ISSN No: 2348-4845
International Journal & Magazine of Engineering, Technology, Management and Research
A Peer Reviewed Open Access International Journal

Resonance Propagation and Mitigation in Grid Connected and Islanding Micro Grids by Using Fuzzy Logic

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ABSTRACT

In this paper, a micro grid resonance propagation model is investigated. To actively mitigate the resonance using DG units, an enhanced DG unit control scheme that uses the concept of virtual impedance is proposed. It can be seen that a conventional voltage-controlled dg unit with an LC filter has a short-circuit feature at the chosen harmonic frequencies, whereas a current-controlled dg unit presents an open-circuit characteristic. Because of completely different behaviors at harmonic frequencies, specific harmonic mitigation methods shall be developed for current controlled and voltage-controlled dg units, respectively. The application of underground cables and shunt capacitor banks may introduce power distribution system resonances. This paper additionally focuses on developing a voltage-controlled dg unit based active harmonic damping technique 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 dip on the grid-side inductor of a dg unit LCL filter. Here we are using fuzzy controller compared to other controller due to its accurate performance. The virtual resistance is principally answerable for micro grid resonance damping. The effectiveness of the proposed damping method is examined using each a single dg unit and multiple parallel dg units. Index Terms—Active power filter, distributed power generation, droop control, grid-connected converter, micro grid, power quality, renewable energy system, resonance propagation, virtual impedance.

I INTRODUCTION

The increasing application of nonlinear loads cans led to significant harmonic pollution in a power distribution system. The harmonic distortion might excite complicated resonances, particularly in power systems with underground cables or subsea cables and. In fact, these cables with nontrivial parasite shunt capacitance will form an LC ladder network to amplify resonances. in order to mitigate system resonances, damping resistors or passive filters can be placed in the distribution networks .however, the mitigation of resonance propagation exploitation passive components is subject to some well understood problems, like power loss and additional investment. Moreover, a passive filter might even bring extra resonances if it's designed or installed without knowing detailed system configurations. To avoid the adoption of passive damping equipment, numerous types of active damping methods are developed.

Among them, the resistive active power filter (R-APF) is often considered as a promising way to understand better performance. Conventionally, the principle of R-APF is to emulate the behavior of passive damping resistors by applying closed-loop current-controlled method (CCM) to power electronics converters. in this management category, the R-APF will be simply modeled as virtual harmonic resistor if it's viewed at the distribution system level. in addition, many changed-APF ideas were additionally developed in the recent literature. In, the separate tuning method was proposed to regulate damping resistances at different harmonic orders. Accordingly, the R-APF basically works as a non linear resistor. In, the operation of multiple Ripsaws also considered, where an interesting

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droop control was designed to offer autonomous harmonic power sharing ability among parallel RAPFs.On the other hand, renewable energy source(RES) based distributed generation (DG) units are adopted to form flexible micro grids and their interfacing converters even have the chance to address different distribution system power quality problems.

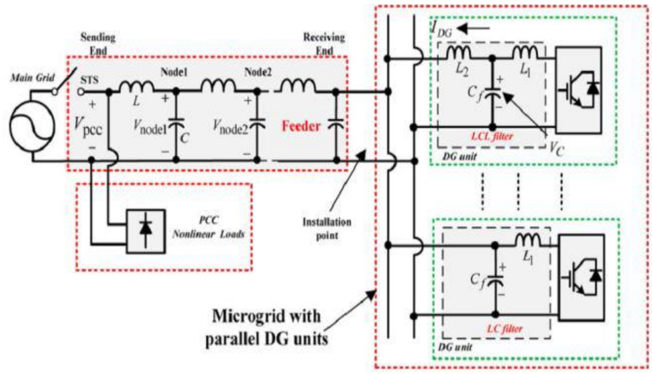

Fig. 1. Simplified one-line diagram of a single-phase Micro grid. Service. Simulated results are provided to confirm the validity of the proposed Method.

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. However, conventional CCM will hardly provide direct voltage support throughout micro grid islanding operation. To beat this limitation, an enhanced voltage-controlled method (VCM) was recently proposed for dg units with high-order LC or LCL filters. It can be seen that the control method in regulates the dg unit as virtual impedance, that is dependent on the present feeder electric resistance. Once the feeder electric resistance is inductive, this method could not provide enough damping effects to system resonance.

II MODELING OF DG UNITS IN MICROGRID SYSTEM

Fig. 1 illustrates the configuration of a single-phase micro grid system, where a few dg units are interconnected to the point of common coupling (PCC) through an extended underground feeder. For the sake of simplicity, this paper only adopts an easy micro grid configuration to demonstrate how the micro grid power quality is affected by resonance propagation. in addition, this paper also assumes that shunt capacitor banks and parasitic feeder capacitances are equally distributed in the feeder. Note that the static transfer switch (STS) controls the operation mode of the microgrid. When the most grid is disconnected from the microgrid, the PCC nonlinear loads shall be supplied by the standalone dg units.

A. DISTRIBUTED PARAMETER MODEL IN GRID-TIED OPERATION

For a protracted feeder, as illustrated in Fig.1, a lumped parameter model isn't able to describe its resonance propagation characteristics. Alternatively, the distributed parameter model was mentioned in [3] and [6], where the voltage distortions at PCC induce a harmonic voltage standing wave on the feeders. Where the kth PCC harmonic voltage is assumed to be stiff and V pcck • Vk(x) and Ik(x) square measure the feeder kth harmonic voltage and harmonic current at position x. The length of the feeder is l

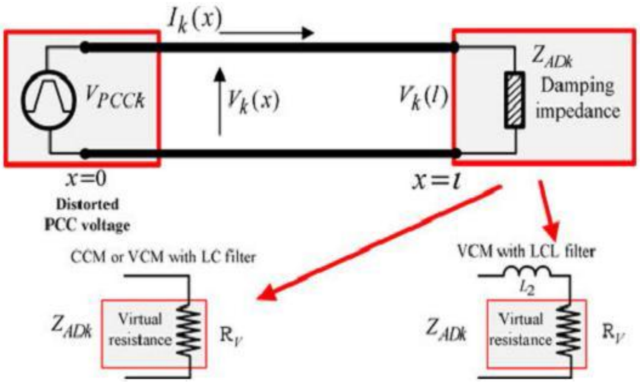

Fig. 2. Equivalent circuit of a single grid connected DG unit at the kth harmonic frequency.

It is easy to obtain the harmonic voltage–current standing wave equations at the harmonic order k as

$$V_k(x) = Ae^{-\gamma x} + Be^{\gamma x} \quad (1)$$

$$I_K(x) = \frac{1}{Z}(Ae^{-\gamma x} - Be^{\gamma x}) \quad (2)$$

Where A and B are constants, which are determined by feeder boundary conditions. Z and γ are the characteristics impedance [3] of the feeder without considering the line resistance as

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International Journal & Magazine of Engineering, Technology, Management and Research
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$$Z = \sqrt{\frac{L}{C}} \quad (3)$$

$$\gamma = jk\omega_f\sqrt{LC} \quad (4)$$

Where ωf is the fundamental angular frequency and L and C are the feeder equivalent inductance and shunt capacitance per kilometer, respectively.

1) DG Units with CCM and R-APF Control: To determine the boundary conditions of the feeder, the equivalent harmonic impedance (ZADk) of the DG unit must be derived. First, the current reference (Iref) of a CCM-based DG unit can be obtained as

$$I_{ref} = i_{reff} - I_{AD} = I_{reff} - \frac{H_D(S).V(l)}{R_V} \quad (5)$$

Where Ireff is the fundamental current reference for DG unit power control, IAD is the harmonic current reference for system resonance compensation, V(l) is the measured installation point voltage at the receiving end of the feeder, HD(s) is the transfer function of a harmonic detector, which extracts the harmonic components of the installation. point voltage, and RV is the command virtual resistance.

$$\omega_{DG} = \omega_f + D_P.(P_{ref} - P_{LPF}) \quad (6)$$

$$E_{DG} = E + D_q.(Q_{ref} - Q_{LPF}) + \frac{K_Q}{S}(Q_{ref} - Q_{LPF}) \quad (7)$$

Where ω f and ω DG are the nominal and reference angular frequencies. E and EDG are the nominal and reference DG voltage magnitudes. PLPF and QLPF are the measured power with low pass filtering. Dp and Dq are the droop slopes of the controller. Note that with the integral control to regulate DG unit voltage magnitude in (7), the steady-state reactive power control error at the grid tied operation is zero. Once the voltage magnitude reference and the frequency reference are determined, the ripple-free instantaneous voltage reference (Vreff) can be easily obtained. The equivalent impedance of VCM-based DG unit with an LC filter has already been tuned to be resistive, by adding a DG line current (IDG) feed-forward term to the voltage control reference . Although previous VCM-based DG equivalent impedance shaping techniques mainly focus on improving the power sharing performance of multiple DG units in an islanding micro grid, similar idea can also be used to mitigate the harmonic propagation along the feeder as

$$V_{ref} = V_{reff} - V_{AD} = V_{ref} - R_V.(H_D(S).I_{DG}) \quad (8)$$

where Vreff is the fundamental voltage reference derived from droop control in (6) and (7), VAD is the harmonic voltage reference for DG unit harmonic impedance shaping, IDG is the measured DG unit line current (see Fig. 1), HD(s) is the transfer function of a harmonic detector, which extracts the harmonic components of DG unit line current, and RV is the virtual resistance command. Note that when a VCM-based DG unit with an LC filter is controlled without any harmonic impedance shaping target [by setting RV= 0 in (8)], it essentially works as short-circuit connection (ZADk = 0) at the harmonic frequencies. Nevertheless, if an LCL filter is adopted as the DG output filter, the VCM-based control method using filter capacitor

Voltage regulation does not address the harmonic voltage drop on the grid-side inductor (L2).Accordingly, the DG unit shall be modeled as the combination of a reactor and a resistor (ZADk = RV+ jkωfL2) when (8) is applied to the DG unit (see Fig. 2). As will be discussed later, the imaginary part of ZADk may affect the voltage harmonic suppression performance of the system. Since a grid connected DG unit using either CCM or VCM can be modeled by equivalent harmonic impedance at the receiving end of the feeder, the following boundary conditions can be obtained:

$$\frac{V_k(l)}{I_k(l)} = Z_{ADK} \quad (9)$$

$$V_k(0) = V_{PCCK} \quad (10)$$

By solving (1), (2), (9), and (10), the harmonic voltage propagation at the harmonic order k can be expressed

$$V(x)_k = \frac{Z_{ADK}\cos h(\gamma(l-x)) + z\sin h(\gamma(l-x))}{Z_{ADK}\cos h(\gamma l) + z\sin h(\gamma l)} V_{pcck.} \quad (11)$$

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As With the obtained equation in (11), the impact of DG active damping scheme to the harmonic voltage propagation along the feeder can be easily analyzed. Note that when the micro grid feeder is purely RL impedance, the DG unit can still work as a virtual harmonic resistor at the end of the feeder. In this case, the DG unit has the capability of absorbing some PCC nonlinear load current if it is designed and controlled properly

B. DISTRIBUTED PARAMETER MODEL IN ISLANDING OPERATION

The previous section focuses on the analysis of grid tied DG units. For an islanding micro grid 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 micro grid 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

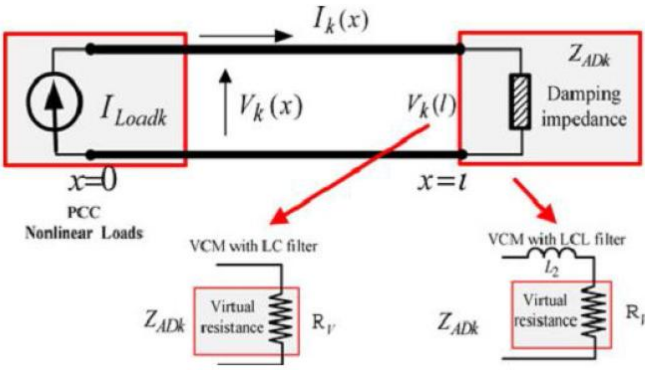

Fig. 3. Equivalent circuit of a single islanding DG unit at the kth harmonic frequency

On the other hand, for the operation of multiple DG units in the micro grid (see Fig. 1), the droop control method in (6) and (7) [by setting KQ = 0 in (7)] shall be employed to realize proper power sharing among these DG units. Considering the focus of this section is to investigate the harmonic voltage damping in a stand-alone islanding system, a single DG unit at the receiving end of the feeder is considered. The circuit model of an islanding system at the harmonic order k is illustrated in Fig. 3, With the knowledge of boundary conditions at both sending and receiving ends as

$$I_k(0) = I_{Loadk} \tag{12}$$

$$\frac{V_k(l)}{I_k(l)} = Z_{ADK} \tag{13}$$

the kth harmonic voltage distortion along the feeder can be obtained

$$V_k(x) = \left(\frac{e^{-\gamma x}}{1+((z-Z_{ADK})/(z+Z_{ADk}))e^{2\gamma l}} - \frac{e^{\gamma x}}{1+((z+\frac{Z_{ADK})}{z-Z_{ADk}}))zI_{Load}} \right) \tag{14}$$

From (14), it can be noticed that the voltage propagation in an islanding system harmonic is also related to the DG-unitequivalent harmonic impedance. In order to maintain satisfied voltage quality, the equivalent harmonic impedance of islanding DG units shall also be properly designed.

IV. REALIZATION OF VIRTUAL DAMPING IMPEDANCE THROUGH DG VOLTAGE CONTROL

It has been clarified that an LCL filter grid-side inductor (L2) can affect the performance of distribution system harmonic suppression, especially in the case of multiple DG units. In order to compensate the impact of LCL filter grid-side inductor, the harmonic voltage damping scheme as shown in (8) shall be further improved.

A. Conventional Voltage Tracking

First, a negative virtual inductor can be produced by VCM. Accordingly, the modified voltage reference is obtained as

$$V_{ref} = V_{reff} - V_{AD} - V_{comp}$$
$$V_{ref} = R_V - H_D(s).I_{DG} - s(-L_2).H_D(s).I_{DG} \tag{16}$$

Comparing (16) to (8), it can be noticed that an additional voltage compensation term VComp is deducted from the voltage control reference. The aim of this voltage compensation term is to cancel the harmonic voltage drop on the grid-side LCL filter

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inductor L2 . Once the modified voltage reference in (16) is determined, a high bandwidth voltage controller, such as deadbeat control, H-infinity control, and multiple loop control, can be selected to ensure satisfied LCL filter capacitor voltage (VC) tracking. By further looking into (16), one can find that the implementation of virtual inductor involves derivative operation, which may adversely amplify system background noises. For instance, if a band stop filter is selected to filter out the fundamental components as

$$H_D(S) = 1 - \frac{2\omega_{BP}S}{S^2+2\omega_{BP}S+\omega_f^2} \quad (17)$$

Where ωBP is the cutoff bandwidth of the band-stop filter, the voltage compensation term V Comp in (16) can be expressed as

$$V_{comp} = S(-L_2).H_D(S)I_{DG} = \left(-sL_2 + \frac{2\omega_{BP}L_2S^2}{S^2+2\omega_{BP}S+\omega_f^2}\right).I_{DG} \quad (18)$$

The diagram of a DG unit with negative virtual inductor control is shown in Fig. 8. As illustrated, the DG unit is interfaced to long feeder with an LCL filter. First, the real power frequency droop control (6) and the reactive power voltage magnitude droop control (7) in the power control loop and are used to determine the fundamental voltage reference Vreff Note that this droop control method can also realize proper fundamental power sharing between multiple islanding DG units, without using any communications between them. VComp in (18) is deducted from the reference voltage Vreff . In order to alleviative the impact of derivative operator in VComp , a highpass filter can be used as an approximation. However, as already been pointed out in and the adoption of highpass filter introduces some magnitude and phase errors, which can degrade the performance of the compensation term V Comp.

B. IMPLEMENTATION OF NONLINEAR VIRTUAL CAPACITOR

In this subsection, a well-understood doubleloop voltage controller is selected for DG unit voltage tracking. In the outer filter capacitor voltage control loop, the proportional and multiple resonant (PR) controllers are used as

$$I_{inner} = G_{outer}(s).(V_{ref} - V_C) = \left(K_p + \sum_K \frac{2k_{ik}\omega_c k^2}{s^2+2\omega_c k^2+(k\omega f)^2}\right).(V_{ref} - V_C) \quad (19)$$

where KP is the outer loop proportional gain, Kik is the gain of resonant controller at fundamental and selected harmonic frequencies, ωck is the cutoff bandwidth, and IInner is the control reference for the inner control loop. In the inner loop controller (GInner(s)), a simple proportional controller (Kinner) is employed and the inverter output current (Iinv) is measured as the feedback.

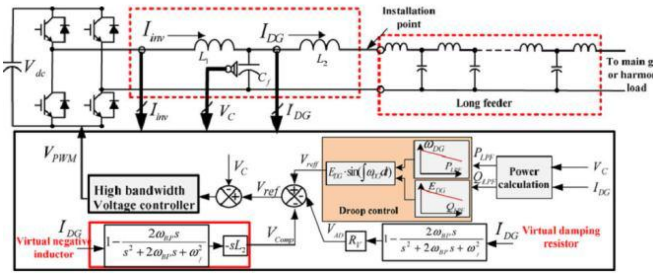

Fig. 8. Mitigation of distribution feeder harmonic propagation using virtual resistor and virtual negative inductor

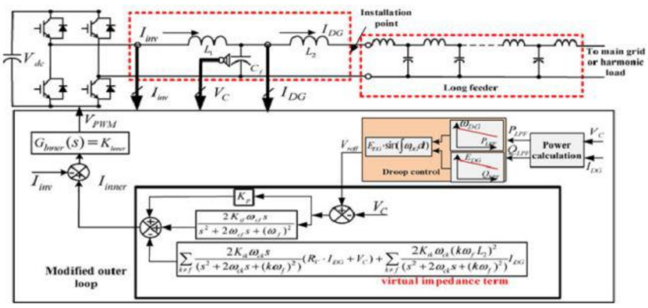

Fig. 9. Mitigation of harmonic propagation using virtual resistor and nonlinear virtual capacitor.

By further utilizing the resonant controllers in (19) 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. To cancel the impacts of LCL filter grid-side inductor without using derivative operation, a nonlinear virtual capacitor with the following frequency-dependent capacitance is needed.

$$L_2(\omega f t) - \frac{1}{C_{vk}(\omega f t)} = 0 \qquad (20)$$

Where ωf is the fundamental angular frequency and CV t is the command capacitance at the harmonic order t. Note that an LCL filter inductance often has some attenuation, if the line current is higher than the current rating of the filter chokes. In this case, an online estimation method can be used to identify the real-time inductance of the LCL filter and the virtual capacitance in (20) shall be modified accordingly. With the control of nonlinear virtual capacitor as shown in (20), the harmonic impact of the inductor L2 could be properly compensated. To realize this task, the traditional harmonic detector in (17) can be replaced by a family of selective harmonic separators to extract DG line current harmonic contain (IDGt) at each selected harmonic frequency. Afterwards, the voltage dropson the nonlinear virtual capacitor can be obtained as

$$V_{comp} = \Sigma_t \frac{1}{sC_{vt}} . I_{DGt} = \Sigma_t \frac{1}{sC_{vt}} . (H_{Dt}(s). I_{DGt}) \qquad (21)$$

Where HDt(s) is the harmonic detector to detect the tth DG harmonic current IDGt. It can also be seen that parallel resonant controllers used in the outer loop voltage control in (19) are essentially a set of band-pass filters with narrow bandwidth ωck and amplified magnitudes Kik . Indeed, the harmonic selective capability has already been embedded in the resonant controllers. If arranged

Table ii
Dg unit parameters

Control Parameter	Value
Rated voltage	RMS 60 V
Rated frequency	$f = 60$ Hz
Droop coefficients	$D_p = 1/300; D_p = 1/300; K_Q = 1/30;$
Proportional gain	$Kp1 = 0.11$
Resonant gain	$Kif = 20, Ki3 = 15, Ki5 = 15, Ki7 = 15, Ki9 = 10$
Cutoff frequency	$\omega_{ck} = 4$ rad/s ($K = f$, 3, 5, 7, and 9)
Inner loop controller	$K_{inner} = 20$
DC link voltage	$V_{dc=240V}$
Sampling and switching frequency	12 kHz
Circuit parameter	Value
LCL filter	$L_1 = 2$ mH $L_2 = 3.5$ mH $C_f = 20$ μF
LC filter	$L_1 = 2$ mH $L_2 = 0$ mH $C_f = 20$ μF (DG unit 1 in Figs. 14 and 15)
Command virtual resistance	$R_V = 5.5$ ω (DG unit in Figs. 10–13) $R_V = 11$ ω (DG unit 1 and DG unit 2 in Figs. 14 and 15)

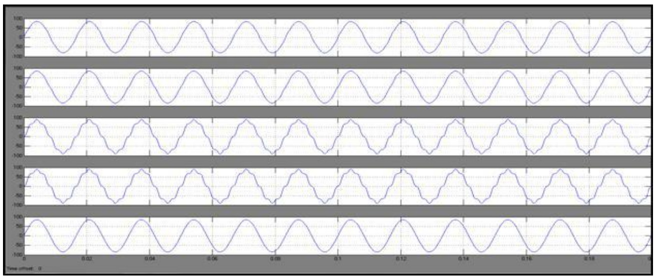

Fig. 10. Harmonic voltage amplification during a single DG unit grid connected operation (without damping) [from upper to lower: (a) PCC voltage (THD = 4.0%); (b) node 1 voltage (THD = 4.56%); (c) node 3 voltage (THD = 10.91%); (d) node 5 voltage (THD = 12.59%); (e) DG unit filter capacitor voltage (THD = 0.38%)].

Properly, resonant controllers can be further utilized to realize the control of virtual nonlinear capacitor. First, the instantaneous DG voltage reference Vreff derived from (6) and (7) is always ripple-free and the fundamental resonant controller can be adopted for Vreff tracking. In addition, the regulation of virtual resistor and virtual capacitor mainly focuses on the performance at selected harmonic frequencies. Therefore, parallel harmonic resonant controllers can be utilized to control these virtual impedances. Once the conventional PR controller is separated into two parts, the modified outer loop control scheme is illustrated as follows:

$$I_{inner} = \left(K_{p1} + \frac{2k_{if}\omega_c f^2}{S^2+2\omega_c f^S+(\omega f)^2}\right).(V_{reff} - V_c) + \Sigma_{K\neq f}\frac{2k_{ik}\omega_c k^2}{S^2+2\omega_c k^S+(k\omega f)^2}.(-V_{AD} - V_{Comp} - V_c) \qquad (22)$$

Combining (20), (21), and (22) yields

$$I_{inner} = \left(K_{p1} + \frac{2k_{if}\omega_c f^S}{S^2 + 2\omega_c f^S + (\omega f)^2}\right).(V_{reff} - V_c) - \sum_{t\neq f}\frac{2k_{ik}\omega_c k^S}{S^2 + 2\omega_c k^S + (k\omega f)^2}.(R_V.H_D(s)I_{DG} + V_c) - \left[\sum_{t\neq f}\frac{2k_{ik}\omega_c k^S}{S^2 + 2\omega_c k^S + (k\omega f)^2}\left(\sum_{t\neq f}\frac{(t\omega_f L_2)^2}{S}H_{Dt}(s).I_{DG}\right)\right] \qquad (23)$$

Note that the HD(s) is a harmonic detector, which has 0 db and 0° response at all selected harmonic frequencies and HDt(s) is a selective harmonic detector which only has 0 db and 0° response at the tth harmonic frequency. By further utilizing the harmonic selective feature of harmonic resonant controllers in the PR controller, (23) can be further simplified as

$$I_{inner} = \left(K_{p1} + \frac{2k_{if}\omega_c f^S}{S^2+2\omega_c f^S+(\omega f)^2}\right).(V_{reff} - V_C) - \Sigma_{t\neq f}\frac{2k_{ik}\omega_c k^S}{S^2+2\omega_c k^S+(k\omega f)^2}.(R_V.I_{DG} + V_c) - \left[\Sigma_{t\neq f}\frac{2k_{ik}\omega_c k(k\omega_f L_2)^2}{S^2+2\omega_c k^S+(k\omega f)^2} I_{DG}\right] \quad (24)$$

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 is shown in Fig. 9. In the revised controller, the harmonic voltage references associated with virtual resistor and virtual capacitor are only regulated by the harmonic resonant controllers. It can be seen that the derivative operator in Fig. 8 is avoided in Fig. 9. It is true that the small proportional gain KP1 in (24) still induces some interference between fundamental and harmonic components regulation. However, the proportional gain in the PR controller is normally very small compared to resonant gains. In this paper, a small proportional gain (KP1 = 0.11) is

Table iii
Harmonic spectrum of a grid connected micro grid without Active damping (corresponding to fig. 10)

	3rd harmonic	5th harmonic	7th harmonic	9th harmonic	11th harmonic	13th harmonic	THD
PCC voltage	2.00%	2.00%	2.00%	2.00%	0%	0%	4.00%
Node 1 voltage	1.91%	2.41%	2.89%	1.31%	0.05%	0.03%	4.56%
Node 3 voltage	1.65%	2.92%	10.37%	0.74%	0.03%	0.04%	10.91%
Node 5 voltage	1.24%	2.57%	12.31%	2.07%	0.01%	0.02%	12.59%
DG voltage	0.02%	0.04%	0.10%	0.14%	0.15%	0.2%	0.38%

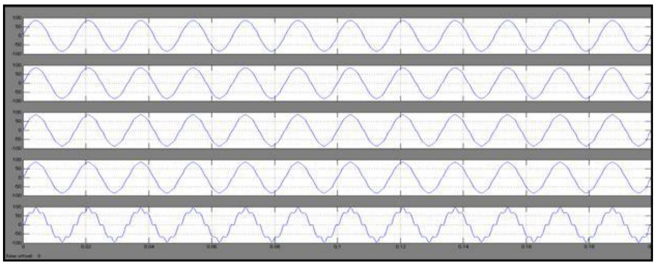

Fig. 11. Harmonic voltage amplification during a single DG unit grid connected operation (with virtual nonlinear capacitor and resistor based active damping) [from upper to lower: (a) PCC voltage (THD = 4.0%); (b) node 1 voltage (THD = 4.1%); (c) node 3 voltage (THD = 3.7%); (d) node 5 voltage (THD = 3.2%); and (e) DG unit filter capacitor voltage (THD = 5.4%)].

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.

V. FUZZY LOGIC CONTROLLER

In FLC, basic control action is determined by a set of linguistic rules. These rules are determined by the system. Since the numerical variables are converted into linguistic variables, mathematical modeling of the system is not required in FC.

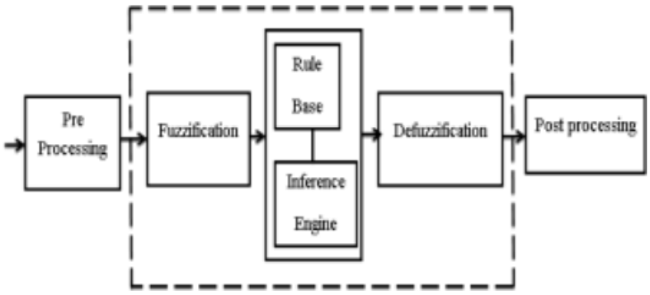

Fig.12.Fuzzy logic controller

The FLC comprises of three parts: fuzzification, interference engine and defuzzification. The FC is characterized as i. seven fuzzy sets for each input and output. ii. Triangular membership functions for simplicity. iii. Fuzzification using continuous universe of discourse. iv. Implication using Mamdani's, 'min' operator. v. Defuzzification using the height method.

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International Journal & Magazine of Engineering, Technology, Management and Research
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TABLE IV: Fuzzy Rules

Change in error	Error						
	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PB	PM	PM	PS	Z
NM	PB	PB	PM	PM	PS	Z	Z
NS	PB	PM	PS	PS	Z	NM	NB
Z	PB	PM	PS	Z	NS	NM	NB
PS	PM	PS	Z	NS	NM	NB	NB
PM	PS	Z	NS	NM	NM	NB	NB
PB	Z	NS	NM	NM	NB	NB	NB

Fuzzification: Membership function values are assigned to the linguistic variables, using seven fuzzy subsets: NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), and PB (Positive Big). The Partition of fuzzy subsets and the shape of membership *CE(k) E(k)* function adapt the shape up to appropriate system. The value of input error and change in error are normalized by an input scaling factor.

In this system the input scaling factor has been designed such that input values are between -1 and +1. The triangular shape of the membership function of this arrangement presumes that for any particular *E(k)* input there is only one dominant fuzzy subset. The input error for the FLC is given as

$$E(k) = \frac{P_{ph(k)} - P_{ph(k-1)}}{V_{ph(k)} - V_{ph(k-1)}} \quad (25)$$

$$CE(k) = E(k) - E(k\text{-}1) \quad (26)$$

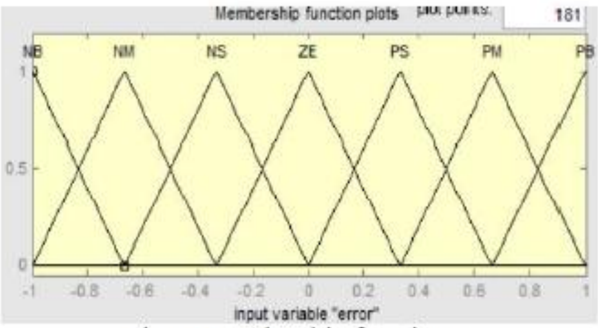


Fig.13.Membership functions

Inference Method:
Several composition methods such as Max–Min and Max-Dot have been proposed in the literature. In this paper Min method is used. The output membership function of each rule is given by the minimum operator and maximum operator. Table 1 shows rule base of the FLC.

Defuzzification: As a plant usually requires a non fuzzy value of control, a defuzzification stage is needed. To compute the output of the FLC, „height" method is used and the FLC output modifies the control output. Further, the output of FLC controls the switch in the inverter. In UPQC, the active power, reactive power, terminal voltage of the line and capacitor voltage are required to be maintained. In order to control these parameters, they are sensed and compared with the reference values. To achieve this, the membership functions of FC are: error, change in error and output

The set of FC rules are derived from

$$u=-[\alpha E + (1-\alpha)*C] \quad (27)$$

Where α is self-adjustable factor which can regulate the whole operation. E is the error of the system, C is the change in error and u is the control variable. A large value of error E indicates that given system is not in the balanced state. If the system is unbalanced, the controller should enlarge its control variables to balance the system as early as possible. One the other hand, small value of the error E indicates that the system is near to balanced state

V. RESULTS

Simulated results have been obtained from a single-phase low voltage microgrid. 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 (see Fig. 1). Each LC filter represents 1 km feeder. The parameters of these LC filters are selected to be the same as these in Table I. To provide some passive damping effects to the feeder, the LC filter inductor stray resistance is set to 0.12 Ω. The detailed DG unit control parameters arelisted in Table II.

A. SINGLE DG UNIT GRID-TIED OPERATION

At first, the performance of a grid-connected DG unit with an LCL filter is examined. The PCC voltage in this simulation is stiff and it has 2.0% distortion at each lower order harmonic frequency (3rd, 5th, 7th, and 9th harmonics).Fig.

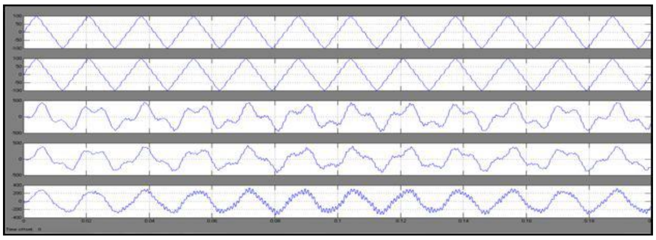


Fig. 14. Harmonic voltage amplification during a single DG unit islanding operation (without damping) [from upper to lower: (a) PCC voltage (THD = 15.2%); (b) node 1 voltage (THD = 14.7%); (c) node 3 voltage (THD = 11.9%); (d) node 5 voltage (THD = 10.5%); and (e) DG unit filter capacitor voltage (THD = 1.6%)].

Table v
Harmonic spectrum of an islanding micro grid without active damping (corresponding to fig. 12)

	3rd harmonic	5th harmonic	7th harmonic	9th harmonic	11th harmonic	13th harmonic	THD
PCC voltage	13.19%	2.95%	0.29%	1.66%	6.58%	0.54%	15.19%
Node 1 voltage	11.96%	3.68%	0.39%	1.07%	6.62%	1.06%	14.67%
Node 3 voltage	10.05%	4.35%	1.45%	0.66%	1.09%	0.61%	11.93%
Node 5 voltage	7.54%	3.83%	1.73%	1.76%	5.98%	0.86%	10.51%
DG voltage	0.10%	0.05%	0.02%	0.45%	1.43%	0.2%	1.60%

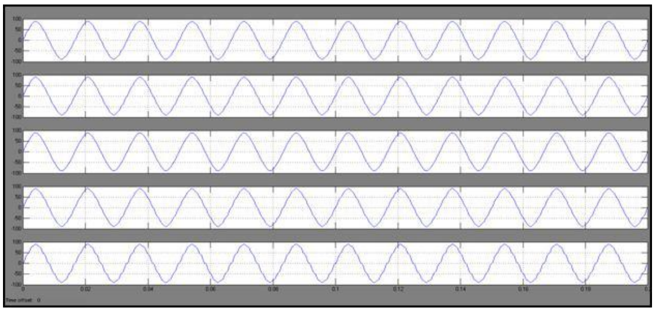


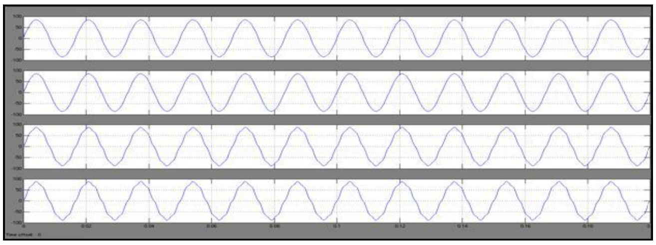
Fig. 15. Harmonic voltage amplification during a single DG unit islanding operation (with virtual nonlinear capacitor and resistor based active damping) [from upper to lower: (a) PCC voltage (THD = 6.1%); (b) node 1 voltage (THD = 6.0%); (c) node 3 voltage (THD = 5.2%); (d) node 5 voltage (THD = 5.3%); and (e) DG unit filter capacitor voltage (THD = 7.1%)].

B. SINGLE DG UNIT ISLANDING OPERATION

In addition to grid-connected operation, the performance of a single DG unit in islanding operation is also investigated. In this case, the PCC lad is a single-phase diode rectifier and it is supplied by the DG unit through long feeder. When the conventional VCM without damping is adopted, the performance of the system is obtained in Fig. 12. Similar to the grid-tied operation, the voltage waveforms at PCC, nodes 1, 3, and 5, and DG unit filter capacitor are shown from channels (a) to (e), respectively.

C. MULTIPLE DG UNITS GRID-TIED OPERATION

To verify the circulating harmonic current between multiple DG units, two grid-connected DG units at the same power rating are placed at the receiving end of the feeder.



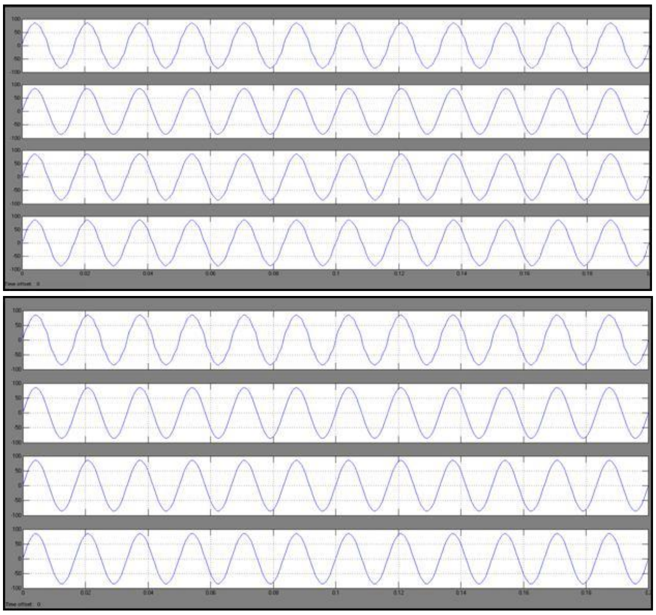


Fig. 16. Harmonic voltage amplification along the feeders (grid-tied operation of two parallel DG units).

VI. CONCLUSION

In this paper, the impacts of voltage controlled and current-controlled distributed generation (DG) units to micro grid resonance propagation are compared. To actively mitigate the resonance using DG units, an enhanced DG unit component of the proposed nonlinear virtual impedance is employed to compensate the impact of dg unit LCL filter grid-side inductor. The resistive element is responsible for active damping. With properly controlled dg equivalent harmonic impedance at chosen harmonic frequencies, the proposed method can even eliminate the harmonic circulating current among multiple dg units with mismatched output filter parameters. Here we are using the fuzzy controller compared to other controllers due to its accurate performance Comprehensive simulations are conducted to substantiate the validity of the proposed method.

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