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Design and Analysis of R-APF for Better Performance of Micro-Grids

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ABSTRACT:
The application of underground cables and shunt capacitor banks may introduce power distribution system resonances. In this paper, the impacts of voltage-controlled and current-controlled distributed generation (DG) units to micro-grid 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. 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 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.

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:

Compared with active front-end converters, diode or thyristor rectifiers still dominate in high-power applications, such as adjustable speed drives, uninterruptible power supply systems, and electrolysis. These equipment always injects a large amount of harmonic current into the power system, which may cause excessive harmonic voltage distortion and even give rise to malfunction of sensitive equipment in the vicinity of the harmonic source. Multiple tuned passive filters are usually installed at the secondary side of the distribution transformer in the industrial facilities to draw dominant harmonic current and provide power factor correction for inductive loads as well [1], [2]. However, unintentional series and/or parallel resonance, due to the passive filters and nonlinear loads and/or the utility, may result in excessive harmonic voltage amplification [3], [4].

Extra engineering work, therefore, must be consumed to calibrate and maintain required filtering performances. Conventional active filters intended for compensating the harmonic current of nonlinear loads cannot address the harmonic resonance issues resulting from the passive filter or the power factor correction capacitor [5]. This paper proposes a hybrid active filter to suppress the harmonic resonance in industrial facilities as well as mitigate harmonic current flowing into the utility. The proposed hybrid active filter is composed of an active filter and a power factor correction capacitor in series connection. The active filter operates as variable damping conductance at harmonic frequencies.

The harmonic conductance is determined according to the voltage total harmonic distortion (THD) at the installation location of the hybrid active filter. Based on this control, the damping performance of the active filter can be dynamically adjusted to maintain harmonic voltage distortion at an allowable level in response to load change and power system variation, where the allowable voltage THD can be regulated according to the harmonic voltage limit in IEEE std. 519-1992 [10]. Since the series capacitor is responsible for sustaining the fundamental component of the grid voltage, the active filter can be operated with a very low dc bus voltage, compared with the pure shunt active filter [11]. This feature is a significant advantage, in terms of both the rated KVA capacity and the switching ripples of the active filter. Several hybrid APF (HAPF) topologies [2-11,15-17] constitute active and passive parts in series and/or parallel have been proposed for reactive power and harmonic current filtering in [3-11]. The most common topologies are shunt HAPF (SHAPF) [3-10] consisting of an APF and passive filter connected in series with each other and series HAPF [11] which is a combined system of shunt passive filter and series APF. An extensive overview of the topological structures is explained in [2].

The controller design is a significant and challenging task due to its impact on the performance and stability of overall system. For this reason, numerous control methods such as pq theory [3-5], fast Fourier transform [5], dq theory [6-7], fuzzy controller [8-9], proportional resonant current controller [10] are controller methods applied in literature. The growing amount of electric energy generated from distributed or decentralized energy resources (DER), mainly of renewable, requires their appropriate grid integration. Thus, the renewable energy source interfacing with grid is the major issue in the electric utility side. Different types of converter topology in grid interconnection have been improved by researchers to develop power quality and efficiency of the electrical system [12-13].

This paper focuses the shunt hybrid active filter interfaces for the renewable energy source with proposed controller. On account of the limitations between existing literatures, the purpose of this paper is the following:

- To provide interconnection between renewable source and grid by using shunt hybrid active power filter (SHAPF) with unidirectional isolated DC-DC converter at dc link.
- To introduce a new control strategy for reactive power compensation and harmonics elimination.
- To adaptively controlled dc link voltage as reactive current component.
- To achieve reactive power compensation this is nearly equal to 99% of load reactive power capacity.

As this paper primarily focuses on the aforesaid four aspects of the shunt hybrid active power filter.

II. OPERATION PRINCIPLE AND CONTROLLER:

A simplified one-line diagram of the proposed hybrid active filter and the associated control are shown in Fig. 1(a). The hybrid active filter unit (HAFU) is composed of an active filtering part and a power factor correction capacitor C in series connection at the secondary side of the distribution transformer in industrial facilities. The harmonic current control, reactive current control and dc link control are achieved by indirect current control. With this control method, any extra start up pre-charging control process is not necessary for dc link. In addition, reactive power compensation is achieved successfully with perceptible amount. Besides, the harmonic compensation performance is satisfactory.

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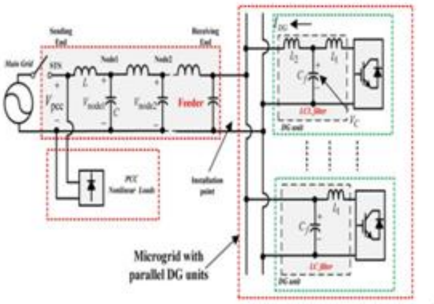
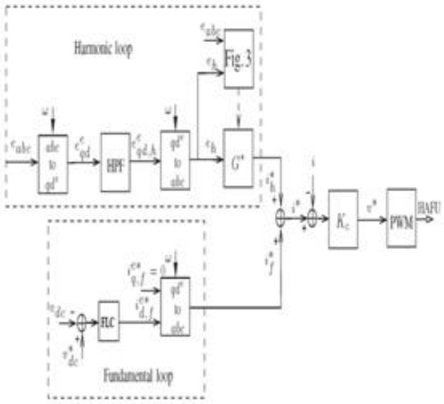


(a)



(b)

Fig. 1. (a) Circuit diagram. (b) Control block diagram

A. Harmonic Loop:

To suppress harmonic resonances, the HAFU is proposed to operate as variable conductance at harmonic frequencies as follows

$$i_h^* = G^*.e_h \qquad (1)$$

Harmonic voltage component is obtained by using the so-called SRF transformation [9], where a phase-locked loop (PLL) is realized to determine the fundamental frequency of the power system [28]. In the SRF, the fundamental component becomes a dc value, and other harmonic components are still ac values.

B. Fundamental Loop:

The first step is to isolate the harmonic components from the fundamental component of the grid currents. This is achieved through dq transformation (1), synchronized with the PCC voltage vector, and a first order low pass filter with cut off frequency of 10 Hz. Then the dq inverse transformation (2) produces the harmonic reference currents in abc referential frame. Therefore, the control ofdc bus voltage is able to be accomplished by exchanging real power with the grid. Thus, the current command i*d,fis obtained by a fuzzy logic controller. The fundamental current command i∗fin the three-phase system is generated after applying the inverse SRF transformation.

$$v_{dc} > 2\sqrt{2}\sum_h \left|\frac{1}{j\omega_h C_f} + j\omega_h L_f\right|.I_h \qquad (2)$$

C. Current Regulator:

The current command i∗is consisted ofi∗handi∗f. Based on the current commandi∗and the measured current i, the voltage commandv∗can be derived by using a proportional controller as follows:

$$v^* = K_c.(i^* - i) \qquad (3)$$

Where Kc is a proportional gain. According to the voltage ecommandv∗, space-vector pulse-width modulation (PWM) is employed to synthesize the required output voltage of the inverter. Fig. 2shows the model of the current control. The computational delay of digital signal processing is equal toone sampling delayT, and PWM delay approximates to half sampling delayT/2.

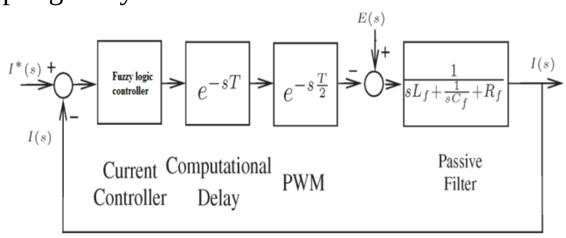


Fig. 2.Closed-loop model of the current control.

D. Conductance Control:

Fig. 3shows the proposed conductance controls. The harmonic conductance command G∗is determined

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according to the voltage THD at the HAFU installation point. The voltage THD is approximately calculated by the control shown in Fig. 3. Here, two low-pass filters (LPFs) with cutoff frequencyf_{LP}=20Hz are realized to filter out ripple components [29],[30]. The error between the allowable THD∗ and the measured THD is then fed into a Fuzzy logic controller to obtain the harmonic conductance command G∗. The allowable distortion could be referred to the harmonic limit in IEEE std. 519-1992 [31].

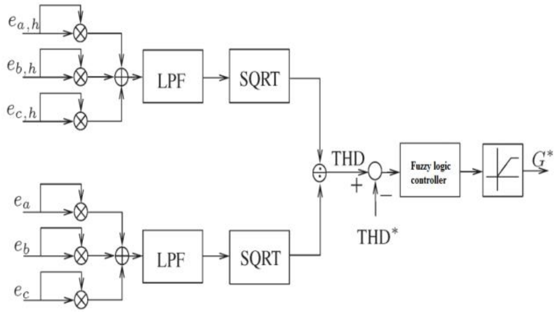

Fig. 3. Conductance control block diagram.

According to IEEE std. 519-1992 [31], voltage THD is limited to 5%, and individual distortion should be below 4%.Thus, THD∗ is set in the range of 3% and 5%. If vs ,hand Rsare neglected, voltage THD at E, due to harmonic current load Ih, can be expressed as follows:

$$THD = X_{pu}\sqrt{\sum_{h}(h.I_{h,pu})^2} \qquad (4)$$

The final reference current consists of three phase harmonic reference current signals, three phase reactive reference current signals and dc link control signals.

III. 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 a long underground feeder.

For the sake of simplicity, this paper only adopts a simple 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 evenly distributed in the feeder [2],[3].Note that the static transfer switch(STS) controls the operation mode of the micro-grid. When the main-grid is disconnected from the micro-grid, the PCC nonlinear loads shall be supplied by the standalone DG units.

A. Distributed Parameter Model in Grid-Tied Operation:

For a long feeder, as illustrated in Fig. 1, a lumped parameter model is not able to describe its resonance propagation characteristics. Alternatively, the distributed parameter model was discussed in [3] and [6], where the voltage distortions at PCC induce a harmonic voltage standing wave along the feeders. To make the discussion more straight forward, we assume that the micro-grid in the feeder receiving end only consists of one DG interfacing converter. In multiple DG-unit-based micro-grid is discussed. With the aforementioned assumption, the equivalent circuit model of a grid-tied micro-grid at the kth harmonic frequency is presentedin Fig. 2, where the kth PCC harmonic voltage is assumed to be stiff and Vpcck • Vk (x)and Ik (x) are the feeder kth harmonic voltage and harmonic current at position x. The length of the feeder is l.

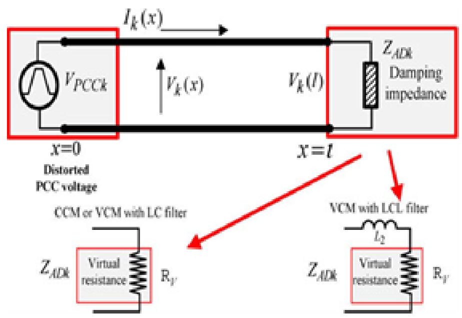

Fig:4 Equivalent circuit of a single grid-connected DG unit at the kth harmonic frequency

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

$$V_k (x) = Ae^{-\gamma x} + Be^{\gamma x} \quad (1)$$
$$I_k (x) = 1/z(Ae^{-\gamma x} - Be^{\gamma x}) \quad (2)$$

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

$$z = 1/LC \quad (3)$$
$$\gamma = jk\omega_f\sqrt{LC} \quad (4)$$

where ω_f is the fundamental angular frequency and L and Care the feeder equivalent inductance and shunt capacitance per kilo meter, respectively

.

1) DG Units with CCM and R-APF Control:

To determine the boundary conditions of the feeder, the equivalent harmonic impedance (Z_{ADk}) of the DG unit must be derived .First, the current reference (I_{ref}) of a CCM-based DG unitcan be obtained as

$$I_{ref} = I_{ref_f} - I_{AD}$$
$$= I_{ref_f} - H_D (s)V (l)/R_V \quad (5)$$

where I_{ref_f} is the fundamental current reference for DG unit power control, I_{AD} is the harmonic current reference for system resonance compensation, V (l) is the measured installation point voltage at the receiving end of the feeder, H_D (s) is the transfer function of a harmonic detector, which extracts the harmonic components of the installation point voltage, and R_V is the command virtual resistance. Without considering the delays in current tracking and harmonic detection, the DG unit works as a small resistor ($Z_{ADk} = R_V$) at the selected harmonic order k. Note that for the conventional CCM-based DG unit without any system harmonic compensation ,the current reference does not include any harmonic contents [corresponding to set R_V as ∞ in (5)].

Consequently,the conventional CCM-based DG unit can be simply modelled as an open-circuit connection at the receiving end.

2) DG Units with VCM and R-APF Control:

In contrast to CCM-based methods, the VCM-based DG units indirectly regulate the power flow through the control of filter capacitor voltage V_C (see Fig. 1). For a conventional VCM-based DG unit without harmonic damping, the voltage magnitude and frequency reference [10] can be obtained from the droop control scheme as

$$\omega_{DG} = \omega_f + D_P \cdot (P_{ref} - P_{LPF}) \quad (6)$$
$$E_{DG} = E + D_q \cdot (Q_{ref} - Q_{LPF}) + K_Q/s(Q_{ref}-Q_{LPF}) \quad (7)$$

where ω_f and ω_{DG} are the nominal and reference angular frequencies .E and E_{DG} are the nominal and reference DG voltage magnitudes. P_{LPF} and Q_{LPF} are the measured power with low pass filtering. D_p and D_q 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 [10],[12]–[13]. Once the voltage magnitude reference and the frequency reference are determined, the ripple-free instantaneous voltage reference (V_{ref_f})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 (I_{DG}) feed-forward term to the voltage control reference [14]. 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

$$V_{ref} = V_{ref_f} - V_{AD}$$
$$= V_{ref_f} - R_V \cdot (H_D (s) \cdot I_{DG}) \quad (8)$$

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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 + jkωf L2) 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 modelled by an equivalent harmonic impedance at the receiving end of the feeder, the following boundary conditions can be obtained:

$$V_k\ I_k = Z_{ADk} \quad (9)$$

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

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

$$V(x)_k = Z_{ADk}\cosh(\gamma(l-x)) + z\sinh(\gamma(l-x)) / Z_{ADk}\cosh(\gamma l) + z\sinh(\gamma l)\ V_{PCCk}\ . \quad (11)$$

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 [9] and[20].

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 author's 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. 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

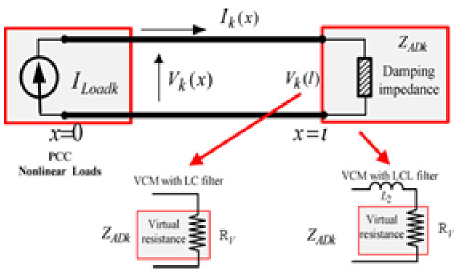

Fig:5 Equivalent circuit of a single islanding DG unit at the kth harmonic frequency.

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, where VCM-based DG unit is also modelled as an equivalent harmonic impedance using the control scheme in (8). The nonlinear PCC load in this case is modelled as a harmonic current source at the sending end of the feeder [3].With the knowledge of boundary conditions at both sending and receiving ends as

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

Vk Ik = ZADk (13)

The kth harmonic voltage distortion along the feeder can be obtained

Vk (x) =e−γx1 + ((z − ZADk)/(z + ZADk))e−2γ_− eγx1 + (z + ZADk)/(z − ZADk)e2γ_zILoadk (14)

From (14), it can be noticed that the voltage propagation in an islanding system harmonic is also related to the DG unit equivalent 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

Vref = Vreff − VAD – Vcomp = Vreff − RVHD (s)IDG-s(L2)HD(s)IDG. (15)

Comparing (15) 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 inductor L2 .Once the modified voltage reference in (15) 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 (15), 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

HD (s) = 1 − 2ωBPss2 + 2ωBPs + ω2 (17)

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

VComp = s(−L2)HD (s)IDG =−sL2 +2ωBPL2s2s2 + 2ωBPs + ω2 IDG. (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 [10], [18] and [19] 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 [10]. VComp in (18) is deducted from the reference voltage Vreff . In order to alleviative the impact of derivative operator in VComp, a high pass filter can be used as an approximation [14]. However, as already been pointed out in [12] and [13], the adoption of high pass filter introduces some magnitude and phase errors, which can degrade the performance of the compensation term VComp.

B. Implementation of Nonlinear Virtual Capacitor:

In this subsection, a well-understood double-loop 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

IInner = GOuter(s) · (Vref − VC) =KP +2Kikωck ss2 + 2ωck s + (kωf)2 _(Vref − VC) (19)

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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.

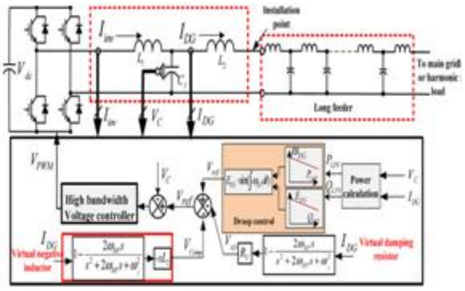

Fig:6 Mitigation of distribution feeder harmonic propagation using virtual resistor and virtual negative inductor.

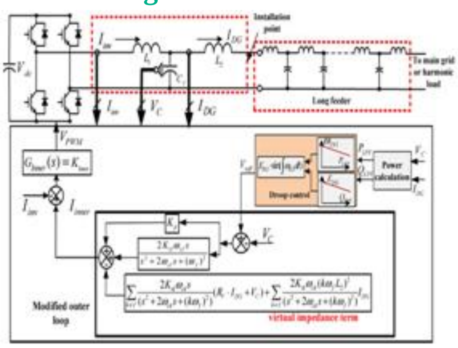

Fig:7Mitigation of harmonic propagation using virtual resistor and nonlinear virtual capacitor.

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:

$$L2 (\omega f\ t) - 1CV\ k(\omega f\ t)= 0 \qquad (20)$$

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 [21] 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 drops on the nonlinear virtual capacitor can be obtained.

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.

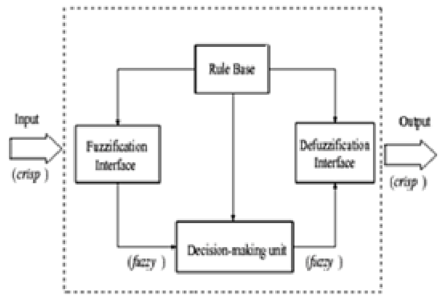

Fig.8. Fuzzy logic controller

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

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of discourse. iv. Implication using Mamdani's, 'min' operator. v. Defuzzification using the height method.

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.

TABLE I: 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

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

$$E(k) = \frac{P_{ph(k)} - P_{ph(k-1)}}{V_{ph(k)} - V_{ph(k-1)}} \qquad (9)$$

$$CE(k) = E(k) - E(k-1) \qquad (10)$$

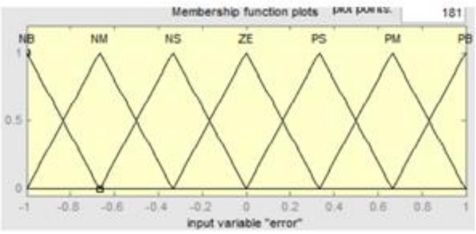

Fig.9. Membership functions

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

$$u = -[\alpha E + (1-\alpha) * C] \qquad (5)$$

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. Set of FC rules is made using Fig.(9) is given in Table 3.

IV. SIMULATION RESULTS:

Simulation studies are carried out using MATLAB/Simulink. The main purpose of the simulation is to evaluate the effectiveness and correctness of the control strategy used in the SHAPF with variations of linear loads. Parameters used in simulations are given in Table I. In simulation, the nominal frequency of the power grid is 50 Hz and the harmonic current source is generated by the three phase diode rectifier.

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A power stage setup was built and tested as shown in Fig8.Table I gives experimental parameters based on the per unit system..

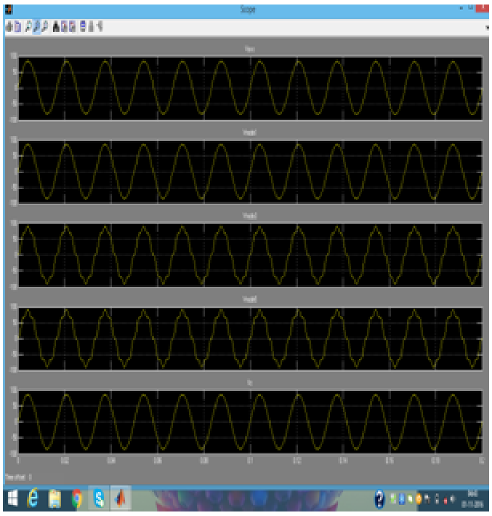

Fig: HARMONIC VOLTAGE AMPLIFICATION DURING A SINGLE DG UNIT GRID CONNECTED OPERATION WITH OUT DAMPING

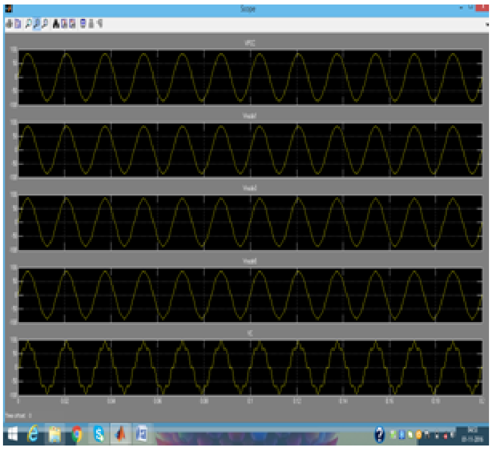

Fig: HARMONIC VOLTAGE AMPLIFICATION DURING A SINGLE DG UNIT GRID CONNECTED OPERATION WITH VIRTUAL NON LINEAR CAPACITOR AND RESISTOR BASED ACTIVE DAMPING

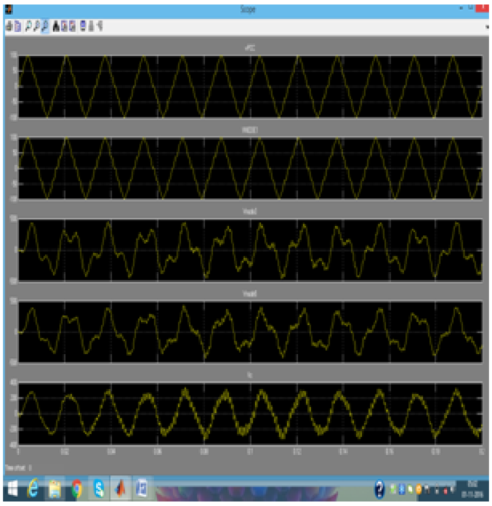

Fig: HARMONIC VOLTAGE AMPLIFICATION DURING A SINGLE DG UNIT ISLANDING OPERATION WITH OUT DAMPING

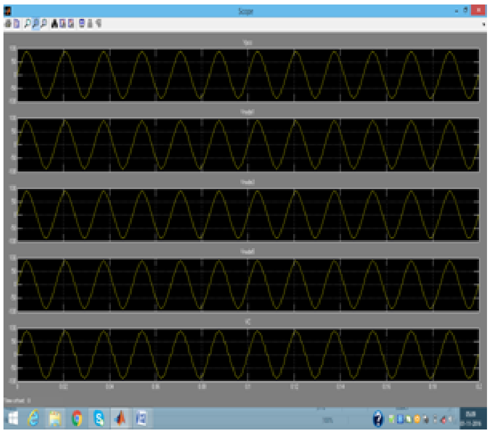

Fig: HARMONIC VOLTAGE AMPLIFICATION DURING A SINGLE DG UNIT ISLANDIG OPERATION WITH VIRTUAL NON-LINEAR CAPACITOR AND RESISTOR BASED ACTIVE DAMPING

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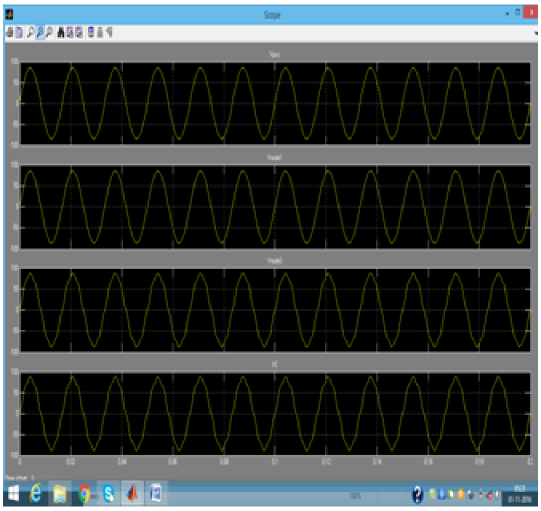

Fig: HARMONIC VOLTAGE AMPLIFICCATION ALONG THE FEEDERS (GRID-TIED OPERATION OF TWO PARALLEL DG UNITS) (DG1:SHORT CIRCUIT,DG2:L IMPEDANCE)

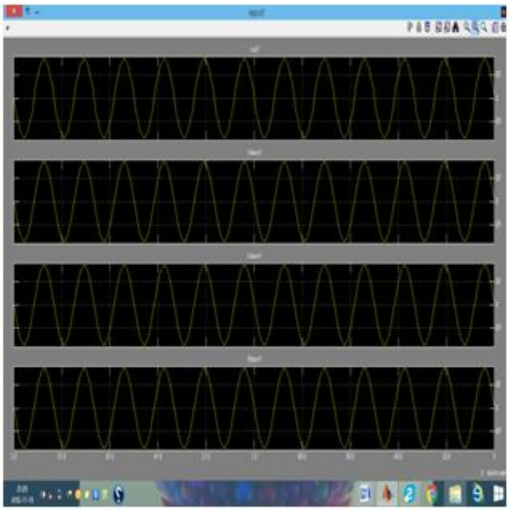

Fig: HARMONIC VOLTAGE AMPLIFICCATION ALONG THE FEEDERS (GRID-TIED OPERATION OF TWO PARALLEL DG UNITS) (DG1:R IMPEDANCE,DG2:R IMPEDANCE)

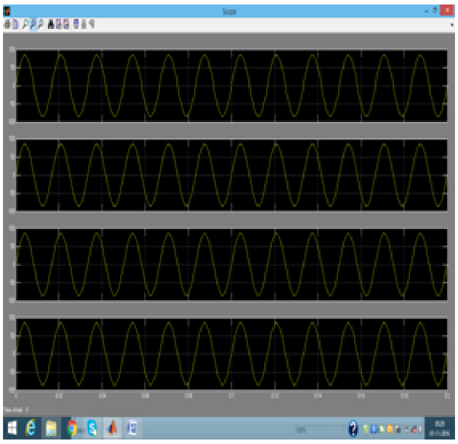

Fig: HARMONIC VOLTAGE AMPLIFICCATION ALONG THE FEEDERS (GRID-TIED OPERATION OF TWO PARALLEL DG UNITS) (DG1:R IMPEDANCE,DG2:RL IMPEDANCE)

V. CONCLUSION:

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. Specifically, the capacitive component of the proposed nonlinear virtual impedance is used to compensate the impact of DG unit LCL filter grid-side inductor. The resistive component is responsible for active damping. 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 pro-posed method.

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