Residential Distribution System Harmonic Compensation
Using PV Interfacing Inverter

GUNUPATI HYMAVATHI¹, SHAIK HAMEED²

¹PG Scholar, Dept of EEE, Quba College of Engineering and Technology, SPSR Nellore, JNTUA, Anantapur, AP, India, E-mail: hymavathigunupati@gmail.com.
²Associate Professor, Dept of EEE, Quba College of Engineering and Technology, SPSR Nellore, JNTUA, Anantapur, AP, India, E-mail: hameedqcet@gmail.com.

Abstract: The increased non-linear loads in today’s typical home are a growing concern for utility companies. This situation might be worsened by the harmonic resonance introduced by the installation of capacitor banks in the distribution network. To mitigate the harmonic distortions, passive or active filters are typically used. However, with the increasing implementation of distributed generation (DG) in residential areas, using DG systems to improve the power quality is becoming a promising idea, particularly because many DG systems, such as photovoltaic (PV), wind and fuel cells, have DG-grid interfacing converters. In this paper, the potential for using photovoltaic (PV) interfacing inverters to compensate the residential system harmonics is explored. A system model including the residential load and DG is first developed. An in-depth analysis and comparison of different compensation schemes based on the virtual harmonic damping impedance concept are then carried out. The effects of the capacitor banks in the system are also studied. The effectiveness of the harmonic compensation strategies under different conditions is verified through analysis and simulations.

Keywords: Distributed Generation (DG), Photovoltaic (PV), Power Quality Improvement, Harmonic Compensation, Renewable Energy, Residential Distribution System.

I. INTRODUCTION

The increasing utilization of electronic devices in today’s homes is a growing concern for utility companies due to harmonic distortions. The harmonic problem could be further complicated by the harmonic resonance introduced by other system components, such as the power factor correction (PFC) capacitors. Besides the degrading power quality, the harmonic current flow is also a concern for the telecommunication industry as this harmonic current flow may interfere with the adjacent telephone lines [1]. Compensating the harmonics in a residential system is difficult because of the dispersed nature of the residential loads. Therefore, lump compensation at a few locations is not every effective [2]. As a result, finding an effective way to compensate the dispersed load harmonics and improve the residential distribution system power quality is an important topic. In addition to having increasing concerns about power quality, the power industry is experiencing a paradigm shift as more renewable energy based distributed generation (DG) systems are being connected to the power distribution network [3], [4]. A typical example is the increasing installation of rooftop photovoltaic (PV) systems in residential areas. As shown in Fig. 1, these PV systems are connected to the grid through DG-grid interfacing inverters, which are used mainly to convert the voltage from the energy source to the voltage that can be readily connected to the grid, and to transfer the real power to the grid. If controlled properly, these DG-grid interfacing converters are able to provide a number of ancillary functions such as power factor compensation, voltage support [5], flicker mitigation [6], system harmonic compensation [7], and unbalance voltage compensation [8] in addition to the primary function of real power injection.

This potential for ancillary services can be realized by properly utilizing the available apparent power rating from the interfacing inverters. Doing so is feasible as most of the time these inverters are not running at their maximum power due to the intermittent nature of renewable energy (such as PV) [9], [10]. The concept of system harmonic compensation using grid interfacing PV inverter has been reported in the literature [11]–[13]. However, the system considered in the previous work is usually too simple (e.g., the system is often comprised of only a few lines and loads) to provide realistic results. Also, the effects of harmonic resonance with other power system components, such as capacitors, are not sufficiently considered in the previous work. Additionally, for a system with distributed loads and DG systems, assigning the harmonic compensation priority to different DG systems to achieve the best compensation result is an important topic that has not been addressed in the literature. This paper addresses the above mentioned issues. A residential distribution system with line impedances, distribution transformers and typical house loads is modeled first. The house load model is created from the aggregated load characteristics of typical residential appliances [14], [15]. This house load model is used to investigate the effect of non-linear residential loads on the power quality of the modeled distribution system.
Then the PV grid-interfacing inverters are connected to the distribution system model and are controlled to improve the power quality by acting as harmonics-damping virtual impedance. The effects of the PV locations on harmonic compensation such as end-of-line [2] and distributed compensation [16], [17] are investigated. An in-depth analysis and explanation of the performance differences are also carried out to provide a guide for properly assigning the harmonics compensation priorities to PV inverters at different locations of the distribution system. These analysis results are verified by simulations of a sample residential distribution system.

![Residential system with PV installations.](image)

Fig. 1. Residential system with PV installations.

The rest of the paper is organized as follows: Section II introduces the concept of virtual impedance-based control of the grid interfacing inverters for harmonics compensation. Section III develops a model of the residential system including the aggregated nonlinear loads in a house, transformer and line, PFC capacitors, and the PV systems. Section III System Modelling Specifically, Section IV discusses the IV. Distribution System Harmonic Compensation Using DG. Sections V discuss the Harmonic Compensation with the Presence of PFC Capacitors. Section VI discuss the simulation results Finally, this work is concluded in Section VII.

II. DG-GRID INTERFACING INVERTER VIRTUAL HARMONIC IMPEDANCE CONTROL

In this work, the PV inverters are controlled as virtual harmonic impedance at the harmonic frequencies to compensate the residential system harmonics. Therefore, before the residential system model and harmonic compensation performances are discussed, the virtual impedance control concept is introduced in this section. Virtual impedance emulates the effect of physical impedance, without the need to connect any physical component to the system. In the DG inverter control, the virtual impedance is implemented by modifying the voltage or current reference or the PWM signal, through digital control of the inverters. Virtual impedance can be either at the fundamental frequency or at the harmonic frequencies. The fundamental frequency virtual impedance is used mainly to facilitate DG power flow control [18], [19] and grid disturbance ride through [20]. The harmonic virtual impedance is mainly used for active damping [21], [22] and distribution system harmonic compensation [23]. As this paper is focused on the system harmonics compensation using PV inverters, the virtual harmonic impedance and its control schemes are discussed in the following subsections.

A. Virtual Harmonic Inductor

A harmonic compensation method by a voltage-controlled DG unit is proposed in [23], where the DG unit is represented as controlled voltage source with output series impedance. The harmonic components of the controlled voltage source, : VDG, is controlled according to the harmonic voltage of the point of common coupling (PCC), , with a positive feedback gain so that VDG_h = - G x VCC_h. As a result, the equivalent harmonic impedance of the DG becomes. Here, can be in the range. Virtual inductive equivalent impedance is introduced in this method to compensate the system harmonics, since the impedance is mainly inductive at harmonic frequencies. This method is quite attractive for use in a micro-grid, where the voltage-controlled DG is important for providing the micro-grid Voltage and frequency control.

B. Virtual Harmonic Resistance

Distribution system harmonics improvement using a current controlled grid-interfacing inverter is discussed in [24] and [25]. In this method, the DG operates like a shunt active power filters (APF) and absorbs the harmonic current generated by the nonlinear load. As a result, the source current becomes harmonic free and the PCC voltage total harmonic distortion (THD) decreases. A popular way to achieve this function is to operate the DG as resistive-APF (R-APF) [26]. Here, the harmonic components of the grid side voltage, , are extracted and the reference harmonic current of the DG is produced by using . As a result, the DG acts as a virtual resistance, , only at the harmonic frequencies. As most residential rooftop PV inverters are current-controlled, the virtual harmonic resistance method is adopted in this work.

C. Control Scheme of PV Inverter with Virtual Harmonic Resistance

With the virtual harmonic resistance control, the PV inverters work as R-APF. A block diagram of the system harmonic damping control is shown in Fig2. The PV system in this example is a two-stage conversion system, which includes a DC-DC converter that steps up the PV output to the DC link voltage level with maximum power point tracking (MPPT) control, and an inverter that connects the system to the grid. The PV system output current reference has two components: (i) the fundamental component, which is produced from the DC link voltage control and power factor control loops (which are not shown in Fig. 2 as the focus here is harmonics compensation), and (ii) the harmonic components, which are used for harmonic compensation. For virtual resistance realization, the reference harmonic current of the PV system is produced by using. Then the reference
Residential Distribution System Harmonic Compensation using PV Interfacing Inverter

current of DG is obtained by combining the fundamental reference and the harmonic current reference. Finally, the PV system output current is controlled with double control loops, containing an outer output current control loop and an inner (LC) filter inductor current control loop [22].

III. SYSTEM MODELING

In this section, the system model including the residential house load, distribution systems with PFC capacitors, and PV inverters (with virtual harmonic impedance control) is first developed. The developed models are then used in the rest of the paper for the analysis of harmonic distortions and compensation performances by using different approaches.

A. Residential Load Modeling

To model a home, different home appliances are modeled as a harmonic current source in parallel with the fundamental impedance as shown in Fig. 3.

\[ i_h = \sum_{n=1}^{N} i_{h,n} \]  

(1)

To obtain such a home model, individual home appliance models, including personal computer (PC), compact fluorescent light (CFL), adjustable speed drive (ASD) fridge, TV, refrigerator, washer, and dryer are generated first. As an example, the harmonic load current data for the CFL and PC are shown in Table I. Note that these data are taken from [14], [29] where the appliance harmonic load current data are measured practically. To construct the home model, these appliances are then connected to hot wire 1, hot wire 2 and neutral as shown in Fig. 4. Finally, the constructed home models are connected to a distribution system model as shown in Fig. 5 [15]. All the appliance models except the dryer are connected between hot wire 1 and the neutral for home model 1, whereas the appliance models are connected between the neutral and hot wire 2 for home model 2. The dryer model is connected between hot wire 1 and hot wire 2 for both home model 1 and home model 2. The parameters used in this paper to model the distribution system are listed in Table II [15]. The distribution system has a 34.4 kV transmission line connected to the 12.47 kV distribution feeders through transmission transformer. The 3-phase distribution feeder has 11 nodes. On each node, a group of 12 houses is connected to the distribution feeder through distribution transformer in a way that the load current is balanced (6 home model 1 and 6 home model 2).
fundamental load impedance at the node, DG represents the DG current at the node, and $I_{hn}$ represents the harmonic current of the non-linear load at the $n$th node. Referring the system to the primary side of the transformer, the equivalent circuit of such a system is shown in Fig. 4 (note that the same symbols as in Fig. 3 are used in Fig. 4 to represent the system. Also, as the analysis here focuses on harmonic frequencies, the source is shorted in Fig. 4).

**Fig. 5. Typical Distribution feeder with DG.**

![Typical Distribution feeder with DG.](image)

**Fig. 6. Equivalent circuit of an N node distribution feeder.**

![Equivalent circuit of an N node distribution feeder.](image)

Additionally, is the voltage at the node? $X_1, X_4, \ldots, X_{3N-2}$ are the currents through $Z_{L1}, Z_{L2}, \ldots, Z_{Ln}$. $X_3, X_6, \ldots, X_{3N}$ are the currents through $Z_{Yn}$. $X_1, X_2, \ldots, X_{3N}$ are taken to be the state variables, $I_{hn}$ is the input, and $V_N$ is the output of the state space model of the system. Then for $N$-node system, there are $3N$ state equations. The $1$-$N,N+1$ to $2N$, and $2N+1$ to $3N$ equations are shown in (3)–(5), respectively:

\[
U_{N(n)}^x = \frac{1}{3}n - I_{hn} + x_3n - 2 + x_3n - 1
\]

\[
\sum_{n=1}^{N} X_3nR \cdot X_3n + x_3nL \times X_3n
\]

\[
-x_3n - x_3n - 1 - 1R \times V_N = x_3n - 2R \times X_3n + X_3n - 2L
\]

\[
2X_3n + n - x_3n - 1 + x_3nL \times X_3n + x_3nL \times X_3n
\]

Solving (3) to (5) yields the $A_N$ and $B_N$ matrices of the state space model while the equation of the system output (6) yields the $C_N$ and $D_N$ matrices of the state space model:

\[
\sum_{n=1}^{N} V_N = V_N - 1 + x_3nR \times X_3n + x_3nL \times X_3n
\]

Hence, the state space model of the system can be obtained as shown in (4) and (5). From the state space model, the transfer function of the system can be easily found by using (6).

**C. Distribution System Modeling With PFC Capacitors**

The installation of the power factor correction (PFC) capacitor in the distribution system makes the harmonic issues complex, and some harmonics can be amplified [30]. Although installing an active power filter may mitigate the harmonics at the point of installation in such a situation, the harmonics may be amplified on the other busses due to the whack and mole effects [2][3]. To investigate the effectiveness of different harmonic compensation schemes in such a situation, a distribution bus with capacitors connected has to be modeled. Fig. 8 shows the equivalent distribution feeder of the distribution system with PFC capacitors. It also includes DG systems connected at the secondary side of the distribution transformer. Referring the system to the primary side of the transformer, the equivalent circuit of such a system is shown in Fig. 9.

**Fig. 7. Typical distribution feeder with DG and PFC capacitors.**

![Typical distribution feeder with DG and PFC capacitors.](image)

The symbols shown in the distribution system of Figs. 8 and 9 are similar to those of Figs. 6 and 7. Additionally, $Z_{C1}, Z_{C2}, \ldots, Z_{Cn}$ are the impedances of the PFC capacitors ($C_{C1}, C_{C2}, \ldots, C_{Cn}$), respectively, at the $n$th node, and $X_4, X_8, \ldots, X_{4N}$ is the voltage across $Z_{Cn}$. Here, $X_1, X_2, \ldots, X_{4N}$ are taken to be the state variables, $I_{hn}$ is the input, and $V_N$ is the output of the state space model of the system. For a $N$-node

**Fig. 8. Equivalent circuit of an N node distribution feeder with DG and PFC capacitors.**

![Equivalent circuit of an N node distribution feeder with DG and PFC capacitors.](image)
Residential Distribution System Harmonic Compensation using PV Interfacing Inverter

System, there are 4N state equations. The 1-NN+1 to
2N, 2N+1 to 3N, 3N+1and to 4N equations are shown in
(10)–(13), respectively:

\[
\begin{align*}
\mathbf{U}_N & = \mathbf{A}_N \mathbf{X}_N + \mathbf{B}_N \mathbf{U}_N \\
\mathbf{U}_N & = \mathbf{A}_N \mathbf{X}_N + \mathbf{B}_N \mathbf{U}_N \\
\mathbf{U}_N & = \mathbf{A}_N \mathbf{X}_N + \mathbf{B}_N \mathbf{U}_N \\
\mathbf{U}_N & = \mathbf{A}_N \mathbf{X}_N + \mathbf{B}_N \mathbf{U}_N
\end{align*}
\]

Solving (9) to (10) yields the \( A_N \) and \( B_N \) matrices of the
state space model while the equation of the system output
(11) yields the \( C_N \) and \( D_N \) matrices of the state space model.

\[
\mathbf{U}_N = \mathbf{C}_N \mathbf{X}_N + \mathbf{D}_N \mathbf{U}_N
\]

Hence, the state space model of the system can be obtained
as shown in (15) and (16). From the state space model, the
transfer function of the system can be found by using (17).
With the obtained residential distribution system models, the
performance of harmonic compensation using PV inverters.

IV. DISTRIBUTION SYSTEM HARMONIC
COMPENSATION USING DG

Residential PV system locations are usually not
controllable as they depends on which residence has the
system installed. However, coordinated control of the PV
inverters in a system is possible, and an optimal
compensation strategy should be identified to obtain the best
harmonic compensation result. The two strategies for
harmonic compensation using the DG interfacing inverters
are the end-of-distribution-feeder(or end-of-line) compensa-
tion [2], and distributed compensation [16], [17]. In a
distribution system with multiple PV systems, the end-of-line
compensation strategy can be implemented by assigning
harmonic compensation priority to the PV inverters
connected at the end of the feeder. On the other hand, the
distributed compensation approach can be implemented by
operating all PV inverters in the harmonic compensation
mode with equal priority. To study the effects of different
compensation approaches, a two-node system is used as an
example in this section. This system gives N=2 in Fig. 6. To
simplify the analysis, it is assumed that both node 1 and 2
have identical loads (ZL,1=ZL,2), the same line parameters
(Zline,1=Zline,2=ZL), and the same transformers (Zf1=Zf2). Then the equivalent circuit for analysis can be obtained as in Fig. 7 with N=2. In this case, we can take
X1, X2, X3, X4 and X5 as the state variables, \( \mathbf{X} \) to be the
input, \( \mathbf{V}_1 \)and \( \mathbf{V}_2 \) and to be the output of the state space
model of the system.

This frequency-related performance of different
compensation methods can be intuitively explained by the
equivalent circuit shown in Fig. 11. At high frequencies, the
impedances \( Z_f \), \( Z_x \) and \( Z_y \) are much higher than the inverter
virtual harmonic impedance \( Z_{VR1} \) and \( Z_{VR2} \). As a result, if
\( Z_{VR1} \) and \( Z_{VR2} \) are connected, most of the adjacent harmonic
load current will flow through \( Z_{VR1} \) and \( Z_{VR2} \). For example,
in the case of DG at node 1 [Fig. 11(a)], most of \( I_{h1} \) will be
absorbed by \( Z_{VR1} \), but \( I_{h2} \) will flow through nodes 1 and 2.
This process will result in a higher at
VTHD nodes 1 and 2. The situation will be similar when a single DG is at node 2 [Fig. 11(b)]. However, in the case of DG at both nodes 1 and 2 [Fig. 11(c)], most of the harmonic content \( I_{h1} \) of and \( I_{h2} \) will be locally absorbed by \( Z_{VR1} \) and \( Z_{VR2} \), respectively. As a result, the voltages at nodes 1 and 2 will be less polluted.

When the harmonic frequency increases, and \( Z_y \) also
increase but the virtual resistance \( Z_{VR1} \) and \( Z_{VR2} \) remains
the same, providing the same level of damping to the load
harmonics.

V. HARMONIC COMPENSATION WITH THE
PRESENCE OF PFC CAPACITORS

Capacitors are often installed in distribution systems for
voltregulation and reactive power compensation. These
capacitors may cause harmonic resonances and affect the
harmonic compensation performance. This section extends
the analysis in the previous sections to include the effects of
PFC capacitors. The voltage profile along the distribution
line with a capacitor is influenced by the capacitor location
and the capacitor’s reactance value. Generally, a capacitor
connected at the end of a distribution network provides the
best performance for improving the voltage profile along the
distribution line by improving the power transfer capability,
voltage regulation, and power factor [32]. However, the most
efficient capacitor placement also depends on the load, load
power factor, line parameters of the distribution network,
and reactance value.

Fig.9. Equivalent circuit of (a) DG at node 1 (b) DG at
node 2 (c) DG at node 1 and node 2.
VI. SIMULATION RESULTS FOR PV
Simulation results for PV as shown in bellow Figs.10 to 12.

![Fig.10. Current through distribution line.](image1)

Fig.10. Current through distribution line.

![Fig.11. current flowing from node 11 to primary side of distribution transformer 11.](image2)

Fig.11. current flowing from node 11 to primary side of distribution transformer 11.

![Fig.12. DG harmonic current at 11th node.](image3)

Fig.12. DG harmonic current at 11th node.

VII. CONCLUSION
In this paper, we explored the idea of using residential system DG-grid interfacing inverters as virtual harmonic resistances to damp the system harmonics and improve the power quality. An in-depth analysis and comparison of different harmonic compensation schemes were conducted to provide a guide for determining whether distributed compensation or end-of-line compensation should be used. After such a determination has been made, proper priorities can be assigned to the inverters in the distribution system for optimal compensation performance. Specifically, the analysis and simulation results showed that the end-of-line compensation provided better damping for low order harmonics, whereas distributed compensation provided better damping for high-order harmonics if the equal equivalent rating of the DG was maintained. In the system without PFC capacitors, this crossover frequency was quite high, and end-of-line compensation performed better. However, the presence of capacitor in the system could significantly reduce this crossover frequency to around the 7th order harmonic, so the decision about which compensation strategy to use must be made according to the system load characteristics. Moreover, the effects of capacitor sizes, line impedance, and length on the crossover frequency were also analyzed in this paper. With the information about a distribution system, the crossover frequency between the two compensation strategies can be determined by using the model developed in this work, and proper priority can be assigned to the PV inverters at different locations.

**Future Work:** We will consider a supervisory control system of the DGs with communication in order to control the participation from each PV inverter automatically according to the identified priority. Also, to provide an accurate effectiveness analysis of the harmonics compensation by using PV inverters throughout the day/season/year, the use of a statistical home model of a residential system and solar irradiance historic data could also be considered.

VIII. REFERENCES