Inverter based on Characterization and Compensation of Harmonics in Residential & Commercial Loads using Shunt filter

C.Shashidhar, P. Ramesh, T. Narasimha

(Sr.Asst. Prof, Dept of EEE in Aurora's Scientific Technological and Research Academy, (JNTU-H), INDIA)
(Assoc. Prof, Dept of EEE in Aurora's Scientific Technological and Research Academy, (JNTU-H), INDIA)
(Asst. Prof, Dept of EEE in Aurora's Scientific Technological and Research Academy, (JNTU-H), INDIA)

Abstract: *This paper uses data obtained from laboratory measurements of typical appliances such as Refrigerator, TV set to verify whether these non- linear loads behave similar to current harmonic sources or voltage-type harmonic sources. Inverter is used as input power supply. The output of inverter 230V is connected to Residential & Commercial Loads through a distribution transformer. Based on the measurements and additional simulations, and comparison from the tabular form it is stated that residential and commercial electronic loads behave essentially like harmonic voltage sources. This behavior helps to explain why shunt compensators and filters may even increase the harmonic current content in the feeder.*
Keywords: *Diode, harmonic distortion, harmonics, nonlinear circuits, series filters, power distribution.*

I. Introduction

Depending on the nonlinear load characteristics, the usual representation of nonlinear loads as a simple combination of harmonic current sources may greatly simplify the analyses of their effects on the overall system under similar conditions where distortion has been derived. However, additional conclusions may not be reliable if any modification is introduced in the circuit, such as the connection of a filter or a change in the loading condition. This certainly limits the usefulness of linear models to study nonlinear processes. A more general model should include not only the harmonic current or voltage sources but also their corresponding admittances or impedances. The main problem of this approach is that the equivalent admittance varies with the circuit operating condition, due to the nonlinear nature of the real load. Another important aspect is that some nonlinear loads should be modeled by harmonic voltage sources rather than by harmonic current sources. Among such loads are diode rectifiers with capacitive output (dc) filter, which constitute the usual interface between electronic loads and the ac feeder. Typical applications of this case are TV sets, computers, electronic ballasts for fluorescent lamps, and even the input rectifier stage of inverters, if line reactors are not used .The classification as harmonic voltage or current source depends on what is being imposed by the nonlinear load. In the case of motor-type loads, the motor inductances limit the cur- rent changing rate, which confers the behavior of harmonic cur- rent source to this kind of loads. In the case of rectifiers with dc output capacitors and without significant series impedance (such as electromagnetic-interference (EMI) filters), it is the dc capacitor that limits the voltage changing rate and confers the behavior of harmonic voltage source to these types of loads. This paper uses data from laboratory measurements and simulations of typical residential loads (refrigerator, TV set, and fluorescent compact lamps) in order to verify whether they behave as current or voltage-source-type loads. To decide which type of source model best fits each case, harmonic shunt filter is added to the circuit and the load response is then analyzed. For pure current source behavior, it is expected that the load imposes fixed harmonic currents and the shunt filter absorbs part of this current according to the admittance, relative to the main feeder. For a pure voltage source type, it is expected that a shunt filter will increase the harmonic current emission of the nonlinear load, since the filter represents a new low-impedance path for the imposed harmonic voltages. It should be stressed that in the simulation studies of this paper, neither harmonic current nor voltage source models were used, but the electronic circuit models representing the respective loads were. The knowledge of the characteristic of nonlinear loads is important in order to understand the behavior of these kinds of loads under different operating conditions, and is especially useful for the select the most effective compensation method to be used effective compensation method to be used.

II. Nonlinear Load Types: Current Source Or Voltage Source

A Current Source Load Type:

Typical home appliances, which impose current distortion, are the electromagnetic devices, such as motors and transformers. Refrigerators, freezers, washing machines, and air-conditioning devices can also be included in this group. In this case, the current distortion depends on the motor's design and varies with the voltage level. In the first laboratory test, measurements have been made with a low-consumption refrigerator (target 26.6 kWh/month). Fig. 1 shows the measured current, voltage, and instantaneous power. The voltage

source is free from distortion. The apparent power resulted in 170 VA, while the power factor (PF) is 0.64 (131var and 108.5 W). The refrigerator current harmonics are shown in Table I. If this load effectively behaves as a harmonic current source, then a shunt harmonic filter, connected as shown in Fig. 2, should be capable of absorbing the load's harmonic currents, according to the relative admittances of the filter (1/Zf) and the feeder (1/Zi). To verify this, a shunt filter, tuned 5% below the 5th harmonic (285 Hz), was designed [4] and connected at the refrigerator (load) input terminals. The filter capacitance (20μF) was selected to fully compensate the displacement factor (fundamental power factor), thus resulting in a filter inductance of 15.6mH. Fig. 3 shows the waveforms after the filter installation. Table I shows that the load current remains almost constant when the filter is connected. The small increment of the fundamental current is due to the voltage increase produced by the reactive compensation (127 to128.8 V) supply was reduced 10.8 dB (3.4 times). This result agrees with the relation obtained from impedance measurements. At 300 Hz, the measured filter impedance is 4.1, the source impedance is 9.4,and the expected 5th harmonic reduction is 3.3 times. Thus, one can conclude that the refrigerator's nonlinearity behaves similar to a harmonic current source and, for this kind of load (refrigerator), the shunt filter was effective.
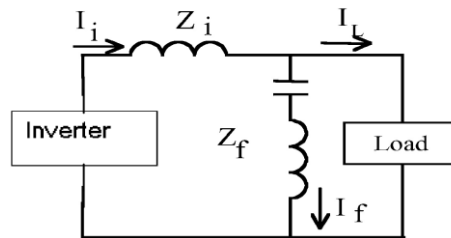
$$\frac{I_i}{I_L} = \frac{Z_f}{Z_f + Zi} \tag{1}$$

Fig. 1   Shunt filter for current source load

TABLE I
REFRIGERATOR CURRENT (RMS VALUE AT 127 V)

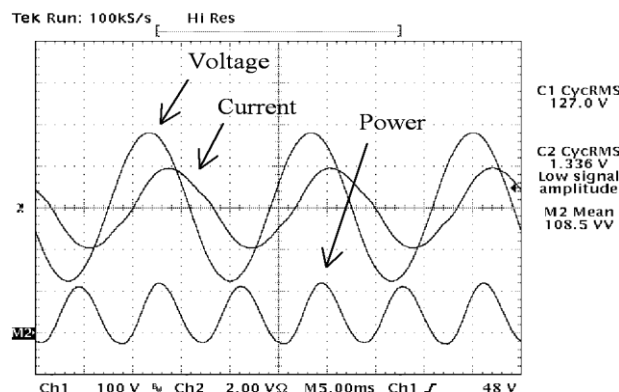| Harmonic order	Without the filter [mA]	With 5th harmonic filter [mA]
1	1.33 A	1.34 A
3	90	89
5	34	36
7	18	18
9	9	9

Fig. 2   Refrigerator's voltage, current, and power waveforms

B. Voltage-Source-Type Load
Fig. 4 shows the circuit of a diode rectifier with a capacitive output filters which, as will be shown, is an example of nonlinear load with harmonic voltage source behavior. As mentioned be- fore, this kind of circuit is present in almost all residential and commercial nonlinear loads, such as computers, video monitors, TV sets, electronic lamp ballasts, etc. For the second test, a 20-in TV set was supplied by the same supply source used in the previous test. Fig. 5 displays the measured voltage and current waveforms. Such load usually absorbs constant power, and the current varies in order to compensate
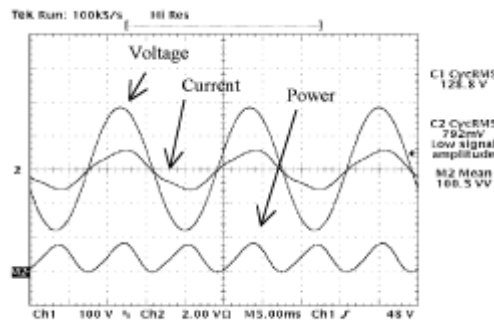
Fig. 3. AC source voltage, refrigerator current, and power absorbed after the filter connection.
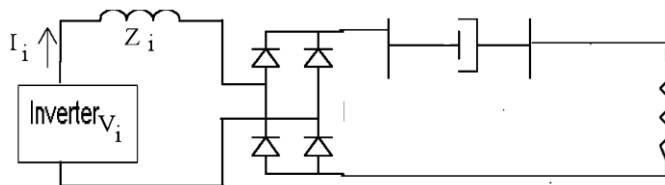

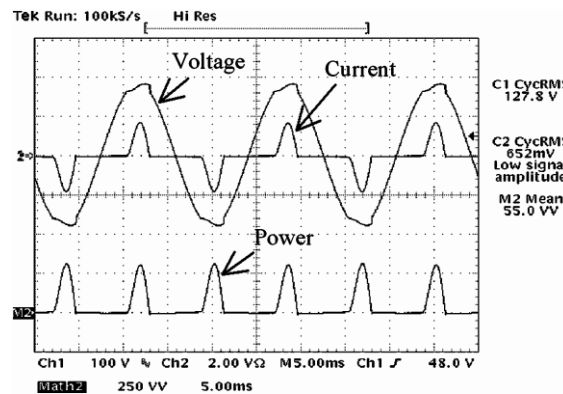Fig 4 Rectifier with output shunt filter

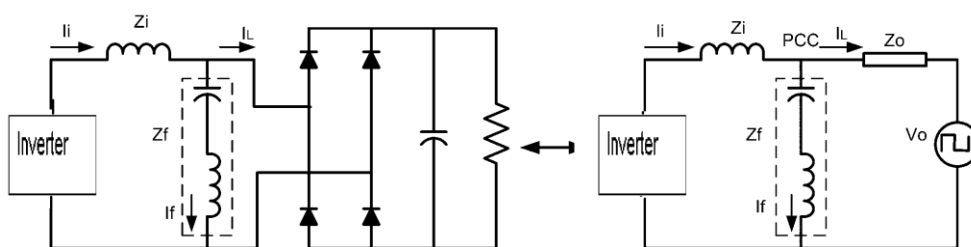Fig. 5. AC source voltage, current, and power absorbed by a TV.

Fig. 6. Load fed by rectifier and harmonic voltage source equivalent, both with Shunt filter.

the input voltage changes. The voltage distortion observed at the PCC is THDV %, while the current THDI reached 108%, and the resulting PF was only 0.66. However the fundamental power factor (displacement factor) resulted 0.97, capacitive. The capacitive behavior at the fundamental frequency of this kind of rectifier is due to the capacitor loading process, which occurs just before the peak value of the mains voltage, so the fundamental component of the current results slightly in advance of the mains voltage. Since any LC harmonic filter also presents a capacitive behavior at the fundamental frequency, it is not possible to design a passive shunt tuned filter that simultaneously reduces the cur- rent distortion and improves the fundamental power factor. The compensation in this case is possible only with series filters or active solutions [3], which are out of the scope of this paper. In order to confirm this behavior, a shunt harmonic filter was considered at the input of a rectifier circuit, as shown in Fig. 6. Equation (2) provides the ac supply harmonic current, including a shunt filter, related to a harmonic voltage load type [1]

(2)

$$\frac{I_i}{V_o} = \frac{Z_f}{Z_o Z_i + Z_o Z_f + Z_i Z_f}.$$

If the load behaves as a pure voltage harmonic source, the Impedance Z_o is zero. This behavior will be different if considerable series inductance is connected to the rectifier, and the equivalent model should include not only the harmonic source but also a series impedance. Unfortunately the load series impedance Z_o can be calculated only for a specific operating condition, because it varies with several parameters (voltage, power, dc capacitor, frequency, etc.).
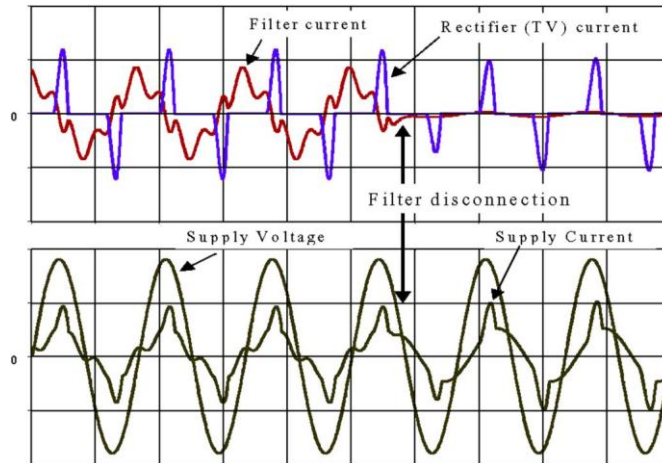

Fig. 7. Simulation results: with and without filter. Top traces: 5th harmonic filter and rectifier currents (2 A/div). Bottom traces: Source voltage (100 V/div) and current (4 A/div).

A modeling method has been proposed in [5], but it is not valid for the discontinuous conduction mode, as is the case of the nonlinear loads considered in this paper. Even without knowing the value of Z_o in (2), it is evident that (1) also does not apply for loads fed through rectifiers with an output capacitor, because I_L is not supposed constant. Next, the harmonic voltage source behavior of this kind of nonlinear load will be verified by simulation and experimentally. Fig. 7 shows the waveforms obtained by simulation of a circuit feeding a linear inductive-resistive load (equivalent to the refrigerator at the fundamental frequency) and a rectifier with capacitive-resistive load (equivalent to the TV set). A 5th harmonic filter, is initially present at the PCC, and is disconnected at the time assigned in Fig. 7.The shunt filter capacitance compensates the fundamental re- active power, so that the resultant displacement factor is close to unity, in spite of the highly distorted current flowing into the mains feeder. Note that the rectifier current increases while the filter is connected. This behavior can be explained if one considers that the nonlinear load behaves similar to a harmonic voltage source. If the load would have a current source behavior, its harmonic current emission would remain constant, even if the filter were connected. Fig. 8 shows a laboratory experimental result, obtained with the same kind of loads (refrigerator and TV) and 5th harmonic filter. The only difference is that the presented voltage is the real distorted network (PCC) voltage instead of the clean simulation voltage source. Considering that the TV power demand varies according to its image and sound adjustments, and in order to have a reproducible test, the following results were obtained for an equivalent rectifier with capacitive filter and constant resistive load. According to Table II, all harmonic current of the nonlinear load increase when the filter is connected. A harmonic current source model for the load cannot explain such behavior.

Table III indicates the corresponding voltage harmonics at the PCC. Note that, due to the 5th harmonic filter action, the 5th ,7th harmonics of the PCC voltage have been reduced, but the
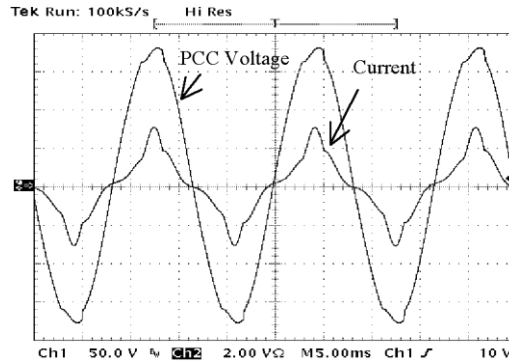
Fig. 8. PCC voltage and source current feeding a TV set; and a refrigerator, with the 5th harmonic shunt passive filter.

TABLE II
RECTIFIER (NONLINEAR LOAD) CURRENT (RMS VALUE AT 127 V)

Harmonic order	Without the filter [mA]	With 5th harmonic filter [mA]
1	571	587
3	485	517
5	345	398
7	194	260
9	80	136
11	42	55
THDI (%)	111%	123%

TABLE III
MEASURED PCC VOLTAGE CHARACTERISTICS
(LOAD: REFRIGERATOR + RECTIFIER)

Harmonic order	Without the filter [%]	With 5th harmonic filter [%]	Capacitive compensation (%)
3	2.2	2.92	2.44
5	2.58	0.83	3.65
7	2.03	1.73	5.07
9	1.08	1.27	4.02
11	0.69	0.66	1.09
THDV(%)	4.46	4.05	7.92

3rd and 9th harmonics increased, resulting a modest reduction of the total voltage distortion (THDV).The last column of Table III shows the effect of a simple capacitive compensation, intended to compensate the displacement factor of the load (refrigerator). In this case, the voltage distortion significantly increases, especially due to the 7th and 9th harmonics growth. This can be explained by the parallel resonance between the shunt capacitor (20μF) and the feeder in- ductance (5 mH), occurring near 500 Hz. Thus, assuming that the nonlinear load behaves like a non-ideal harmonic voltage source, it is necessary to consider also the resonance between the capacitor and the source impedance. but according to Fig. 6, the harmonic voltage component at the PCC can be estimated by

$$\frac{V_{h\text{PCC}}}{V_{oh}} = \frac{Z_i//Z_f}{Z_o + Z_i//Z_f}. \quad\quad\quad\quad\quad\quad\quad\quad\quad (3)$$

TABLE IV
SUPPLY CURRENT COMPONENTS (RMS VALUE AT 127 V; LOAD: REFRIGERATOR + RECTIFIER)

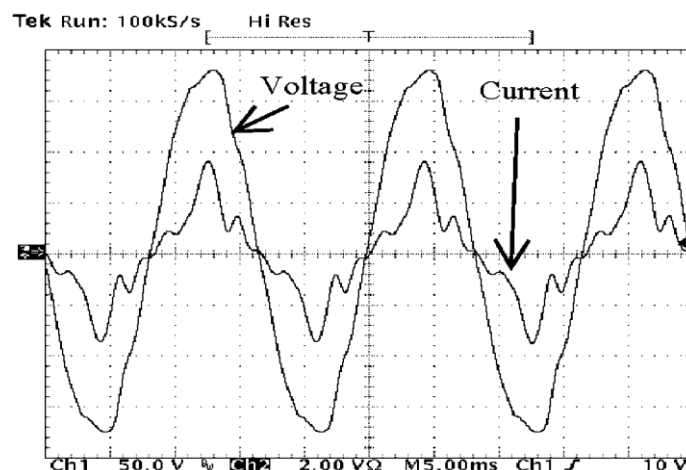| Harmonic order	Without the filter [A]	With 5th harmonic filter [A]
1	1.89	1.55
3	0.474	0.639
5	0.337	0.111
7	0.189	0.164
9	0.078	0.093
11	0.041	0.040
THDI (%)	32.8%	43.7%

Fig. 9. Refrigerator + TV load, with capacitive shunt compensation, and dis- torted supply voltage.

Table IV shows the ac mains current harmonics. Although the LC filter has reduced the 5th and 7th harmonic components in the mains feeder, it has increased the 3rd and 9th harmonic flows, thus increasing the overall supply current distortion. The fundamental current was reduced due to the reactive power compensation and therefore the THDI (%) resulted larger with the filter connected. It is important to mention that if the supply voltage already contains the harmonic component intended to be filtered, the use of shunt compensation can even produce the opposite effect in terms of waveform improvements. In this case, the resulting low-impedance path will drive current from the supply, increasing the current and voltage distortion on the feeder. This situation is illustrated in Fig. 9, showing the effect of the capacitor connected at the terminals of the load. If the supply voltage already contains harmonic distortion, the resonance amplifies the correspondent harmonic current. In this case, the 7th and 9th harmonics are amplified.

Acknowledgements

About the Authors:

Mr. C.Shashidhar at present is a Sr. Assistant Professor department of Electrical & Electronics Engineering, Aurora's Scientific, Technological & Research academy Hyderabad Andhra Pradesh, India. He received B.Tech. degree in Electrical and Electronics Engineering from J.N.T.U Hyderabad in2006 , M.Tech Power Systems Engineering from Acharya Nagarjuna University,India. He published several papers in various National, International Conferences and Journals. His research interests accumulate in the area of Power Systems, Power Quality Improvement, Renewable energy sources and Distribution system.

Mr. P.Ramesh at present is a Associate Professor department of Electrical & Electronics Engineering, Aurora's Scientific, Technological & Research academy Hyderabad Andhra Pradesh, India. He received B.Tech. degree in Electrical and Electronics Engineering from J.N.T.U Hyderabad in2000 , M.Tech Power Systems Engineering J.N.T.U Hyderabad , in 2012. He published several papers in various National, International Conferences and Journals. His research interests accumulate in the area of Power Systems, Power Quality Improvement, Renewable energy sources and Distribution system

Mr. k.Narasimha at present is a Assistant Professor department of Electrical & Electronics Engineering, Aurora's Scientific, Technological & Research academy Hyderabad Andhra Pradesh, India. He received B.Tech. degree in Electrical and Electronics Engineering from J.N.T.U Hyderabad in2013 , He is currently pursuing M.Tech (Power Sya\stems) from J.N.T.U, Hyderabad India. His research interests accumulate in the area of Power Systems, Power Quality Improvement, Renewable energy sources and Distribution system

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