Development Of A VCM Based Harmonic Controlled Dg-Grid Interfacing Converters

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Abstract— **Now a days the non-linear loads and power electronic based DG systems involvement is increased and these are may introduce power quality issues to the distribution power systems. If we use DG grid interfacing converters properly and regularly then they will improve distribution system efficiency and power quality. This paper mainly discuses on the distribution system harmonic control through DG grid interfacing converters. There is two DG systems in general, one is current controlled DG and another one is voltage controlled DG. There is major previous works on harmonic compensation are done in current controlled DG .But hear a new harmonic control scheme using voltage controlled method is developed in this paper. This method is having more flexibility and similar compensation performance when compare to current controlled DG .This voltage controlled method provides direct voltage and frequency support to grid because of avoiding harmonic current tracking loop. This proposed systems simulated by using MATLAB/SIMULINK.**

Index terms : Distributed Generation(DG), Circulating current, Distributed active power filter(APF),Power quality, Harmonic compensation.

I INTRODUCTION

Now a days most of the energy industries are able to fundamental changes as more distributed energy resource based DG (distributed generation) units are connected to grid. Because of increasing conventional energy cost, energy security and green house gas emissionns. These DG sytems uses the environment friendly renewable energy sources easily. Major DG sytems are connected to the grid through power electronic interfacing converters .The increased involvement of DG may introduce several challenges such as harmonics, voltage regulations problems, protection interferences, voltage sags etc.While DG interfacing converters may introduce power quality issues to the distribution power system, if they designed and controlled properly, they will able to improve system efficiency and power quality. There is many ancillary services can also provided through DG when sufficient power rating is available. These services include power factor compensation, voltage support, flicker mitigation, system harmonic compensation[3]-[5], [21], imbalance voltage compensation[6],[11] etc. The extra apparent power rating is achievable due to interminent nature of many power electronic based DG systems [such as wind, photovoltaic etc].Further the development of smart grid and micro grid concepts and the associated advancement of communication, technology and control techniques for power electronics- interfaced DG, the control of DG to improve system power quality is becomes promising topic. Major power electronic interfaced DG systems use voltage source inverters[VSI] as interfacing inverter. The control mechanism of a VSI is mainly consists of two types. One is current control method (CCM)) and another one is voltage control method (VCM). CCM is widely adopted in active power filters(APF'S) to decrease the system harmonics[7]-[10],[12],[22]. For micro grid applications, particularly in islanding operation, the DG unit is desired to operate with

VCM because of providing voltage and frequency support for loads[17]-[19].This VCM based v-f droop control will control the DG interfacing converters. Hear current controlled compensation is used for APF applications and cannot be implemented directly. In order to overcome this limitation a new VCM based harmonic control method is developed which is don't having current loop and harmonic current reference. This paper starts with brief explanation of harmonic compensation based on CCM in Section II and VCM based harmonic compensation in Section III. The proposed method is more flexible and gives similar compensation when compare to CCM based compensation .The comparison between two methods is explained in section IV. At last the simulation results are provided in section V. Mainly harmonic compensation is focused on this paper and also proposed control method is extended to address other voltage quality problems [e.g voltage flicker and imbalance].

II. CCM-BASED COMPENSATION

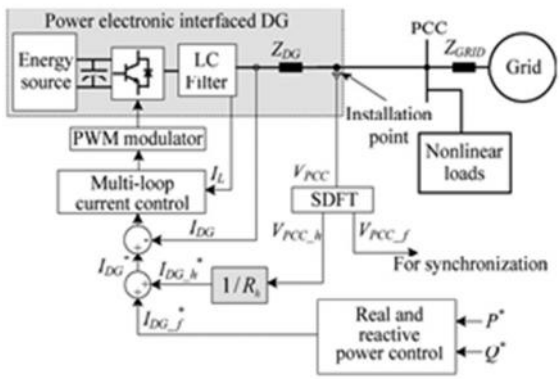

Fig. 1.Compensation scheme for current-controlled DG

Before going to discuss proposed VCM based harmonic compensation ,the CCM based harmonic compensation is explained in this section. The selection of PCC voltage(point of common coupling) quality improvement using current controlled grid connected DG has been taken in [3]-[5].Generally this method uses to control the DG unit as shunt APF(active power filter),Because hear the DG unit absorbs harmonic currents of non-linear loads and leaves a better source current and PCC voltage with lower total harmonic distortion(THD).The best way to achieve this function is to control the DG as resistance APF(R-APF) [10],[12],[21],[22],where PCC voltage is measured and harmonic components are extracted to gives reference harmonic current of a DG(I_h^*= VPCC_h/Rh) .So DG unit acts as small resistance($R_{h)}$ at harmonic frequencies.

To improve the system performance a discrete frequency tuned distributed APF is developed in [8] and [9]. The distributed active filtering system(DAFS) is having more effective solution to expand multiple shunt active filter in the system to damp the harmonic resonance. The block diagram of compensation scheme for current controlled DG is as shown in fig 1.From the diagram the fundamental reference current (I_f^*) is obtained from power control loop.The real power reference can be obtained by using maximum power point tracking in photovoltaic or wind system ,the maximum system efficiency control like in fuel cell system. The reactive power command is produced from the voltage support requirements or load power factor compensation algorithms.If the unity power factor is desired for DG ,then reactive power command is set to zero. So harmonic current reference(I_h^*) is produced by requirement of power quality improvement and power rating of a DG unit.

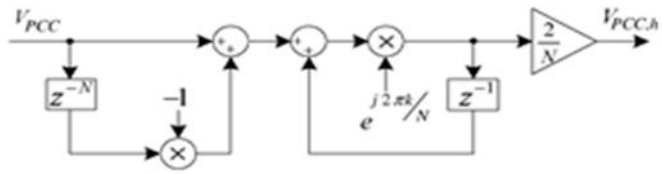

Fig. 2. SDFT for fundamental and harmonic component extraction.

The reference harmonic current generation and the current tracking loop designed carefully because there is a chance to obtain conflicts between PCC voltage harmonics and the primary function of real power injection of a DG system. Traditionally the separation of harmonic and fundamental components of PCC voltage uses high or low pass filter in either the stationary or synchronous frame[13].This filtering introduces the magnitude and phase errors in the extracted signals which leads to inaccurate compensation performance. On the other hand ,it is need to avoid the high-order harmonic tracking due to limited current control bandwidth. The current tracking and inaccurate harmonic voltage extraction may increases these high order or even lead to system instability.So most significant low order harmonics in a system would be more appropriate[such as 5th,7th,11th harmonics].

To extract the harmonics in selective manner ,resonant filters are used in[5].The resonant filters has fast change of phase angle around the resonant frequencies. As a result even small variation of resonant frequencies may introduce substantial phase errors in extracted signals. To extract the harmonics accurately we can use the sliding discrete fourier transform[SDFT][14].The SDFT for fundamental and harmonic component extraction is shown in figure 2.From the figure 2 SDFT having simple structure with sliding window[with N points] and can be realized easily in DSP for real-time implementation. The z-domain transfer function for the hth harmonic can be described as

$$H_{SDFT} = \frac{1-Z^{-n}}{1-e^{\frac{j2\pi h}{N}} \cdot Z^{-1}} \qquad (1)$$

Once the harmonic voltage is obtained ,the harmonic current reference can be produced by using designed harmonic resistance R_h or frequency varying conductance Y_h.Hear the values of R_h and Y_h will affects the compensation performance.Normally smaller R_h will gives better compensation performance but it reduces the DG system stability.The available rating of DG also determines the value of R_h in order to avoid problem with the primary function of power generation.The DG's available rating can be realized through an adoptive control algorithm [4],[5],[8],[9] or by an integral ontroller[12].By adding the harmonic current reference and fundamental reference from power control loop,we

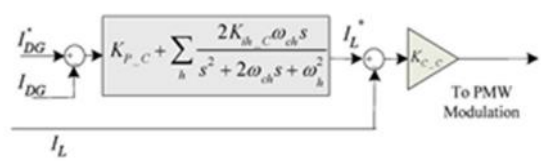

Fig. 3. Multiloop current tracking diagram.

Can get DG reference current. The multi loop current tracking diagram as shown in figure 3. From the controller diagram the currents I_{DG}^* and I_{DG} are DG reference and feedback currents.To achieve good fundamental and harmonic current tracking performance a current controller based on p^+ resonant controllers[at fundamental and harmonic frequencies of interest] can be used [15],[16].

$$H_C(s) = K_{P_C} + \sum_h \frac{2K_{ihc}\omega_{ch}s}{s^2+2\omega_{ch}s+\omega_h^2} \qquad (2)$$

where ω_h is the system fundamental and harmonic frequency, ω_{ch} is the cutoff bandwidth at each frequency, K_{P_C} is the proportional control gain at all frequencies, K_{ih_C} is internal gain at each frequency.To improve dynamic response and stability of control scheme ,the inverter side induction current I_L tracking loop with proportional

controller K_{c_C} is also added in figure 3. At last it should be noted that the feeder impedence is small and DG unit is connected to grid through an LCL filter ,then voltage meadured at the installation point can very close to pcc voltage. Therefore remote PCC voltage measurement is not required for this compensation scheme.

III. PROPOSED VCM-BASED COMPENSATION

CCM is mostly employed for grid connected DG inverters ,the voltage controlled DG can also adopted as discussed in [17]-[19]. If a DG system operated in islanding mode, the VCM will provide seamless operation and also provide necessary voltage and frequency support.

(A) Principle of Harmonic Compensation :

The equivalent circuit of single DG grid system as shown in figure 4.from the diagram DG unit represented as controlled voltage source V_{DG} with an output series impedence Z_{DG} .The grid described as a voltage source $V_{GRID}$and grid impedence Z_{GRID}.

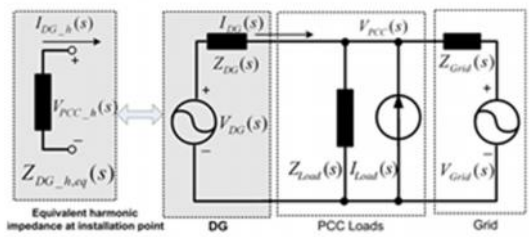

Fig. 4. Equivalent circuit of a single DG–grid system with VCM.

The PCC non-linear load is shown in the middle as a harmonic current source and passive loads. If the DG harmonic voltage (V_{DG}_h) is controlled by using pcc harmonic voltage (V_{pcc}_h) as

$$V_{DG_h}(s) = -G \cdot V_{PCC_h}(s) \qquad (3)$$

The equivalent harmonic impedence of DG at installation point can be derived given below

$$I_{DG_h} = (V_{DG_h} - V_{PCC_h})/Z_{DG_h}$$

$$= -(1 + G)V_{PCC_h}/Z_{DG_h}$$

$$Z_{DG_h,eq} = -V_{PCC_h}/I_{DG_h} = Z_{DG_h}/(1 + G) \qquad (4)$$

where I_{DG}_h is the DG harmonic current and Z_{DG}_h is the DG harmonic impedance. This equivalent impedance at harmonic frequencies is also shown in the left side of Fig. 4 .

From the previous analysis ,it is clear that by controlling the DG harmonic voltage with positive feedback gain of G properly, then the DG harmonic impedence will scaled down by a factor of (1+G) .So the harmonic impedence at the DG side can be lower than that at grid side. As a result major non-linear load current will be absorbed by DG unit, leaves improved grid current and PCC voltage. So clearly note that higher G value will further reduce the PCC voltage harmonics .

With G=0,system will be a standard voltage controlled DG without any active compensation. Hear harmonic current is shared automatically to the DG and grid side harmonic impedences.This is similar to current controlled method, where DG current is sinusoidal if the active power filtering function is not enabled.

Furthermore, it is known that the focus of v-f droop control of parallel DG systems is fundamental power flow. So DG current is like to have harmonic problems. The proposed method may also used to control the DG current with lower harmonics and better THD. If the DG harmonic current is attenuated properly with negative DG, the performance will be similar to conventional current controlled DG.

The value of G can be controlled with a range from -1 to ∞ for different compensation requirements or DG operation objectives. Select the practical limit of G tends to have over modulation problems and makes system unstable. At last it is important to note that G should not be less than – 1 ,this will introduce capacitive equivalent impedence, which may be induce system resonance.

In this work $G > 0$ is named as harmonic compensastion, $G < 0$ is defined as harmonic rejection mode, G = 0 is named as uncontrolled mode.

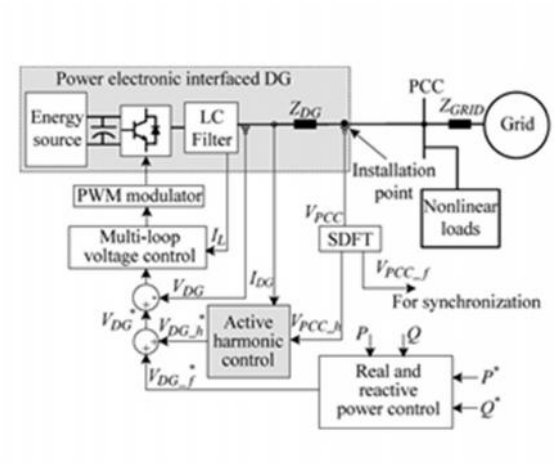

Fig. 5. Proposed control strategy for voltage-controlled DG.

The proposed voltage controlled DG scheme is as shown in figure 5. From the figure 5 SDFT block will separates fundamental and harmonic components of PCC voltage. Hear fundamental voltage is useful for grid voltage synchronization and DG fundamental real and reactive power calculation. The harmonic component are used to generate the inverter reference harmonic voltage .From the control diagram of VCM the real and reactive power block will produce the fundamental reference of the DG voltage. While reference DG voltage is produced by the active harmonic control block .

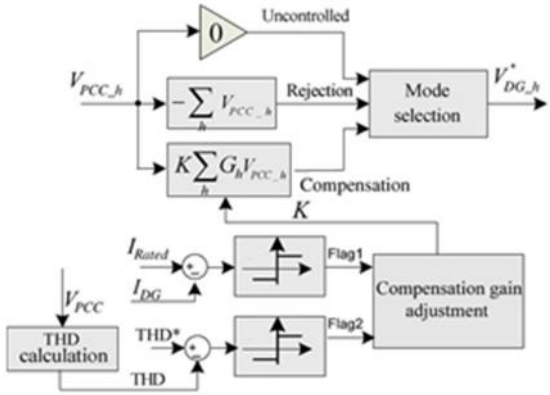

Fig. 6. Active harmonic control algorithm (based on VCM)

The active harmonic control mechanism is as shown in figure 6. As earlier said, this control block can be operated in three modes. They are compensation, rejection, uncontrolled mode.The 'Compensation gain adjustment ' block is added to avoid overrating operation and possible conflict with primary function of real power control .By using adoptive controller [4] ,[5],[8],[9] or simple integral controller [12],this algorithm sets the value of K ,which will changes the effective gain G_h is lower for high order harmonics. At last it will be noted that harmonic rejection mode G_h= -1 is used for all the selected harmonics in this work.

B. Analysis of the Proposed Control Strategy :

From the fig.4, 5, 6

$$I_{LOAD}(s) + V_{DG}(s)/Z_{DG}(s) + V_{Grid}(s)/Z_{Grid}(s) - V_{PCC}(s)/Z_{parllel}(s) = 0 \quad (5)$$

$$1/Z_{Parallel}(s) = 1/Z_{DG}(s) + 1/Z_{Grid}(s) + 1/Z_{load}(s) \quad (6)$$

Consider $Z_{load}(s)$ is much higher than $Z_{Grid}(s)$ and $Z_{DG}(s)$ and $v_{Grid}(s) \approx 0$ at harmonic frequencies .If the DG harmonic voltage is controlled actively (harmonic compensation/rejection), then PCC harmonic voltage and DG harmonic current attenuation ratios when compared to uncontrolled mode can be obtained as shown in below.

$$\frac{V_{PCC,Active}(s)}{V_{PCC,uncontrolled}(s)} \approx \frac{Z_{DG}(s)+Z_{Grid}(s)}{Z_{DG}(s)+(1+G)\ .Z_{Grid}(s)} \times 100\% \quad (7)$$

$$\frac{I_{DG,Active}(s)}{I_{DG,uncontrolled}(s)} \approx \frac{(Z_{DG}(s)+Z_{Grid}(s)).(1+G)}{Z_{DG}(s)+(1+G)\ .Z_{Grid}(s)} \times 100\% \quad (8)$$

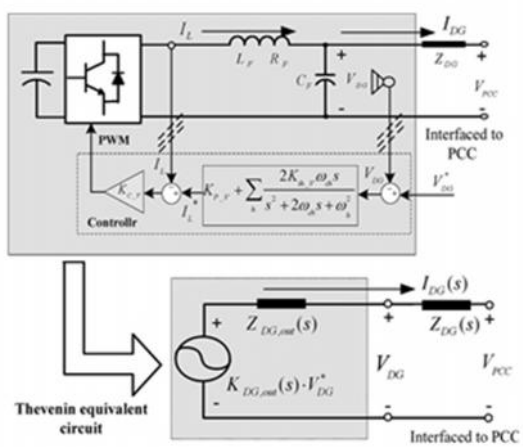

Fig. 7. Multiloop voltage control and its Thevenin equivalent circuit

Multiloop VCM is applied due to tracking of voltage reference properly. The total multiloop DG voltage control block is shown in figure 7.Here ,the parallel P^+ resonant controllers for fundamental and different harmonic components are used as outer voltage loop controller and inner proportional current control (K_{c_v}) uses the LC filter inductor current as feedback.

The closed loop dynamic behavior of DG is evaluated by Thevenin equivalent circuit is shown in lower part of figure 7.This is expressed in

$$V_{DG} = K_{DG,OUT}(s).V_{DG}^{*} - Z_{DG,out(s)}.I_{DG} \quad (9)$$

Where $Z_{DG,out(s)}$ and $K_{DG,OUT}(s)$ are the equivalent DG output impedence and voltage tracking gain associated with the multiloop voltage control scheme and V_{DG}^{*} is reference DG voltage. From the figure 7 the $Z_{DG,out(s)}$ and $K_{DG,OUT}(s)$ are derived as in

$$K_{DG,Out}(s) = \frac{H_V(s)Kc_V\,M(s)N(s)}{1+M(s)N(s)+H_V(s)KC_VM(s)N(s)+M(s)KC_V} \qquad (10)$$

$$Z_{DG,Out}(s) = \frac{N(s)(1+Kc_{V}M(s))}{1+M(s)N(s)+H_V(s)KC_VM(s)N(s)+M(s)KC_V} \qquad (11)$$

where $M(s) = 1/(L_F s + RF)$ and $N(s) = 1/(C_F s)$ are the transfer functions related to the *LC* filter parameters (L_f, R_f, and C_f are the filter inductance, inductor stray resistance, and filter capacitance, respectively).The transfer function of the outer loop voltage controller $H_v(s)$ is

$$H_v(s) = K_{P_V} + \sum_h \frac{2K_{ih_c}\omega_{ch}s}{s^2+2\omega_{ch}s+\omega_h^2} \qquad (12)$$

The accurate DG equivalent harmonic impedence at the PCC when dynamics of voltage controller are considered is given as

$$Z_{DG,eq} = \frac{Z_{DG}(s)+Z_{DG,out}(s)}{1+G.K_{DG,out}(s)} \qquad (13)$$

IV. COMPARISON BETWEEN VCM AND CCM

Both CCM and VCM can efficiently control the DG real and reactive power and compensate the pcc harmonic voltage. Following are the comparison between the two methods.

1) In without compensation mode, the ccm will pushes all harmonic currents to grid side automatically. So the PCC voltage is polluted due to harmonic voltage drops on the source impedence. But the voltage controlled DG can share the non linear load current with the source according to their respective impedences. So with the conventional control VCM leads to better PCC voltage compared to ccm

2) Let the DG system operating in intentional islanding mode, the VCM has the advantage of seam less control transition for operating mode. In contrast, the ccm has the difficulties in islanding operation,as it is difficult to provide voltage and frequency support in islanding mode.

3) The VCM is more flexible with harmonic compensation, rejection and uncontrolled modes. Where the harmonic rejection operation gives similar performance as the ccm without compensation.

V.SIMULATION RESULTS

The proposed harmonic control strategies are verified are verified through Matlab/simulink. Hear both ccm and VCM are implemented for harmonic compensation. While in the simulation the non-linear load at the PCC is three phase diode rectifier with parallel connected capacitor(1000 µF) and resistor(25 Ω) at the DC side. The system parameters used in simulation are listed in table I.

TABLE I

PARAMETERS IN THE SIMULATION

PARAMETERS	RANGES
Grid Voltage V,	104 V,60 Hz(3 phase)
DC link Voltage	260 v
LC Filter	L=1.25mH, C=40µF
DG impedence	R=1Ω, L=2.5mH
Grid impedence	R=1Ω, L=2.5mH
Switching Frequency	12KHz
Power Reference	P*=300 W, Q*=125 Var

1) CCM :

The current controlled interfacing inverter tested in simulation with 5th harmonics is compensated. The performance of current controlled DG without harmonic compensation is shown in figure 12

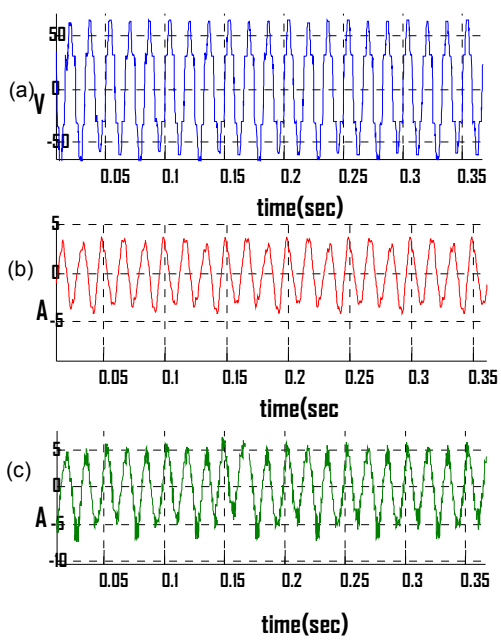

Fig. 12. Current-controlled method without harmonic compensation. (a) PCC phase voltage. (b) Grid current. (c) DG current

From the figure the DG current has very little harmonic current and the grid supplies the non-linear load current. Therefore PCC voltage is polluted due to harmonic voltage drop on the grid impedence. The performance of CCM with harmonic compensation is shown in figure 13.

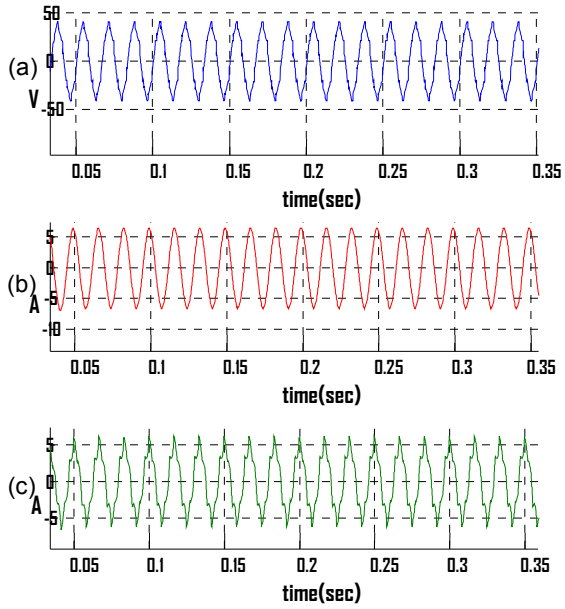

Fig. 13. CCM with harmonic compensation. (a) PCC phase voltage. (b) Grid current. (c) DG current.

As expected that the low resistence R_h at the selected harmonic frequencies, the DG unit absorbs most of the non-linear load currents and leaves improved pcc voltage, grid current as shown in the figure 13 (a),(b).The figure 14 and 15 represents the harmonic analysis of PCC voltage in ccm without and with harmonic compensation.

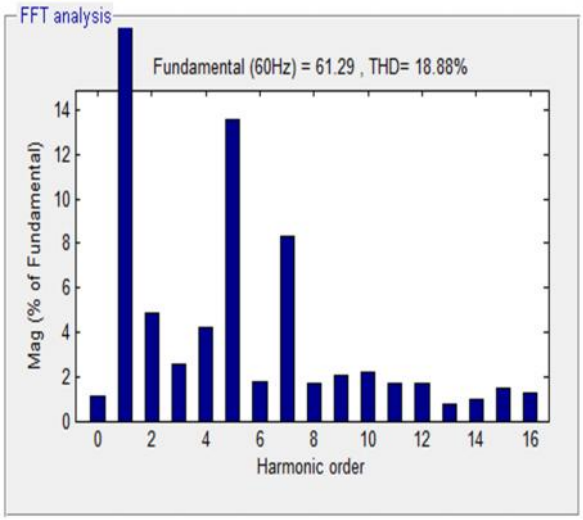

Fig 14: harmonic analysis of PCC voltage without compensation(CCM)

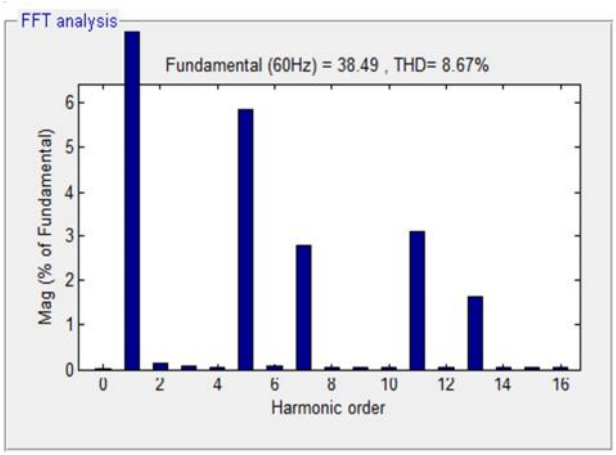

Fig 15: harmonic analysis of PCC voltage with compensation(CCM)

From the figures 14 and 15 ,The THD of the PCC voltage without compensation is 18.88 % and the harmonic distortion is reduced to 8.67 % by applying the current controlled harmonic compensation method.

***2) VCM*:**

The voltage controlled DG and different operating modes are also tested in simulation, and the results shown in figures 16-18.

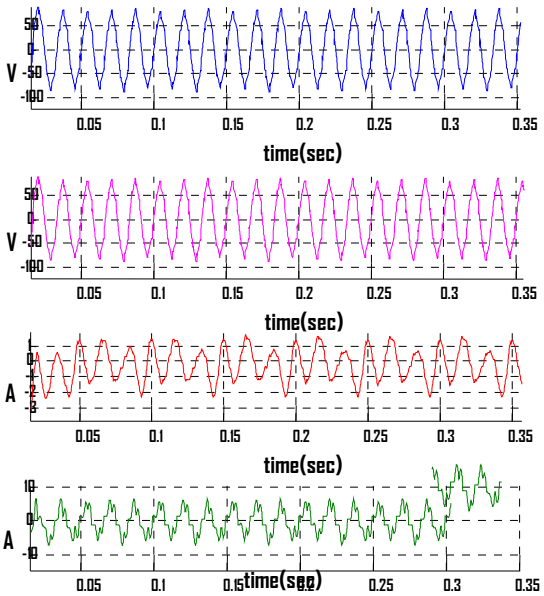

Fig. 16. VCM without compensation. (a) PCC phase voltage. (b) DG phase voltage. (c) Grid current. (d) DG current

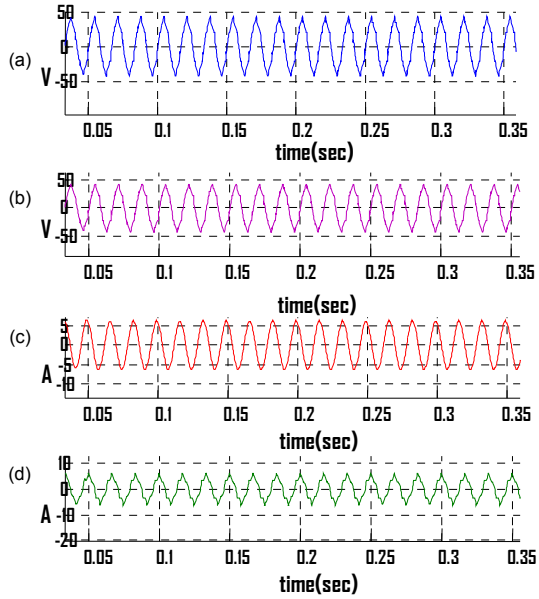

Fig. 17. VCM with harmonic compensation. (a) PCC phase voltage. (b) DG phase voltage. (c) Grid current. (d) DG current

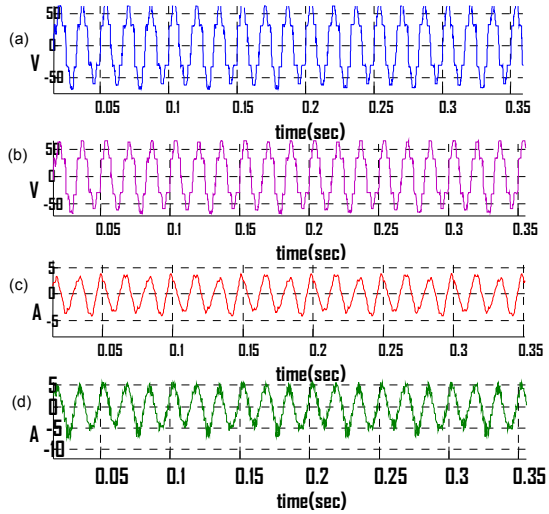

Fig. 18. VCM with harmonic rejection. (a) PCC phase voltage. (b) DG phase voltage. (c) Grid current. (d) DG current.

Figure 16 shows VCM without any harmonic compensation ,where the DG unit is controlled with pure sinusoidal voltage (see the fig.16(b)).In this mode, DG and grid share non-linear load current as we see from fig.16(c) and (d).Consequently, the PCC voltage is distorted due to non-linear load currents through the grid impedence.

The VCM with harmonic compensation is shown in figure 17[with $G_5 = 12$, $G_7 = 12$, $G_{11} = 5$].The dg impedence is reduced by a factor (1+G_h).So the most of the non-linear current is supplied by the DG unit. Therefore the grid current and PCC voltage is improved as shown in figure 17.

At last, harmonic rejection mode is tested with $G_h = -1$. Due to high equivalent impedence at harmonic frequencies the DG current is sinusoidal. In this case, the grid provides all non-linear load current. So the grid current and voltage are distorted as shown in fig.17.The harmonic analysis under different modes as shown in fig.19, 20,and 21.

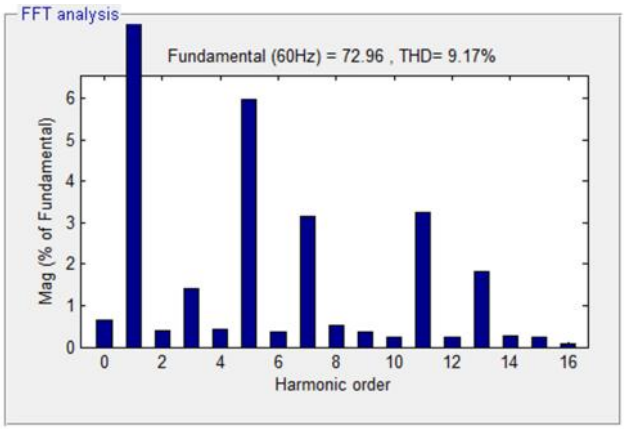

Fig 19: harmonic analysis of PCC voltage without compensation(VCM)

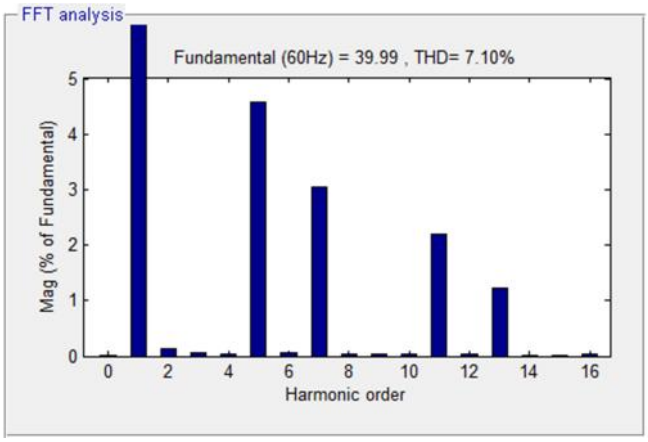

Fig 20: harmonic analysis of PCC voltage with compensation(VCM)

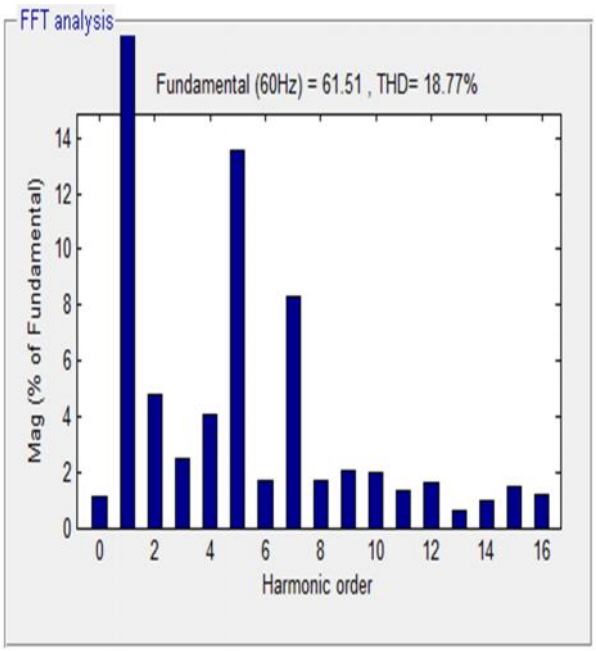

Fig 21:harmonic analysis of PCC voltage with harmonic rejection(VCM)

The PCC voltage has 9.17% THD in VCM without harmonic compensation mode. The PCC voltage distortion is reduced to 7.10 % in harmonic compensation mode. At last harmonic rejection mode introduces the polluted PCC voltage with THD of 18.77 %.

VI. CONCLUSION

This paper mainly focuses on the opportunities of distribution system power quality improvement using system DG interfacing inverters. Hear both current controlled and voltage controlled methods are implemented and their PCC voltage harmonic compensation schemes are investigated and compared. It has been shown that the proposed VCM scheme can operate at compensation, rejection and uncontrolled modes, which is more flexible than current controlled DG. Furthermore, the VCM method can be easily incorporated into the v-f droop control scheme of DG systems in microgrid. The proposed harmonic control methods have been verified by the simulation by using MATLAB/Simulink.

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