilometers feeder with distributed parameters, a DG unit with an LCL filter is connected to PCC through a ladder network with six identical LC filter units. Each LC filter represents 1 km feeder.

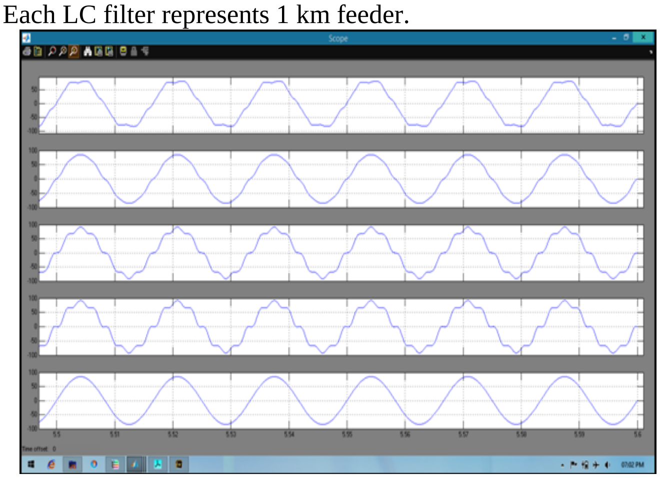


Fig.4. Harmonic voltage amplification during a single DG unit grid connected operation (without damping) (a) PCC voltage (b) node 1 voltage (c) node 3 voltage (d) node 5 voltage (e) DG unit filter capacitor voltage.

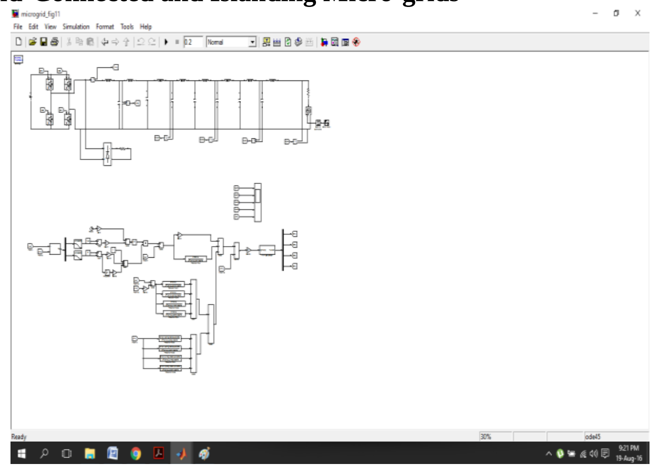


Fig.5. simulation circuit of harmonic voltage amplification during a single dg unit grid connected operation (with virtual nonlinear capacitor and resistor based active damping).

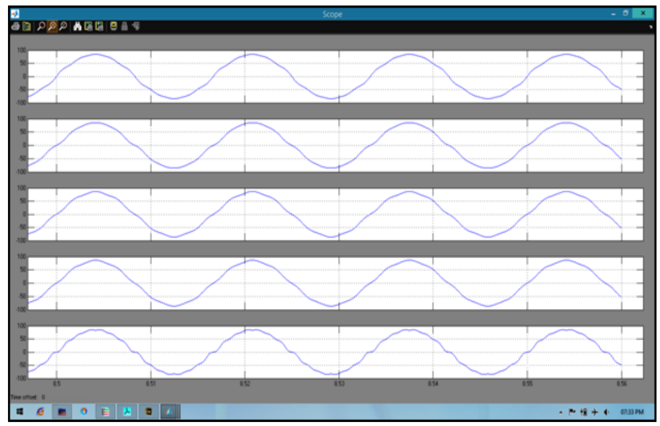


Fig.6. Harmonic voltage amplification during a single DG unit grid connected operation (with virtual nonlinear capacitor and resistor based active damping) (a) PCC voltage (b) node 1 voltage (c) node 3 voltage (d) node 5 voltage (e) DG unit filter capacitor voltage.

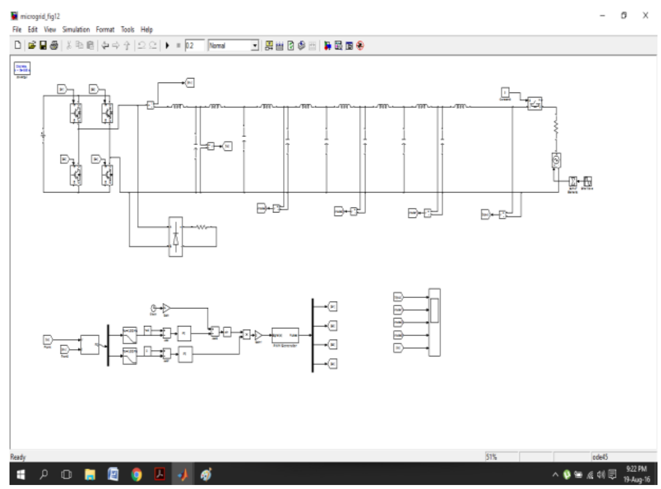


Fig.7. simulation circuit of harmonic voltage amplification during a single dg unit islanding operation (without damping).

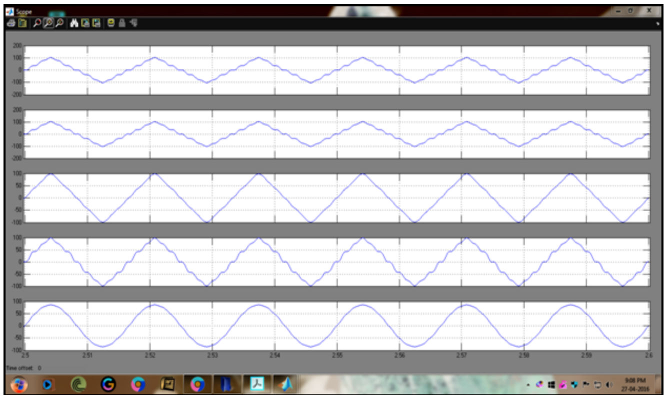


Fig.8. Harmonic voltage amplification during a single DG unit islanding operation (without damping) (a) PCC voltage (b) node 1 voltage (c) node 3 voltage (d) node 5 voltage (e) DG unit filter capacitor voltage.

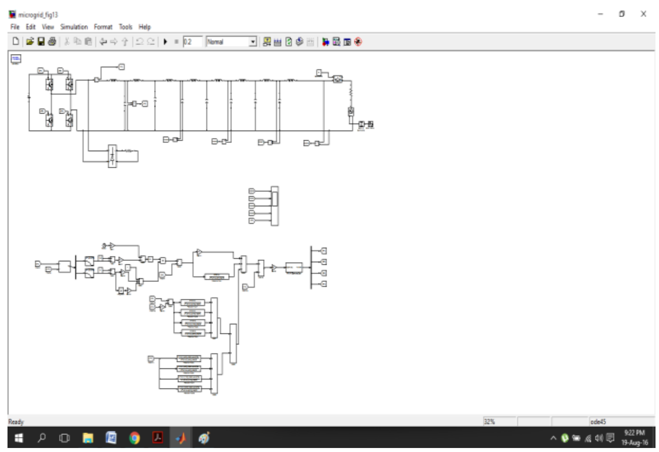


Fig.9. simulation circuit of harmonic voltage amplification during a single dg unit islanding operation (with virtual nonlinear capacitor and resistor based active damping).

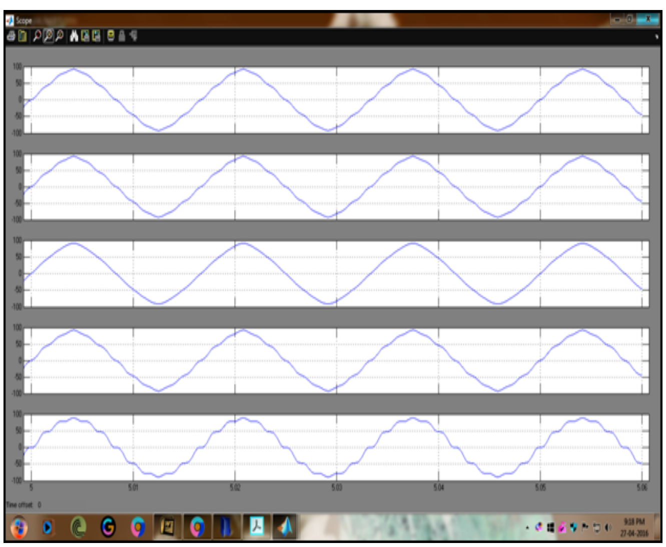


Fig.10. Harmonic voltage amplification during a single DG unit islanding operation (with virtual nonlinear capacitor and resistor based active damping) (a) PCC voltage (b) node 1 voltage (c) node 3 voltage (d) node 5 voltage (e) DG unit filter capacitor voltage.

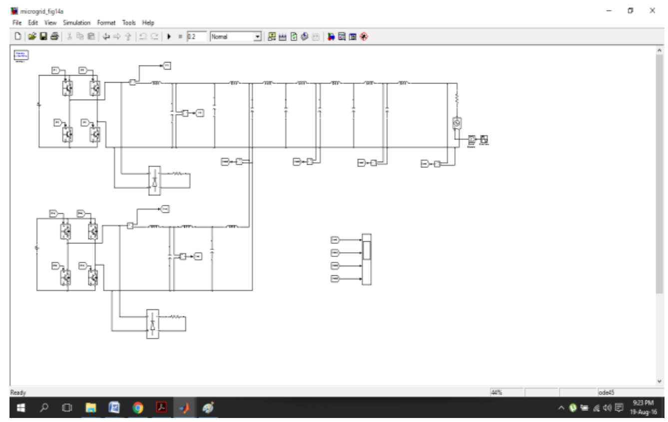
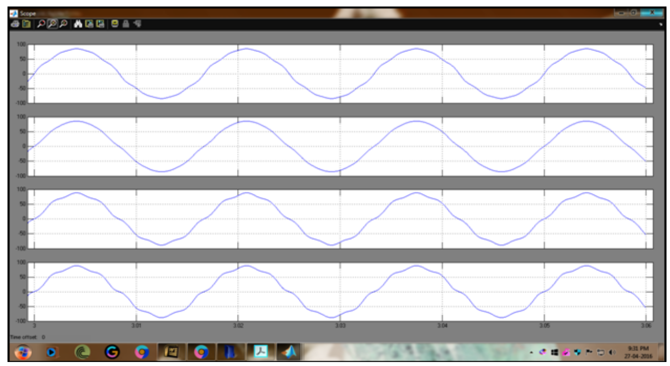
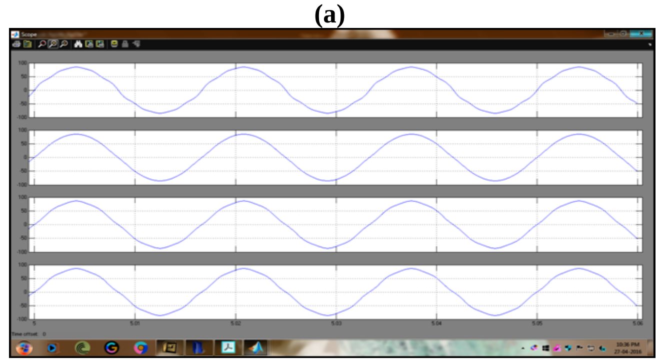


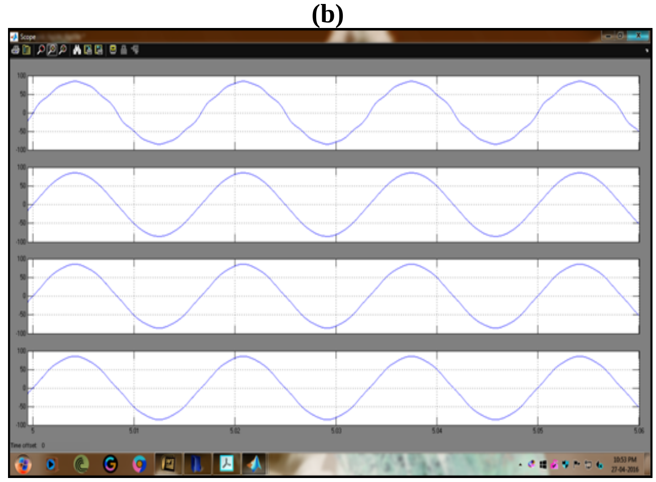
Fig.11. Harmonic voltage amplification along the feeders (grid-tied operation of two parallel DG units).



(a)



(b)



(c)

Fig.12. Harmonic voltage amplification along the feeders (grid-tied operation of two parallel DG units).

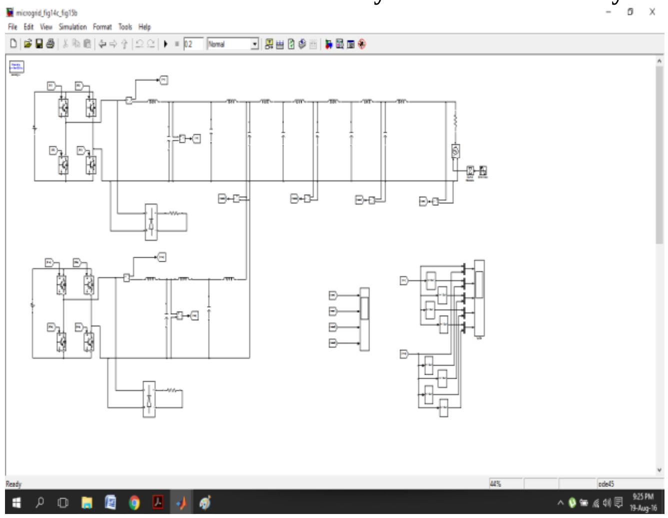
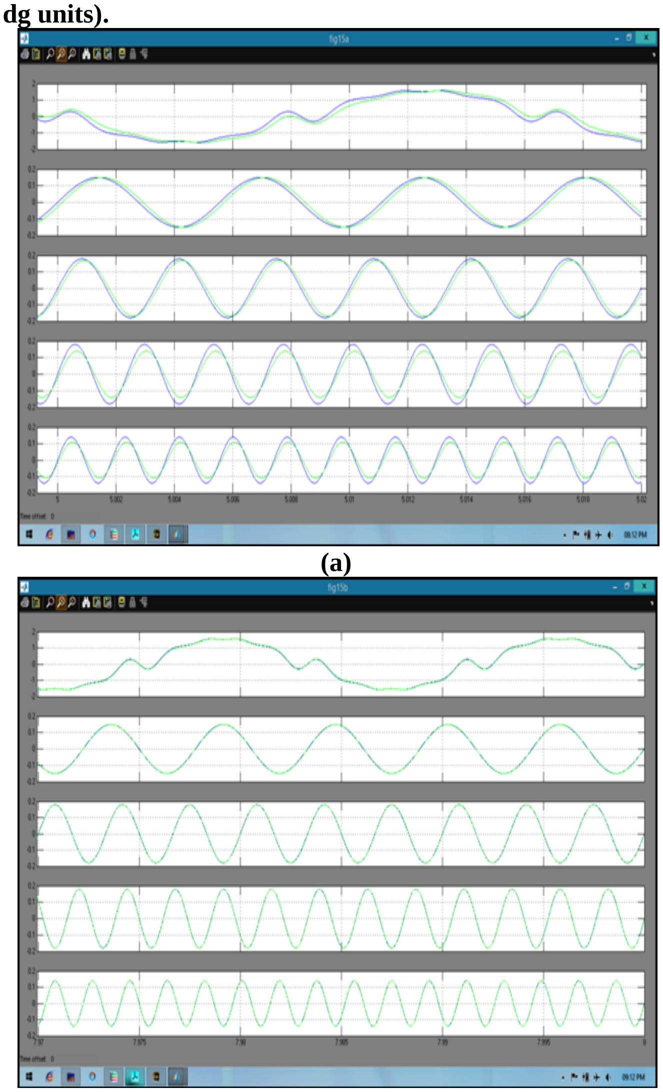


Fig13. DG unit 1 and DG Unit 2 line currents and their harmonic components (grid-tied operation of two parallel dg units).



(a)

(b)

Fig.14. DG Unit 1 and DG unit 2 line currents and their harmonic components (grid-tied operation of two parallel dg units).

IV. CONCLUSION

In this paper, a microgrid resonance propagation model is analyzed. To dynamically mitigate the resonance using DG units, an improved DG unit control scheme to uses the concept of virtual impedance is proposed. Particularly, the capacitive component of the proposed nonlinear virtual impedance is used to balance the impact of DG unit LCL filter grid-side inductor. The resistive component is accountable for active damping. With appropriately controlled DG equivalent harmonic impedance at chosen harmonic frequencies, the proposed method can also reduce the harmonic circulating current among multiple DG units with mismatched output filter parameters. Comprehensive simulations are conduct to confirm the validity of the proposed method.

V. REFERENCES

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