Active Harmonic and Hysteresis Mitigation in Grid-Connected DG Units with H Infinity Controller

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Abstract—The application of nonlinear loads may cause distribution system power quality issues to utilize DG unit interfacing converters to actively compensate harmonics, an hysteresis current control approach is used, which seamlessly integrates system harmonic mitigation capabilities with the primary DG power generation function. As the hysteresis current controller has to independently control fundamental and harmonic DG currents, local nonlinear load harmonic current detection and distribution system harmonic voltage detection are not necessary for the proposed harmonic compensation method. Moreover, a closed-loop control scheme is employed to directly derive the fundamental current reference with hysteresis current control technique. The proposed power control scheme effectively eliminates the impacts of steady-state fundamental current tracking errors in the DG units. Thus, the single-phase active filter control for testing the command and control strategy was used a single-phase voltage source inverter (full bridge) and the harmonic compensation functions are activated. In addition, this paper also briefly discusses the performance of the proposed method when DG unit is connected to a grid with frequency deviation. Simulated results from a single-phase DG unit validate the correctness of the proposed methods using MATLAB/Simulink.
Index Terms **– Distributed generation, hysteresis control, active filter, harmonic compensation, voltage source inverter**

I. INTRODUCTION

The applications of distributed generation (DG), large numbers of DG units have been expected to delivery energy to the grid/loads via power electronic inverters. Subsequently, a concept solution, i.e., microgrids, has drawn considerable attention, in which local generation and loads are viewed as subsystems that can support the grid collectively, and isolate the microgrid's loads from the grid during disturbances. Several essential aspects on microgrids are continuously reported in the literature, namely accurate power sharing control, seamless operation-mode transfer, stability issues of microgrids, and auxiliary grid support.

However, those inverter topologies together with control certainly influence harmonic interactions between DG inverters and distorted grids. Depending on the penetration levels of DG inverters and practical grid parameters, harmonic resonances can also appear at frequencies within the inverter control bandwidth. This is the frequency range of interest, for which harmonic distortion impact of DG inverters will be studied. This paper mainly focuses on DG inverters of microgrids operating as current sources at the grid-connected mode where the grid voltage has background harmonic distortion. A similar analytical pattern can be applied to DG inverters of microgrids with voltage control at the islanding-operation mode.

To minimize harmonic interactions between DG inverters and polluted grids, first of all, each individual inverter should have a good current control design in order to mitigate its current distortion impact in a distorted grid. The existing approaches are to increase the control bandwidth and to reduce the sensitivity of the inverter to grid harmonic voltages by applying different controllers and control loop design. However, the control parameters of the inverter are usually tuned by trial and error based on harmonic analysis of currents so as to ensure the output current complying with current distortion limits. It is not a handy approach to design controllers in such a way because there is no guidance to impose restriction in the inverter design. Therefore, approaching from another point of view, this paper proposes to introduce output impedance constraints to inverter control design in order to get acceptable results in a distorted grid. To clarify this proposal, the output impedance modeling of the inverter and detailed analysis are presented.

To compensate distribution system harmonic distortions, a number of active and passive filtering methods have been developed. However, installing additional filters is not very favorable due to cost concerns. Alternatively, distribution system power quality enhancement using flexible control of grid connected DG units is becoming an interesting topic, where the ancillary harmonic compensation capability is integrated with the DG primary power generation function through modifying control references. This idea is especially attractive considering that the available power from backstage renewable energy resources is often lower than the power rating of DG interfacing converters. For the local load harmonic current compensation methods as discussed in, an accurate detection of local load harmonic current is important. Various types of harmonic detection methods have been presented, such as the Fourier transformation- based detection method in, the detection scheme using instantaneous real and reactive power theory in, second-order generalized integrator (SOGI) in, and the delayed-signal-cancellation-based detection.

Nevertheless, harmonic extraction process substantially increases the computing load of DG unit controllers. For a cost-effective DG unit with limited computing ability, complex harmonic extraction methods might not be acceptable.

II. HARMONIC COMPENSATION

In conventional method, a linear current control scheme for single-phase grid-connected PV inverters used. A resonant harmonic compensator is connected in series with the tracking regulator (the standard harmonic compensator location is in parallel with the tracking regulator). This location provides an accurate synchronization with the grid voltage without the need for a PLL algorithm. As a result, the series harmonic compensator efficiently attenuates the grid voltage distortion with a lower computational time in relation to the standard control scheme.

The DG real and reactive power control performance shall not be affected during the harmonic compensation. To satisfy this requirement, the fundamental DG current reference shall be calculated according to power references. Conventionally, the fundamental current reference can be determined based on the assumption of ripple-free grid voltage with fixed magnitude, and the PLL is used to synchronize the fundamental current reference with the main grid. However, considering that PoC voltage magnitude often varies due to the distribution system power flow fluctuations, this method may cause nontrivial power control errors.

Alternatively, the fundamental current reference can also be calculated through the "power-current transformation", where only the detected PoC voltage fundamental component is used in the calculation. However, for a DG unit with the ancillary harmonic compensation capability, the interactions between distorted DG current and PoC harmonic voltages may contribute some DC real and reactive power bias, and these power bias cannot be directly addressed in the control method. In order to ensure accurate power tracking performance, a closed-loop DG power control is necessary.

To simplify the operation of DG units with ancillary harmonic compensation capabilities while maintaining accurate power control, this paper proposes an improved current controller with two parallel control branches. The first control branch is responsible for DG unit fundamental current control, and the second one is employed to compensate local load harmonic current or feeder resonance voltage. In contrast to the conventional control methods with harmonic detection, the PoC voltage and local load current can be directly used as the input of the proposed current controller, without affecting the harmonic compensation accuracy of the DG unit.

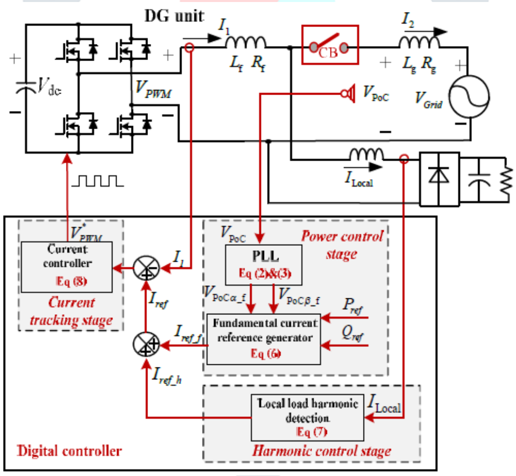


Fig. 2.1 Local Load Harmonic Current Compensation

Fig. 1 illustrates the configuration of a single-phase DG system, where the interfacing converter is connected to the distribution system with a coupling choke (L_f and R_f). There is a local load at PoC. In order to improve the power quality of grid current (I_2), the harmonic components of local load current (I_{Local}) shall be absorbed through DG current (I_1) regulation. The DG unit control scheme is illustrated in the lower part. As shown, its current reference consists of two parts. The first one is the fundamental current reference (I_{ref_f}), which is synchronized with PoC voltage (V_{PoC}) as

$$I_{ref\_f} = \frac{\cos(\theta) \cdot P_{ref} + \sin(\theta) \cdot Q_{ref}}{E^*} \qquad (2.1)$$

Where θ is the PoC voltage phase angle detected by PLL, P_{ref} and Q_{ref} are the real and reactive power references, and E is the nominal voltage magnitude of the system. However, the current reference generator in (2.1) is not accurate in controlling DG power, due to variations of the PoC voltage magnitude. To overcome this drawback, an improved power control method with consideration of PoC voltage magnitude fluctuations was developed.

The fundamental PoC voltage $V_{PoC\alpha\_f}$ and its orthogonal component $V_{PoC\beta\_f}$ (quarter cycle delayed respect to $V_{PoC\alpha\_f}$) are obtained by using SOGI as

$$V_{\mathrm{PoC}\alpha\_f} = \frac{2\omega_{D1}s}{s^2 + 2\omega_{D1}s + \omega_f^2} \cdot V_{\mathrm{PoC}} \qquad (2.2)$$

$$V_{\mathrm{PoC}\beta\_f} = \frac{2\omega_{D1}\omega_f}{s^2 + 2\omega_{D1}s + \omega_f^2} \cdot V_{\mathrm{PoC}} \qquad (2.3)$$

Where ω_{D1} is the cutoff bandwidth of SOGI and ω_f is the fundamental angular frequency.

For a single-phase DG system, relationships between the power reference and the fundamental reference current can be established in the artificial stationary α − β reference frame as follows:

$$P_{\mathrm{ref}} = \frac{1}{2} \cdot (V_{\mathrm{PoC}\alpha\_f} \cdot I_{\mathrm{ref}\alpha\_f} + V_{\mathrm{PoC}\beta\_f} \cdot I_{\mathrm{ref}\beta\_f}) \qquad (2.4)$$

$$Q_{\mathrm{ref}} = \frac{1}{2} \cdot (V_{\mathrm{PoC}\beta\_f} \cdot I_{\mathrm{ref}\alpha\_f} - V_{\mathrm{PoC}\alpha\_f} \cdot I_{\mathrm{ref}\beta\_f}) \qquad (2.5)$$

Where $I_{\mathrm{ref}\alpha\_f}$ and $I_{\mathrm{ref}\beta\_f}$ are the DG fundamental current reference and its orthogonal component in the artificial α − β reference frame; Similarly, $V_{\mathrm{PoC}\alpha\_f}$ and $V_{\mathrm{PoC}\beta\_f}$ are PoC fundamental voltage and its orthogonal component, respectively.

According to (2.4) and (2.5), the instantaneous fundamental current reference ($I_{\mathrm{ref\_f}}$) of a single-phase DG unit can be obtained as

$$I_{\mathrm{ref}\_f} = I_{\mathrm{ref}\alpha\_f} = \frac{2(V_{\mathrm{PoC}\alpha\_f} \cdot P_{\mathrm{ref}} + V_{\mathrm{PoC}\beta\_f} \cdot Q_{\mathrm{ref}})}{V_{\mathrm{PoC}\alpha\_f}^2 + V_{\mathrm{PoC}\beta\_f}^2} \qquad (2.6)$$

Moreover, to absorb the harmonic current of local nonlinear load, the DG harmonic current reference ($I_{\mathrm{ref\_h}}$) is produced

$$I_{\mathrm{ref}\_h} = G_D(s) \cdot I_{\mathrm{Local}} = \sum_{h=3,5,7,9,\ldots} \frac{2\omega_{D2}s}{s^2 + 2\omega_{D2}s + \omega_h^2} \cdot I_{\mathrm{Local}} \qquad (2.7)$$

Where GD (s) is the transfer function of the harmonic extractor, to realize selective harmonic compensation performance, GD (s) is designed to have a set of band pass filters with cutoff frequency ω_{D2}. With the derived fundamental and harmonic current references, the DG current reference is written as $I_{\mathrm{ref}} = I_{\mathrm{ref\_f}} + I_{\mathrm{ref\_h}}$. Afterward, the proportional and multiple resonant controllers are adopted to ensure rapid current tracking

$$\begin{aligned} V_{\mathrm{PWM}}^* &= G_{\mathrm{cur}}(s) \cdot (I_{\mathrm{ref}} - I_1) \\ &= \left(K_p + \sum_{h=f,3,5,\ldots,15} \frac{2K_{ih}\omega_c s}{s^2 + 2\omega_c s + \omega_h^2}\right) \\ &\quad (I_{\mathrm{ref}\_f} + I_{\mathrm{ref}\_h} - I_1) \end{aligned} \qquad (2.8)$$

Where V^*_P is the reference voltage for pulse width modulation (PWM) processing, K_p the proportional gain of the current controller $G_{cur(s)}$, K_{ih} the resonant controller gain at the order h, ω_c the cutoff frequency of the resonant controller, and ω_h is the angular frequency at fundamental and selected harmonic frequencies.

It should be pointed out that the objective of local load harmonic compensation is to ensure sinusoidal grid current I_2 in Fig. 2.2. In this control mode, DG unit should not actively regulate the PoC voltage quality. As a result, the PoC voltage can be distorted especially when it is connected to the main grid through a long underground cable with nontrivial parasitic capacitance. In this case, the feeder is often modeled by an LC ladder. To address the resonance issue associated with long underground cables, the R-APF concept can also be embedded in the DG unit current control, as illustrated in Fig. 2.2. Compared to Fig. 2.1, the DG harmonic current reference in this case is modified as

$$I_{\mathrm{ref}\_h} = \left(-\frac{1}{R_V}\right) \cdot (G_D(s) \cdot V_{\mathrm{PoC}}) \qquad (3.9)$$

Where RV is the virtual damping resistance at harmonic frequencies, with this harmonic current reference (3.9), the DG unit essentially works as a small equivalent harmonic resistor at the end of the feeder, when it is viewed at power distribution system level. By providing sufficient damping effects to the long feeder, the voltage quality at different positions of the feeder can be improved.

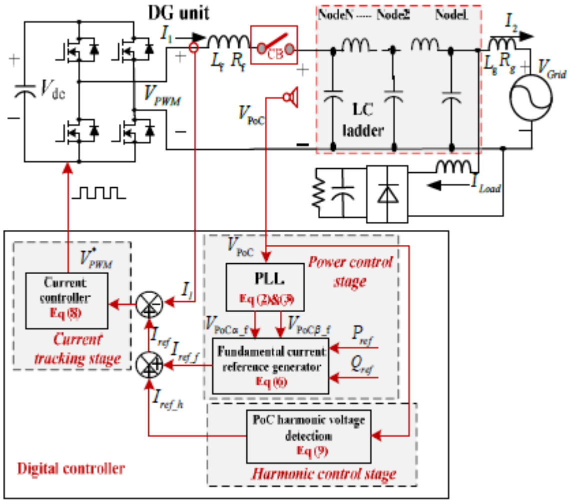
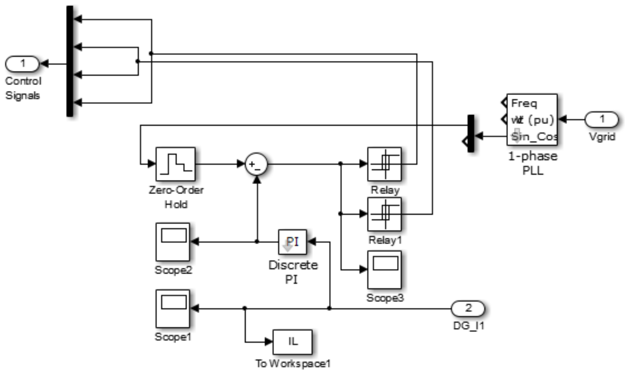


Fig. 2.2 DG unit with PoC harmonic voltage mitigation capability

III. CONTROLLER

The main aim of the control scheme is to maintain constant voltage magnitude at the point where a sensitive load is connected, under system disturbances. In this control scheme it measures the RMS voltage at the load point and no requirements of reactive power measurements. Here the sinusoidal PWM technique is used for the switching of VSC offers simplicity and good response. The input of the controller is an error signal which is obtained from the reference voltage and the value RMS of the terminal voltage measured at load point. Than PI controller will process this error signal and then the output is the angle δ which is given to the PWM signal generator. The PWM generator generates the sinusoidal PWM waveform or signal. The angle of output of PI summed with phase angle of the balanced supply voltages which is assumed to be 120o to produce the desired synchronizing signal, required to operate the PWM generator. Now the error signal by comparing reference voltage with the RMS voltage measured at the load point is processed by PI controller which in return generates the required angle to drive the error to zero, i.e., the load RMS voltage is brought back to the reference voltage. Hysteresis control block of this is given in fig 3.1.

To generate the switching signals for the VSC valves, the modulated signal hysteresis control is compared against a triangular signal. The amplitude modulation index of signal and the frequency modulation index of the triangular signal are the main parameters of the sinusoidal PWM scheme [3,4].Complete compensation is not achieved in case of nonlinear load though this strategy is easy to implement and is robust and can provide partial reactive power compensation without harmonic suppression.



3.1 Hysteresis Control

IV. SIMULATION RESUTLS

A. Harmonic Compensation of Local Non- load

The DG unit with a local diode rectifier load is tested in the simulation and circuit shown in fig. 4.1. The configuration of the system is the same as shown in Fig. 2.1, and PoC is connected to a stiff controlled voltage source (to emulate the main grid) with nominal 50 Hz frequency. The main grid voltage contains 2.8% third and 2.8% fifth harmonic voltages. In this simulation, the reference power is set to 600W and 200 var. The detailed simulation parameters of the system are shown in Table 4.1.

When the local load harmonic current is not compensated by the DG unit, the performance of the DG unit is of DG current of local load harmonic compensation I_1 shown in Fig. 4.2. That, the DG current is sinusoidal with 5.78% total harmonic distortion (THD) and at the same time, the harmonic load currents flow to the main grid is illustrated in Fig. 4.3. Once the local load harmonic current compensation is activated by setting $I_{ref\_h} = I_{Local}$, the performance of the system is shown in Fig. 4.4. Although harmonic extractions are not used in this simulation, the proposed method can still realize satisfied local load harmonic current compensation, resulted in an enhanced grid current quality with 5.88% THD. Meanwhile, DG unit current is polluted with 201.5% THD.

Simulation Parameter	Values
Grid Voltage	230V/50Hz
DG Filter	L_f = 6.5mH, R_f = 0.15Ω
Feeder filter	L_g = 6.5mH, R_g = 0.15Ω
LC ladder with five identical LC filter	*L*=1.0mH, *C*=25μF for each LC filter
Sampling/Switching frequency	20kHz/10*k*Hz
DC link voltage	Simulation 550V
Real power control *k*p1, *k*I1	*k*p1=0.00001, *k*I1=0.001
Reactive power control *k*p2, *k*I2	*k*p2=0.00001, *k*I2=0.001
LPF time constant	0.0322 Sec
Proportional gain *Kp*	48
Resonant gains Kih	1500(*h*=*f*); 900 (*h*=3, 5, 7, 9); 600 (h=11, 13, 15)
Resonant controller bandwidth w_c	4.1rad/s
R_V (for PoC harmonic voltage compensation)	5Ω

Table 4.1 Simulation Parameters

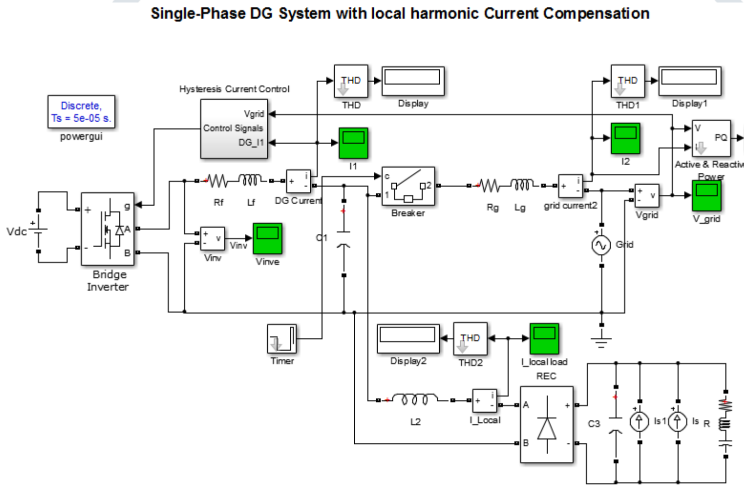


Fig. 4.1 Simulation circuit of Local Load harmonic current compensation

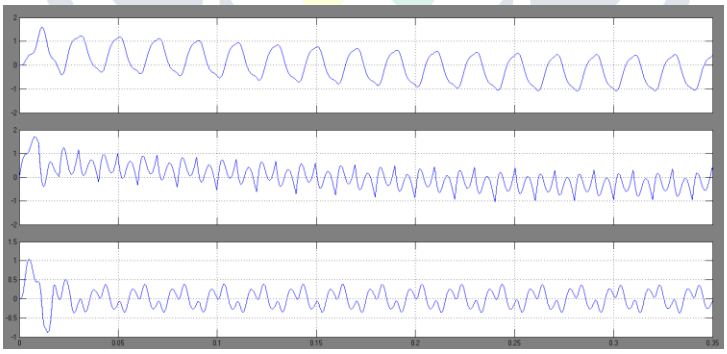


Fig. 4.2 Performance of DG unit local load current harmonic compensation (a) grid current, (b) DG current, (c) local current

As the DG unit also provides 200var reactive power to the grid, it can be seen that the fundamental current reference is slightly lagging of the PoC voltage.

The effectiveness of the hysteresis control strategy is verified in Fig. 4.3, where the real and reactive power is calculated. When the conventional open-loop power control is applied, it can be noticed that the DG output real and reactive power control is not accurate. On the other hand, as the proposed control strategy regulates DG output power in a closed-loop manner, it guarantees zero steady-state power tracking error. The Performance of DG unit during harmonic rejection for local load current harmonic compensation as shown in Fig. 4.2 (a) grid current, (b) DG current, (c) local current and Power flow of DG unit during local load current compensation in Fig. 4.3.

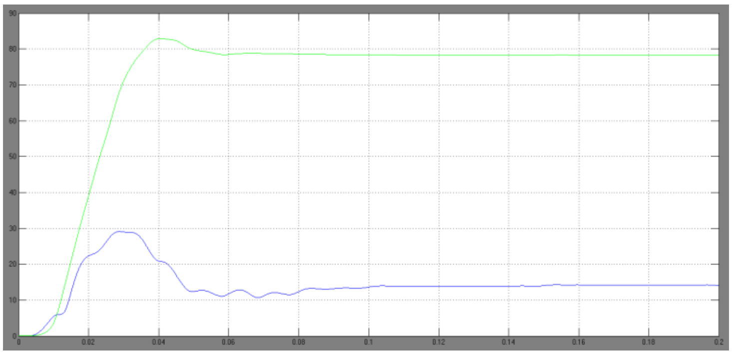


Fig. 4.3 Power flow of DG unit during local load current compensation (ref PQ in rms)

B. Compensation of Feeder Resonance Voltage

The feasibility of the proposed method in compensating feeder resonance voltages, the DG unit is connected to the stiff main grid with five cascaded LC filters (see Fig. 2.1). The inductance and capacitance of each LC filter is 1mH and 25μF, respectively.

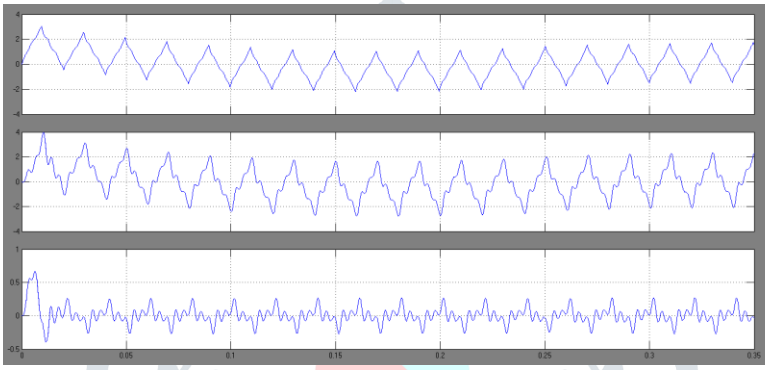


Fig. 4.4 DG unit during feeder resonance voltage (a) grid current, (b) DG current, (c) local current

The performance of this system is shown in Figs. 4.4 are the performance of the proposed controller under DG unit feeder resonance voltage mode (Iref h = 0).

As the PoC voltage is distorted with 13.6% THD, due to the resonance aggregated in the local load harmonic compensation. Since the fundamental current (I_{ref_f}) is synchronized with the non-filtered PoC voltage and its orthogonal component, it is also distorted as presented in the lower part. Although the fundamental current reference is distorted, the DG current is sinusoidal with 5.61% THD. Meanwhile, the main grid current contains nontrivial harmonics with 34.2% THD. When the feeder resonance voltage compensation is enabled by controlling the DG unit as a virtual resistance [R_V = 5] at selected harmonic frequencies, the PoC harmonic voltage in this case is mitigated and its THD reduces to 3.07%.

C. Performance of Voltage Mitigation

The performance of the DG unit under grid voltage frequency deviation is also examined and circuit shown in fig. 4.9 as PoC voltage mitigation. In this test, the bandwidth (ω_c) of resonant controllers at harmonic frequencies is selected as 16 rad/s. As a result, the performance of current tracking can be less sensitive to grid voltage frequency variations. In Fig. 4.6, the DG unit power reference is 600W/600var and the grid voltage frequency is fixed to 50 Hz before 1.0 s for PoC of grid current, DG current, local current and shown in fig. 4.5 shown as PoC DG current. During this time range, it can be seen that DG unit absorbs the harmonic current from local nonlinear loads and the grid current THD is only 5.05%. At the time instant 1.0 s, the grid frequency jumps to 52 Hz.

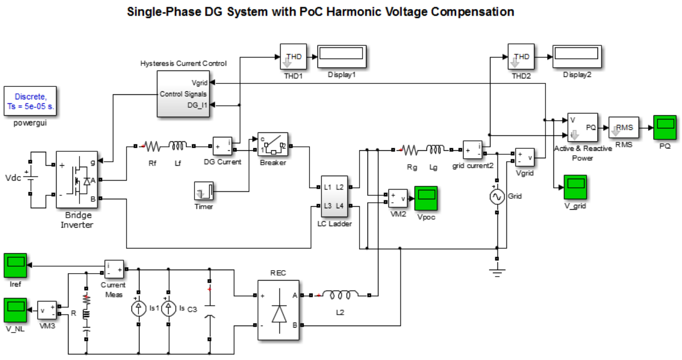


Fig. 4.5 Simulation Circuit of PoC harmonic Voltage mitigation

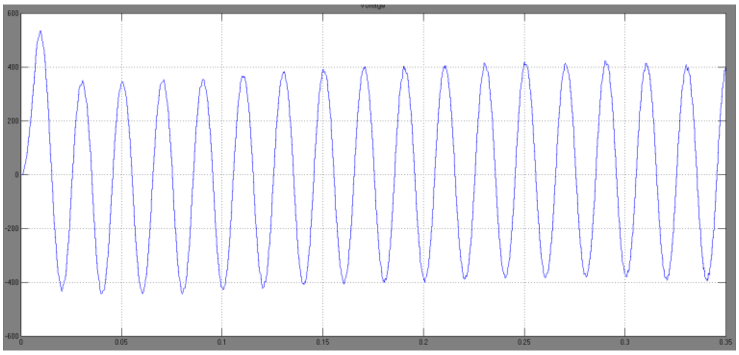


Fig. 4.6 PoC Voltage V_{PoC}

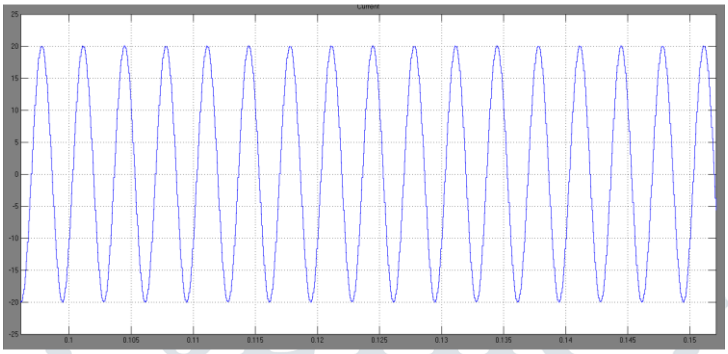


Fig. 4.7 PoC fundamental current I_{ref_f}

In the case of grid frequency variation, it can be seen that the proposed method still maintains satisfied harmonic compensation of performance with 5.99% grid current THD. It is emphasized here that in a real DG system, the frequency deviation is typically lower, e.g., for the small photovoltaic (PV) systems, the allowed frequency deviation range is –0.7 to 0.5 Hz. The DG unit needs to be disconnected from the utility when the grid frequency deviation is out of this range. If very larger frequency variation is present, a frequency estimator could be used to update the PR control parameters. As discussed earlier, such a frequency estimator will be simpler than a PLL.

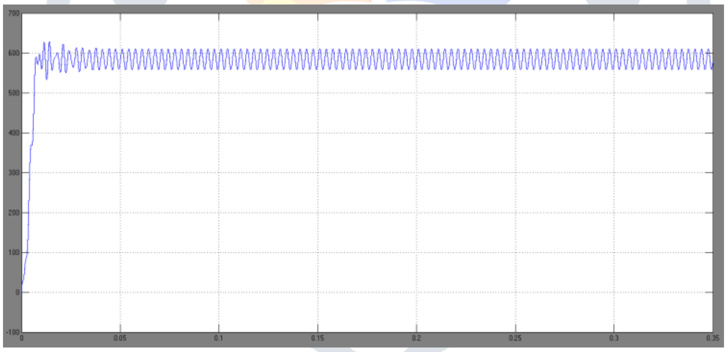


Fig. 4.8 PoC mitigation of local load voltage

The associated current waveforms during PoC voltage compensation of grid voltage compensation are same as for the PoC harmonic mitigation as shown in Fig. 4.6, 4.7, 4.8, 4.9, 4.10 and also overall grid voltage is shown in fig. 4.9. It is obvious that DG current has more distortions (with 35.09% THD shown in 4.2 and 4.8), while the main grid current THD reduces to 8.12%.

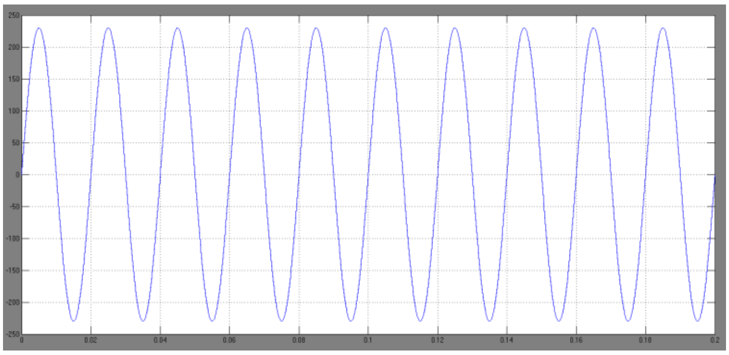


Fig. 4.9 PoC mitigation of Grid Voltage V_{gird}

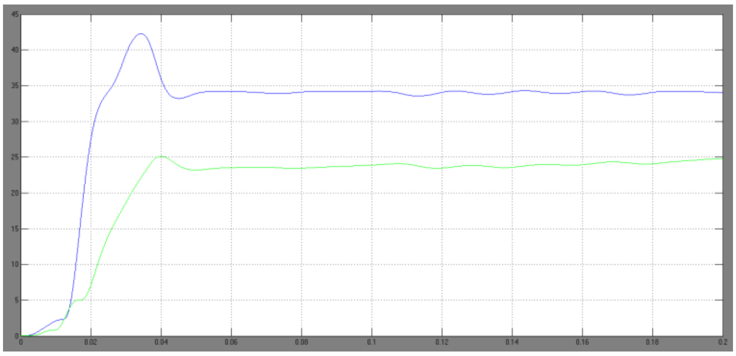


Fig. 4.10 Power flow with LC ladder ref P-Q_{rms}

Finally, the power flow performance of the DG unit using the proposed power control scheme is shown in Fig. 4.14. From the time range 0 to 1.0 s, the DG unit is controlled to eliminate DG harmonic currents ($I_{ref\_h} = 0$). From 1.0 to 1.5 s, feeder resonance voltage compensation is slowly activated by changing R_V from infinity to 5 Ω. I t can be seen that the power control is always accurate during the transitions between different control modes.

V. CONCLUSION AND FUTURE SCOPE

A simple harmonic compensation strategy is proposed for current-controlled DG unit interfacing converters hysteresis current control. By separating the conventional proportional and multiple resonant controllers into two parallel control branches, the proposed method realizes power control and harmonic compensation without using any local nonlinear load harmonic current extraction or PoC harmonic voltage detection. Moreover, the input of the fundamental power control branch is regulated by a hysteresis closed-loop current control scheme, which avoids the adoption of PLLs. These control method ensures accurate power control even when harmonic compensation tasks are activated in the DG unit or the PoC voltage changes. The simulated results from a single-phase DG unit verified the feasibility of the proposed strategy.

Future Scope and Extension

The performance of active filter will be implemented by developing different methods of simulation circuitry to eliminate the impacts of steady-state fundamental current tracking errors in the DG units with the help of various control techniques like, H-infinity control, fuzzy logic control, sliding mode control. Thus, the harmonic compensation functions are activated with renewable energy resources in simulation or hardware.

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