A VOLTAGE-CONTROLLED DG UNIT-BASED DAMPING METHOD FOR MICRO GRID

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Abstract: ***Islanded operation, due to the effects of mismatched line impedance, the reactive power could not be shared accurately with the conventional droop method. To improve the reactive power sharing accuracy, this paper proposes an improved droop control method. The proposed method mainly includes two important operations: error reduction operation and voltage recovery operation. The sharing accuracy is improved by the sharing error reduction operation, which is activated by the low-bandwidth synchronization signals. However, the error reduction operation will result in a decrease in output voltage amplitude.***

Therefore, the voltage recovery operation is proposed to compensate the decrease. The needed communication in this method is very simple, and the plug-and-play is reserved. Simulations and experimental results show that the improved droop controller can share load active and reactive power, enhance the power quality of the micro grid, and also have good dynamic performance.

IndexTerms - Distributed Generation (DG), Micro Grid, Maximum Power Point (MPP), Voltage-controlled method, LCL filter

I. INTRODUCTION

The increasing application of nonlinear loads can led to significant harmonic pollution in a power distribution system. The harmonic distortion may excite complex resonances, especially in power systems with underground cables or subsea cables. In detail, these cables with nontrivial parasite shunt capacitance can appearance an *LC* ladder network to intensify resonances. In arrange to mitigate structure resonances, damping resistors otherwise passive filters can be located in the distribution networks [1,2]. Nevertheless, the mitigation of resonance propagation using passive components is subject to a few well understood issues, such as power loss and additional investment. Moreover, a passive filter may even bring additional resonances if it is designed or installed without knowing detailed system configurations.

To avoid the adoption of passive damping equipment, various types of active damping methods have been developed [3,4]. 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 [5-8]. In this control category, the R-APF can be simply modeled control was designed to offer autonomous harmonic power sharing ability among parallel R-APFs. On the other hand, renewable energy source (RES) based distributed generation (DG) units have been adopted to form flexible micro grids and their interfacing converters also have the opportunity to address different distribution system power quality issues [9,10]. For current-controlled DG units, the auxiliary R-APF function can be seamlessly incorporated into the primary DG real power injection function by modifying the current reference [11]. But, conventional CCM can only just provide direct voltage support throughout microgrid islanding operation. To overcome this limitation, an enhanced voltage-controlled method (VCM) was recently proposed for DG units with high-order *LC* or *LCL* filters [12].

Islanded Mode Piagi and Lasseter [10] argued that the intentional islanding of generation and loads has the potential to provide a higher local reliability than that provided by the power system as a whole. Micro grids can operate either interconnected to the main distribution grid, or even in isolated mode [13]. From the grid‘s point of view, a micro grid can be operated within a power system as a single aggregated load and as a small source of power and other services supporting the network. For a customer, it is a low voltage distribution service with additional features like increase in local reliability, improvement of voltage and power quality, reduction of emissions, decrease in cost of energy supply etc. With the advent of renewable technology, researchers and designers have made remarkable progress in the development of different islanded hybrid system based algorithms [14]. A control scheme is proposed for a three phase isolated photovoltaic (PV)-diesel micro grid without energy storage element [15]. The scheme aims to: track maximum power from the PVA, regulate the load voltage, compensate the load unbalance viewed by the diesel generator, and to control the diesel-engine speed. Below block diagram of one- line single phase micro grid the virtual capacitors eliminate the impact of LCL filter grid-side inductor as well as the virtual resistor is interfaced to the receiving end of the feeder to give active damping service. This is due to increase in harmonics drastically. According to the Electric Power Research Simulated results are provided to confirm the validity of the proposed method is figure 1.

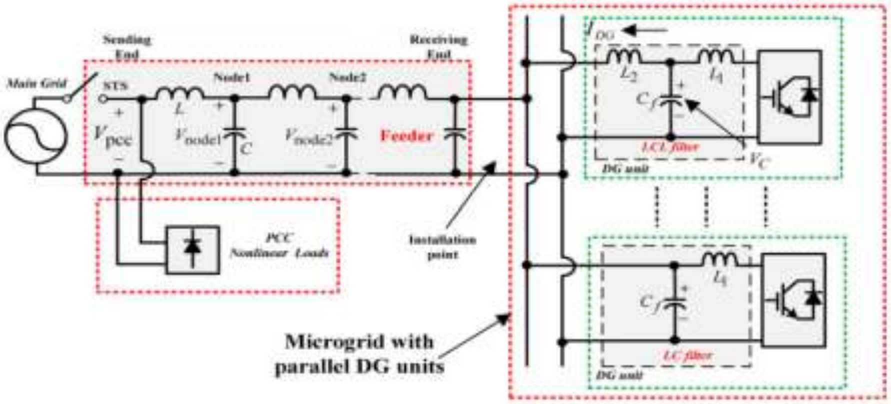

Fig.1. Simplified one-line diagram of a single-phase micro grid

II. DISTRIBUTION SYSTEM WITH MULTIPLE DGS

Distributed otherwise dispersed generation may be defined as generating resources further than central generating stations to placed close to load being served, usually at customer site. It serve as an alternative to or improvement of the traditional electric power system. The normally used distributed resources are wind power, photo voltaic, hydro power. The figure shows the single line diagram of the distribution system with multiple DGs. Small localized power sources, usually known as "Distributed Generation" (DG), have suit a popular alternative to bulk electric power generation. There are many reasons for the growing popularity of DG; however, on top of DG tending to be more renewable, DG can serve as a cost effective alternative to major system upgrades for peak shaving or enhancing load capacity margins. Additionally, if the needed generation facilities could be constructed to meet the growing demand, the entire distribution and transmission system would also require upgrading to handle the additional loading. Therefore, constructing additional power sources and upgrading the transmission system will take significant cost and time, both of which may not be achievable.

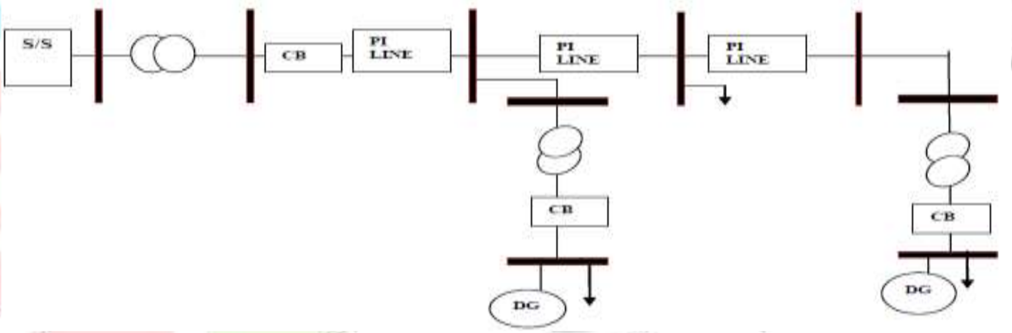

Fig.2. Single line diagram of Distributed system with multiple DG

2.1 DROOP CONTROL STRATEGIES IN DG'S

Conventional electric power systems are facing continuous and rapid changes to alleviate environmental concerns, address governmental incentives, and respond to the consumer demands. The notion of the smart grid has recently emerged to introduce an intelligent electric network. Improved reliability and sustainability are among desired characteristics of smart grid affecting the distribution level. These attributes are mainly realized through micro-grids which facilitate the effective integration of Distributed Energy Resources (DER). Micro-grids can operate in both grid-connected and islanded operating modes. Proper control of micro-grid is a prerequisite for stable and economically efficient operation.

2.2 DROOP CHARACTERISTIC TECHNIQUES

The droop control method has been referred to as the independent, autonomous, and wireless control due to elimination of intercommunication links between the converters. Improved reliability and sustainability are among desired characteristics of smart grid affecting the distribution level. These attributes are mainly realized through micro-grids which facilitate the effective integration of Distributed Energy Resources (DER). The conventional active power control (frequency droop characteristic) and reactive power control (voltage droop characteristic), those illustrated in Fig. 2 is used for voltage mode control. The conventional active power control (frequency droop characteristic) and reactive power control (voltage droop characteristic), those illustrated in Fig 2 is used for voltage mode control.

Principles of the conventional droop methods can be explained by considering an equivalent circuit of a VSC connected to an AC bus. If common AC bus voltage $V_{com}\angle 0$ is and the converter output impedance and the le impedance are lumped as a single effective line impedance of $Z\angle\theta$. The complex power delivered to the common AC bus is calculated as

$$S = P + jQ = VI^* \qquad (1)$$

Where,

$$I^* = (\bar{E} - \bar{V} \quad /\bar{Z})^* \qquad (2)$$

Putting (2) in (1),

$$\text{S} = \frac{Eve^{(\theta-\delta)}}{z} = \frac{V^2 e^{j\theta}}{z} \qquad (3)$$

Applying Euler's formula on equation (3), results in the following equations for active and reactive power:

$$P = \frac{EV\ COS(\theta-\delta)}{Z} - \frac{V^2\ COS\theta}{Z} \qquad (4a)$$

$$Q = \frac{EVsin(\theta-\delta)}{Z} - \frac{V^2 sin\theta}{z} \qquad (4b)$$

Where Z=R+jX and θ = 90°.

Considering small line length the phase angle separation δ is taken as a small value. Hence, sinδ = δ and cosδ= 1. With X>>R, (4a) and (4b) can be written as a system of observing the parameters.

$$\text{P} = \frac{EVCOS\delta}{X} - \frac{V^2}{X} \sim \frac{EV}{X} - \frac{V^2}{X} \qquad (5)$$

Therefore, from (4) and (5) it can be concluded that active power (P) can be varied by changing the angle $\delta$and the reactive power can be controlled by changing the voltage E. This results in the decoupling of the active and reactive power and hence they can be controlled separately. In an islanded Microgrid due to the lack of communication channel each of the DGs are not aware of the phase angle information of other DGs. Therefore, frequency droop is used as the conventional method for load sharing.

2.2.1 FREQUENCY DROOP

As frequency ω can be represented as change of the angle (dδ/dt), the active power (P) can be controlled by controlling the frequency ω and the reactive power (Q) by varying the voltage (E) as per (4) and (5) therefore the conventional frequency voltage droop characteristics can be expressed as:

$$\omega = \omega_0 - mP \qquad (6)$$

$$E = E_0 - nQ \qquad (7)$$

Where P and Q are the average values calculated from instantaneous active and reactive power. ω_0 and E_0 are the rated frequency and voltage output of the DG unit, With m and n as the frequency droop co-efficient and voltage droop co-efficient respectively.

The average active and reactive powers are calculated by deploying a low pass filter (LPF).The average active and reactive powers are calculated by deploying a low pass filter (LPF). The LPF with a reduced bandwidth results in a slow dynamic response of the system. Also, the droop control is limited by the maximum allowed limit of the deviation of the frequency (2%) and the voltage (5%). Therefore, the conventional droop method is modified in order to improve the dynamic response and also to maintain the frequency within its safe limits. In case of reactive power, the average value is obtained by delaying the output current and voltage by 90° before passing through the LPF. PD control is applied over the output of the LPF, which improves the dynamics of the system . The modified voltage amplitude can be expressed as:

$$E = E_0 - nQ - n_d \frac{dq}{dt} \qquad (8)$$

In case of the active power, the phase angle ($\emptyset = \frac{dw}{dt}$) is adjusted by implementing a PID controller on the output of the LPF. The modified expression can be rewritten as:

$$\emptyset = -\int_{-\infty}^{t} P\, dt - m_p \text{P} - m_d \frac{dp}{dt} \qquad (9)$$

In both the equation (8) and (9) m and n are used to fix the steady state droop characteristics, whereas end (derivative coefficient for reactive power), mp and md (proportional and derivative coefficients respectively for active power) takes care of the stability and the transient response of the system. Control of the steady state frequency deviation can also be achieved by only applying a PD control action on the non-dc component of the active power$\tilde{p}$, which is obtained by passing the average active power (obtained using LPF) through a high pass filter (HPF). As per the modified frequency droop can be expressed as:

$$\omega = \omega_{max} - m_p\,\tilde{p} - m_d\,\frac{d\tilde{p}}{dt} \qquad (10)$$

The slope m is increased to m’ = m+Δm, which will lead to the increase of $\Delta\omega$ or decrease of P. This can be further explained by Figure

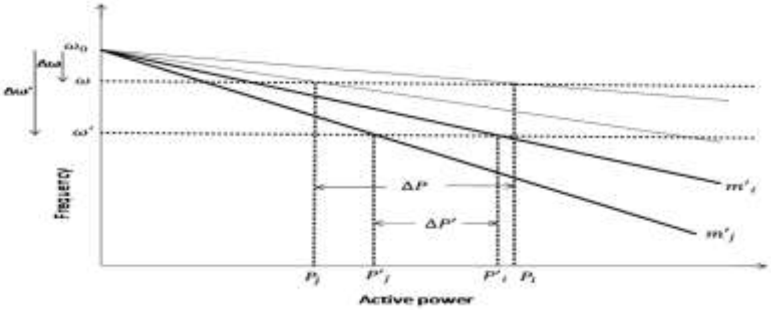

Fig.3. Frequency deviations with active power sharing

In Fig. 3 $m'_i > m'_j$ which results in $\Delta p < \Delta p'$ Therefore it can be concluded that on increasing the droop coefficients increases the accuracy of load sharing, i.e. the difference in the power shared (Δp) by the DGs decreases (similarly for voltage droop). But it comes at the cost of increase in the frequency ($\Delta w < \Delta w'$), which makes it difficult to keep the frequency within its allowed limits; hence it results in system instability.

2.2.2 ADAPTIVE DROOP CONTROL

In this approach an Adaptive droop control has been implemented, which is capable of changing the gain value with the change in load demand and the DG supply. This control action is based on equation (10), which deals with the change in power supplied by the DG and the change in load demand, with the objective to keep the system frequency (ω) within its safe limit. Therefore, a high value of droop coefficient is selected when the power supplied by DG goes below the rated power (P_0), whereas a low droop gain results in faster steady state where the load power demand is high. This method uses a threshold active ($P_{itchers}$) and reactive power (Q_{ithres}), which are load dependent, in order to compare with the active (Pi) and reactive (Q_i) power outputs of the ith DG unit to set the value of the droop coefficient.

2.3 VOLTAGE CONTROL BY MEANS OF DG UNITS

Currently, most DG units convey an amount of power to the electrical network that is self-governing of the state of the network. This input power is determined exclusively by the energy source micro-grids or utility feeders are considered (e.g., maximum power point tracking in the case of photovoltaic panels and wind turbines, or heat as the crucial driver in combined heat and power (CHP) units). Also, most units are current controlled in a grid following control tactic. In this, grid-forming and grid following control strategy in grid-connected

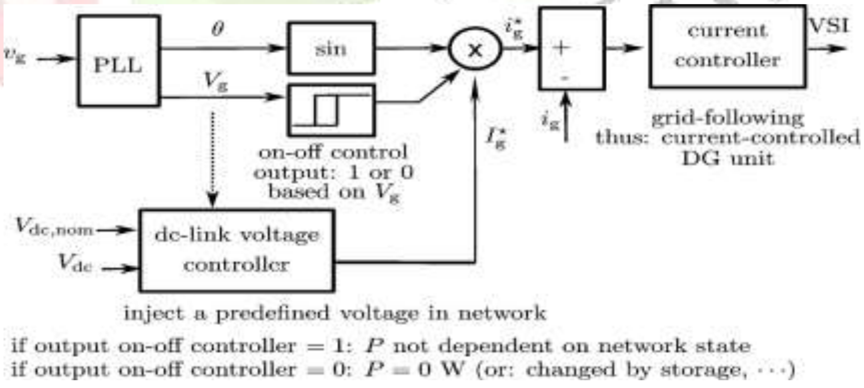

Fig.4. Grid-following unit with ON-OFF control based on the terminal voltage.

First, conservative grid-following controllers with ON-OFF control, as depicted in Fig. 4, are painstaking. The phase angle of the orientation current is obtained by tracking the terminal voltage by using a phase-locked loop (PLL). The current amplitude is obtained by dc-link voltage controller maintenance the dc-link voltage constant, while the input dc power is self-governing of the state of the network.

III. GRID-FORMING UNIT WITH VOLTAGE-BASED DROOP CONTROL

The voltage-based droop (VBD) control strategy, which has been presented for islanded micro grids is applied in the grid-connected units to change their P based on the network state. The active power can be altered by changing the input from the energy source (biomass supply, changing the wind turbines pitch angle, deviating from maximum power point (MPP) in a photovoltaic system), by using energy storage or shifting the local load. The control principles of the VBD controllers are summarized The cascaded operation of the V_g/V_{dc} droop controller, enabling ac- and dc-side balancing of the inverter, and the P_{dc}/V_g droop controller for the voltage limiting without inter unit communication. It also shows a so-called constant-power band with a width dependent on the nature of the energy source, which is clarified in Fig.5.

Renewable energy sources with large constant-power bands are triggered by more extreme voltages to alter their delivered power compared to the units with smaller constant-power bands. Communication is not required for this different reaction of the units on the terminal voltage. The P_{dc}/V_g droop is generic and can be adapted according to the nature of the energy source. For a photovoltaic system, for example, in Fig. 6, assuming operation in the MPP ($P_{dc,\ nom}= P_{MPPT}$), the system cannot by itself respond to under voltage conditions.

The grid-following units, these DG units can easily limit the injected current since their voltage-control loop is often composed of an outer voltage and an inner current control loop. The grid-following DG units are mostly equipped with a power factor- one controller. In the grid-forming controllers, this is inherently present as well. The reason is that the Q/f droop control operates at Qnom in case f=fnom. The conventional generators force the grid frequency to its nominal value through secondary control.

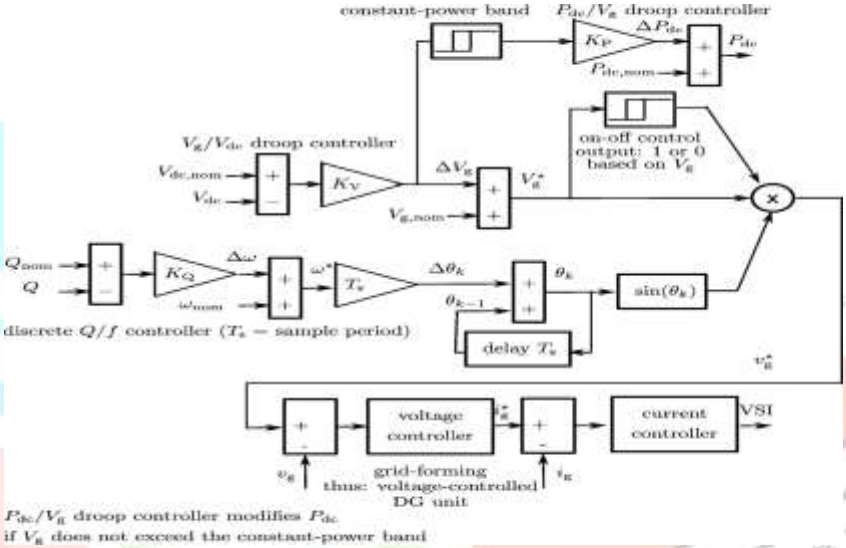

Fig. 5. Grid-forming unit with VBD control.

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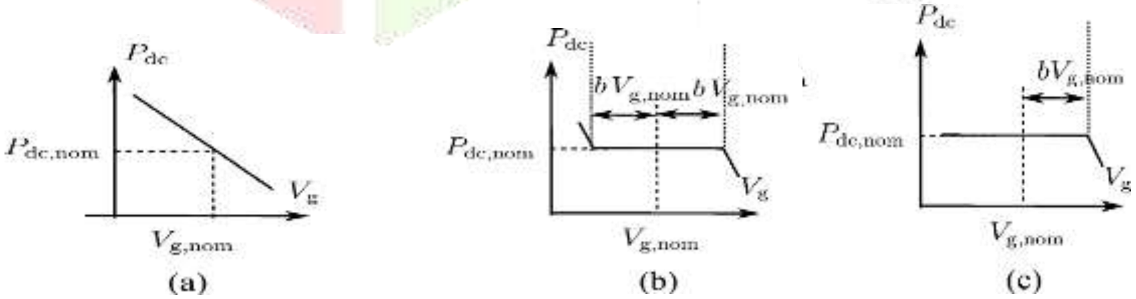

Fig.6. Constant power bands, with a width h=2b, of dispatch able versus less dispatch able DG units. (a) Dispatch able unit. (b) Less controllable unit. (c) renewable energy sources.

The above characteristics graph shows the constant power band at the dispatch able DG units, less controllable unit and renewable energy sources of the width.

IV. SIMULATION RESULTS

Simulated results have been obtained from a single-phase low voltage micro grid. 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.

Harmonic Voltage Amplification During A Single DG Unit Grid Connected Operation Without Damping

In which the combination of an active filter in series with a shunt passive filter is considered a significant design configuration for medium and high voltage applications. The passive filter is designed to reduce the voltage stress applied to the switches in the active filter. This design is in its infancy of development however, further research is still needed to assess the effectiveness of the configuration.

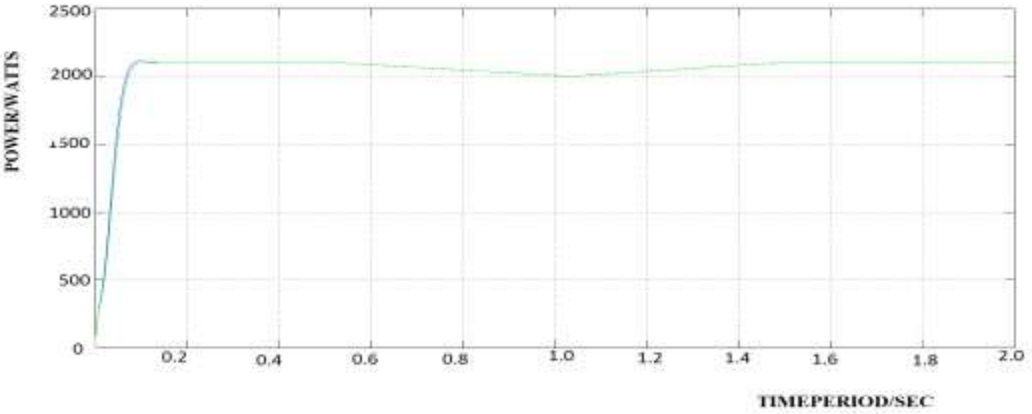

Fig. 7. Output active powers of two inverters with the improved droop control (without damping)

Harmonic voltage amplification during a single DG unit grid connected operation. The DC link contains a capacitor and once charged, this capacitor voltage is the voltage source which controls the current waveform by PWM techniques in Fig.7. The voltage across the terminals of the capacitor often fluctuates due to the fact that energy is either supplied or expelled. To regulate and maintain terminal voltage levels, a reference voltage is chosen in Fig. 8. The difference between the actual capacitor voltage and the predefined reference voltage determines the active component of power required to compensate for losses in the filter.

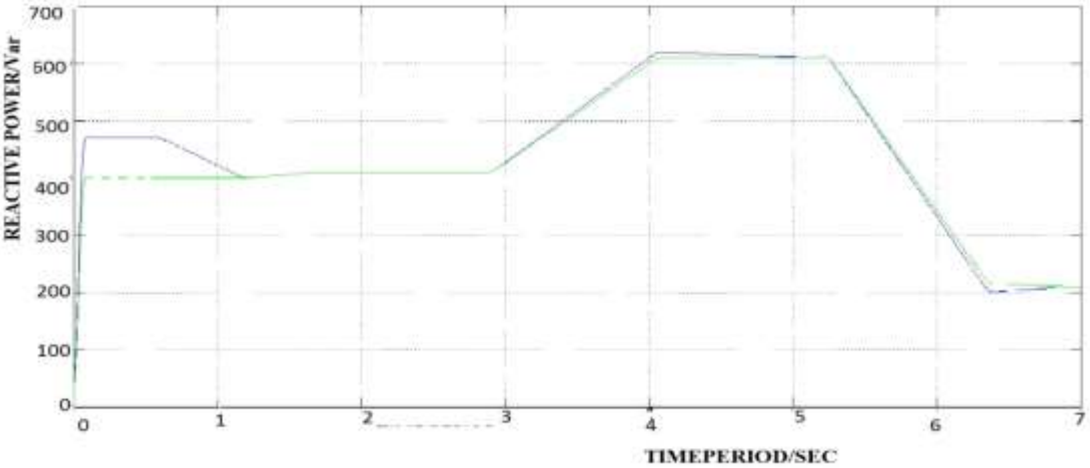

Fig. 8. Reactive power sharing performance of the improved droop control (with load changing) (with virtual nonlinear capacitor and resistor based active damping)

Harmonic Voltage Amplification During A Single DG Unit Islanding Operation (Without Damping):

These results agree with the discussion in Fig. 9. Moreover, when the nonlinear virtual capacitor control is also applied to DG unit 2, the harmonic voltage drop on its LCL filter grid-side inductor can be compensated and it also behaves as a virtual harmonic resistor. First, the real power frequency droop control and the reactive power voltage magnitude droop control in the power control loop. The harmonic voltage drop on its LCL filter grid-side inductor can be compensated and it also behaves as a virtual harmonic resistor.

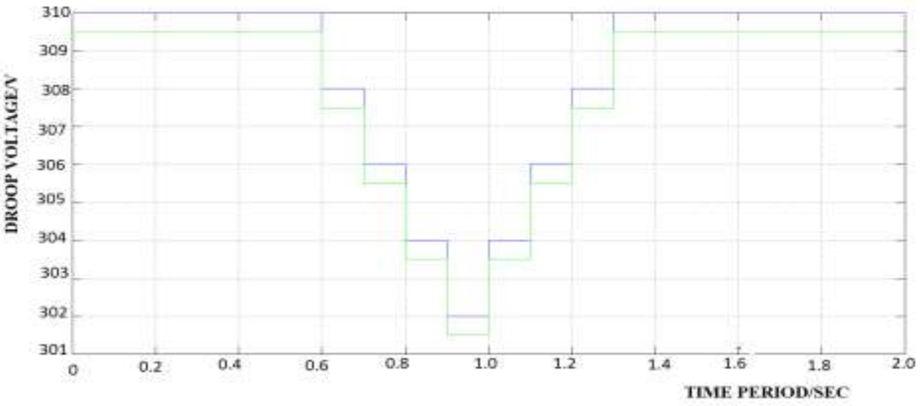

Fig. 9. DG output of the inverters when 0.02-s time delay occurs in synchronization signel of DGI unit without damping)

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. When only a single DG unit is placed in the islanding system, constant voltage magnitude and constant frequency (CVMCF) control can be used. On the other hand, for the operation of multiple DG units in the microgrid (see Fig. 1).

Harmonic Voltage Amplification During A Single DG Unit Islanding Operation (With Virtual Nonlinear Capacitor and Resistor Based Active damping):

As illustrated, the DG unit is interfaced to long feeder with an LCL filter. First, the real power frequency droop control and the reactive power voltage magnitude droop control in the power control loop. The system appears some harmonic circulating currents as shown in Fig. 10.

These results agree with the discussion Moreover, when the nonlinear virtual capacitor control is also applied to DG unit 2, the harmonic voltage drop on its LCL filter grid-side inductor can be compensated and it also behaves as a virtual harmonic resistor. First, the real power frequency droop control and the reactive power voltage magnitude droop control in the power control loop.

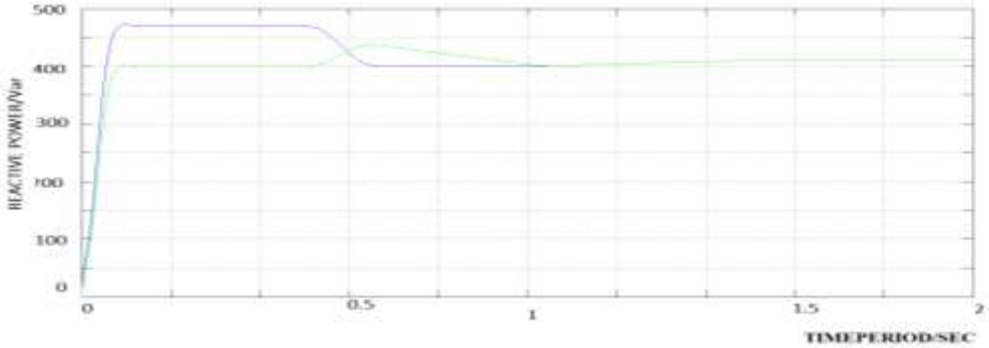

Fig. 10. Output reactive powers of the two inverters when 0.02-s time delay occurs in synchronization signal of DGI unit (with virtual nonlinear capacitor and resistance damping)

Harmonic Voltage Amplification along The Feeders (Grid-Tied Operation of Two Parallel DG Units):

With properly controlled DG equivalent harmonic impedance at selected harmonic frequencies, the proposed method can also eliminate the harmonic circulating current among multiple DG units with mismatched output filter parameters. Comprehensive simulations are conducted to confirm the validity of the proposed method. In which the combination of an active filter in series with a shunt passive filter is considered a significant design configuration for medium and high voltage applications in Fig. 11. The passive filter is designed to reduce the voltage stress applied to the switches in the active filter. This design is in its infancy of development however, further research is still needed to assess the effectiveness of the configuration.

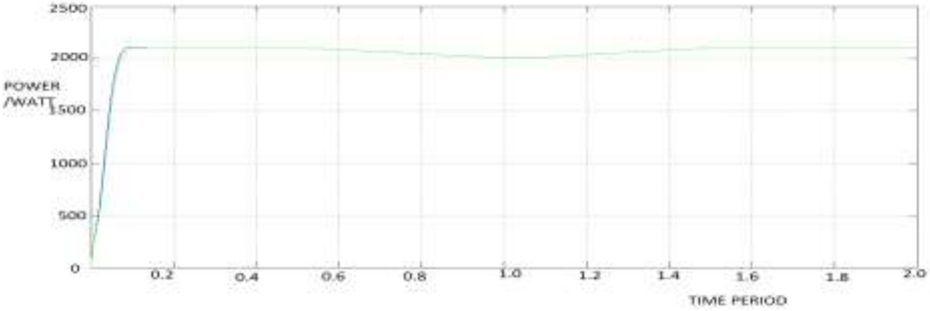

Fig. 11. Output active power of two inverters with the improved droop control

Output reactive power of the two inverters when 0.02-s time delay occurs in synchronization signel of DGI unit (grid-tied operation of two parallel dg units)

The effects of its LCL filter grid-side inductor, the associated voltage waveform is shown in the third column of Fig. 12. Although the difference between the second and third columns of Fig. 12 is not very obvious, the harmonic circulating current between parallel DG units can be noticeable. The associated voltage waveform is shown in the third column of Fig. 14. Although the difference between the second and third columns of Fig. 12 is not very obvious, the harmonic circulating current between parallel DG units can be noticeable.

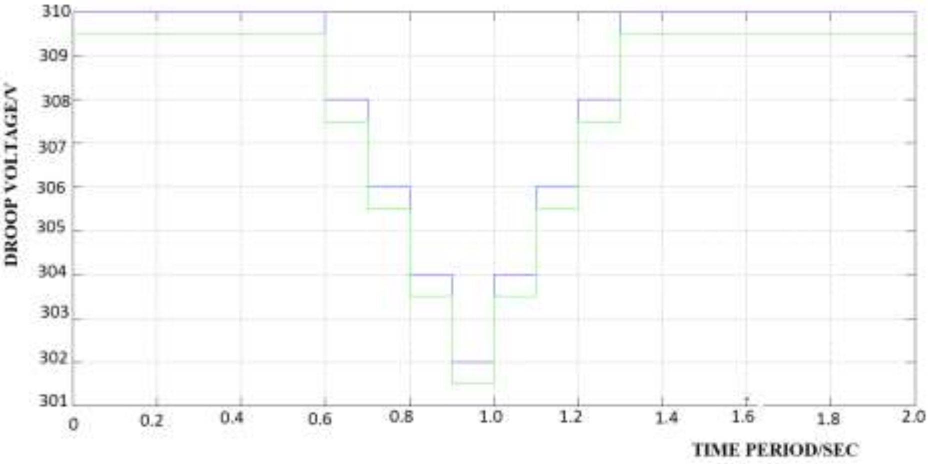

Fig. 12. DG output voltage of the inverters when 0.02-s time delay occurs in synchronization signal of DG unit

V. CONCLUSION

In this paper, a micro grid 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.

This paper also focuses on developing a voltage-controlled DG unit-based active harmonic damping method for grid-connected and islanding micro grid systems. An improved virtual impedance control method with a virtual damping resistor and a nonlinear virtual capacitor is proposed. The nonlinear virtual capacitor is used to compensate the harmonic voltage drop on the grid-side inductor of a DG unit *LCL* filter. The virtual resistor is mainly responsible for micro grid resonance damping. The effectiveness of the proposed damping method is examined using both a single DG unit and multiple parallel DG units.

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