THD Mitigation in Line Currents of 6-Pulse Diode Bridge Rectifier Using the Delta-Wye Transformer as a Triplen Harmonic Filter

A. N. Arvindan and B. Abinaya
Dept. of Electrical & Electronics Engineering, SSN College of Engineering, Anna University (Chennai), India

***Abstract*—The uncontrolled three-phase bridge rectifier has the least line current distortion among six-pulse rectifiers; however, its total harmonic distortion (THD) of 31.08% is unacceptable as per the contemporary power quality standards. This paper seeks to address the issue by elimination of triplen harmonics in the line currents by providing a delta-wye transformer at the ac interface i.e. between the three-phase supply and the diode bridge rectifier. The triplen harmonics circulate in the delta loop of the primary winding but are not manifested in the line currents thus reducing their THD values. The efficacy of the technique is proved by simulations considering the bridge rectifier with and without the delta-wye transformer of vector group Dy1. Experimental results with the Dy1 transformer and without it are presented.**

***Keywords*— diode bridge rectifier, improved power quality, total harmonic distortion, triplen harmonics.**

I. Introduction

THE three-phase diode bridge is, perhaps, the most popular of the six-pulse rectifiers and is extensively used, however, with the stringent contemporary power quality standards [1], [2] stipulating specific permissible levels of total harmonic distortion (THD) at the ac utility interface, it is subject to investigation to confirm and verify its compliance with the latest expectations. With the advent of improved power quality ac-dc converters [3] it has become imperative to explore techniques to improve the power quality at the ac interface of the three-phase diode bridge rectifier. The topology has been subject to investigation for harmonic reduction [4]–[6] at the ac interface for almost two decades and several new methods [5]-[9] have been suggested including hysteresis current control [7] and current injection [8]. Modification [10] of prevalent techniques too has been advocated. It is well established [11] that the six-pulse diode bridge topology, shown in Fig. 1, has a total harmonic distortion (THD) of 31.08% at the ac interface that is well above the 5% norm as stipulated by IEEE 519-1992. This paper investigates the effect of connecting the six-pulse diode bridge topology to the three-phase ac utility via a delta-wye (Δ-Y) transformer in terms of trapping the triplen harmonics in the delta loop, thus eliminating them from the ac utility line currents and also thereby improving the THD at the utility.

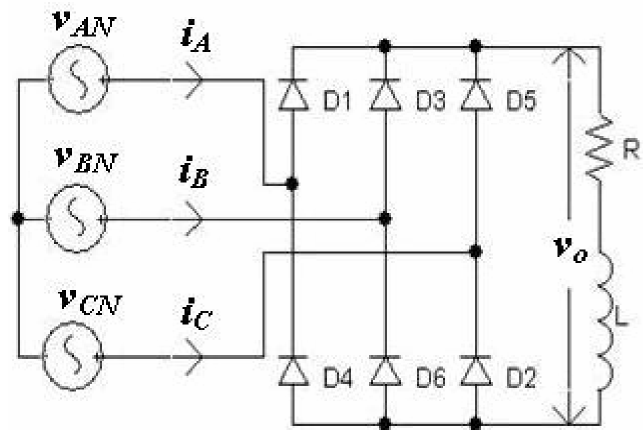

Fig. 1. An ac utility directly connected to a three-phase diode bridge rectifier feeding an inductive load.

II. Harmonics In A Rectifier

For an ideal p-pulse rectifier, drawing level load current, with no losses, and no overlap, only harmonics of the order

$$r = mp \pm 1$$

(where m = 1, 2, 3, etc.) are present in the input current, and they are of magnitude 1/r times the fundamental. Equation shows that the higher the pulse number p, the more harmonics will be eliminated, as mp = n, n being the order of the harmonics present in the voltage waveform and r the order of the input current harmonic.

The assumption of level load current is often unjustified for the above statements to be true, and in practice, at large firing delays, the harmonic components differ from the simple relationship of 1/r to the fundamental.

A. *Triplen Harmonics*

In respect to balanced three-phase systems, some general observations can be made. The triplen harmonics, that is, those of order 3*m*, where *m* = 1, 2, 3, etc., are all in phase with each other at all instants as illustrated by:

A. N. Arvindan was with Asea Brown Boveri (ABB), Bangalore. He is now a full professor with the Department of Electrical and Electronics Engineering, SSN College of Engineering, Anna University, Chennai.(Phone:+91-44-27475063; fax: +91-44-27474844; e-mail: lkana0@yahoo.com).

B. Abinaya is a PG scholar in the Department of Electrical and Electronics Engineering, SSN College of Engineering, Anna University, Chennai. (e-mail: abinaya_b2000@yahoo.com).

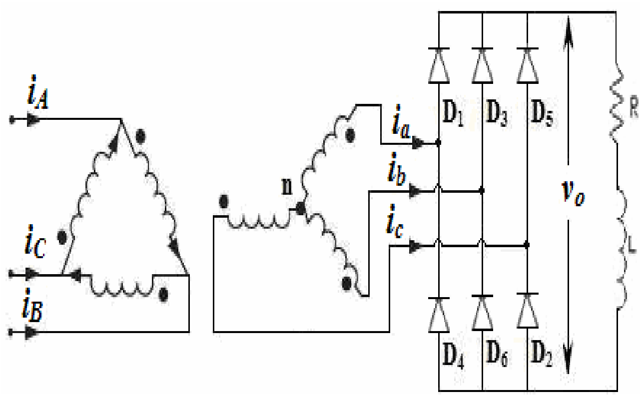

Fig. 2. An ac utility source connected via delta-wye (Dy1) transformer to a three-phase diode bridge rectifier feeding an inductive load.

$$i_{a(3m)} = I \sin 3m\omega t$$

$$i_{b(3m)} = I \sin[3m(\omega t - 2\pi/3)] = I \sin 3m\omega t$$

$$i_{c(3m)} = I \sin[3m(\omega t + 2\pi/3)] = I \sin 3m\omega t$$

Hence, $$i_{a(3m)} = i_{b(3m)} = i_{c(3m)} \quad (1)$$

This clearly implies that the triplen harmonics are in phase. In symmetrical component theory the flow of triple-frequency components is similar to a zero-sequence component, with the neutral current being three times that in each line.

B. *Positive Sequence Harmonics*

Harmonics of order (3*m* + 1) can be expressed as:

$$i_{a(3m+1)} = I \sin[(3m+1)\omega t]$$

$$i_{b(3m+1)} = I \sin[(3m+1)(\omega t - 2\pi/3)] = I \sin[(3m+1)\omega t - 2\pi/3]$$

$$i_{c(3m+1)} = I \sin[(3m+1)(\omega t + 2\pi/3)] = I \sin[(3m+1)\omega t + 2\pi/3]$$

A harmonic of order (3*m* + 1) such as seventh (*m* = 2) are of the same sequence as the fundamental.

C. *Negative Sequence Harmonics*

A harmonic of order (3*m* - 1) is at a reversed (negative) sequence to that of the fundamental. For example, a fifth (*m* = 2) harmonic will set up a reverse torque component in an induction motor if its input contains such a harmonic.

III. Δ-Y TRANSFORMER AS A TRIPLEN HARMONIC FILTER

The delta-wye (Δ-Y) transformer is available with several vector groups including ones without and with its neutral terminal on the wye side being accessible. The vector group Dy1 is considered for investigation and the corresponding topology with the six-pulse diode bridge rectifier is shown in Fig. 2. The neutral on the wye side is not accessible for this vector group connection. If the wye neutral is not connected to the load, then the absence of the neutral means that there can be no triplen harmonic components in the line currents.

IV. SIMULATION OF SIX-PULSE DIODE BRIDGE TOPOLOGIES

The two topologies of the three-phase diode bridge rectifier including one wherein the rectifier bridge is directly coupled to the ac utility are simulated for resistive and inductive loading and an estimate of the harmonic distortion in the line currents at the input of the rectifier and at the ac utility is obtained for each configuration.

A. *Assumptions*

The three-phase ac utility is presumed to be ideal i.e. it has zero impedance and, therefore, lossless apart from being balanced and possessing time invariant frequency of 50 Hz. The phase sequence is assumed to be ABC for all the simulations. The power diodes in the rectifier are also assumed to be ideal from the commutation perspective in that the turn-on and turn-off times are considered to be negligible. The effects of the source and load inductances on the output voltage, V_o are ignored i.e. the commutation or overlap angle, μ, is presumed to be zero. The effect of reverse recovery time of the diodes on V_o is also ignored. The simulations pertaining to the topology that employs the delta-wye transformer configuration assumes that the operation of the rectifier is well within the magnetic core saturation limit.

B. *Simulation Parameters*

The simulation parameters and data for the diode rectifier topologies are shown in Table I. The simulation parameters are defined as follows:

R = Load resistance
L = Load inductance
R1 = R2 = DC bus resistors
C1 = C2 = DC link capacitors

Delta-wye transformer of 440V/440V, 1.5 KVA rating is used in the simulation of the topology with transformer. The voltage ratio of 1:1 is deliberate to emphasize and investigate the use of the transformer as a harmonic filter. The rating of the delta-wye transformer used is based on the following technical data:

Power factor of the 6-pulse diode bridge rectifier = 0.9542
No load current (I_o) = 5% of the full load current (I_{fl})
Magnetising current (I_m) = 0.75 I_o

TABLE I
SIMULATION PARAMETERS AND DATA

Converter Topology	Load	R Ω	L mH	R_1 & R_2 Ω	C_1 & C_2 μF	Total Harmonic Distortion (THD) Of Line Currents %	
Three-phase bridge rectifier connected directly to ac utility	Resistive	250	-	-	-	29.87	
	Inductive	220	377.9	-	-	30.40	
Three-phase bridge rectifier connected via Dy1 transformer to ac utility	Resistive	250	-	-	-	Primary Winding	28.43
						Secondary Winding	30.25
	Inductive	220	377.9	-	-	Primary Winding	28.69
						Secondary Winding	30.53

V. Simulation Results And Discussions

A. *Power Quality for AC Utility Directly Connected to 3-phase Rectifier*

1) Rectifier Feeding Resistive Load: In this section the results pertaining to the six-pulse diode bridge topology directly connected to the 3-phase ac utility are depicted and discussed. Fig. 3 shows the three line currents at the ac interface that are also the input currents of the rectifier. The dc link voltage and the corresponding load current for a resistive load are shown in Fig. 4. The dc link current and voltage waveforms are in phase as expected with a ripple frequency of 300Hz i.e. six times that of the 50Hz ac utility frequency. Between two half pulses, each of width 1.666ms at either end of the 20ms time period corresponding to the 50Hz fundamental frequency of the ac utility, there are five

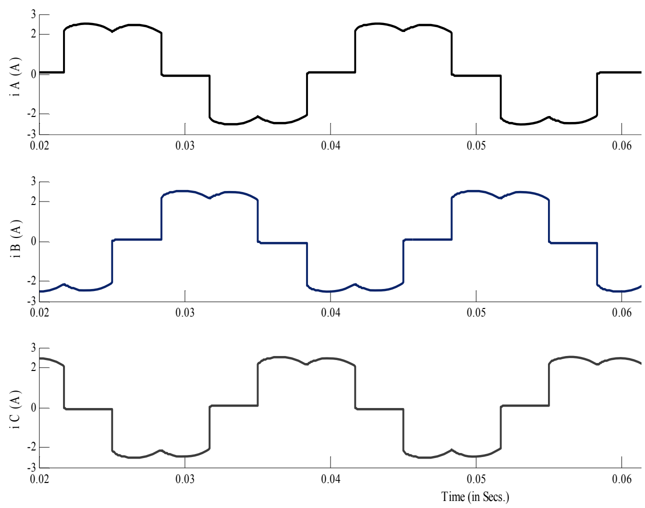

Fig. 3. Line currents of ac utility directly connected to a three-phase diode bridge rectifier feeding a resistive load.

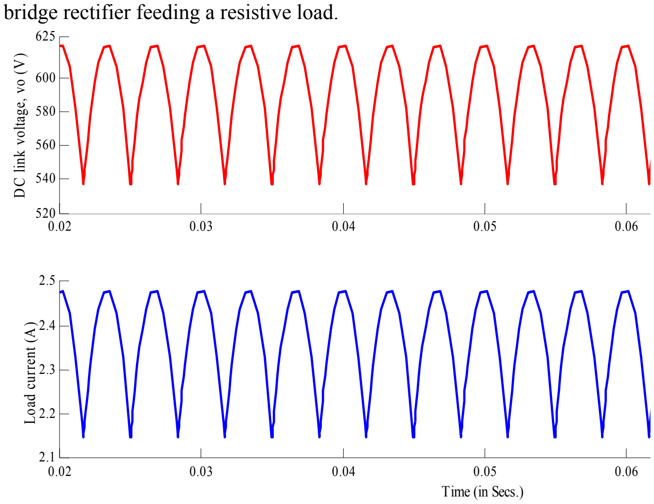

Fig. 4. DC side voltage and current of the 3-phase diode bridge rectifier feeding a resistive load and directly connected to ac utility.

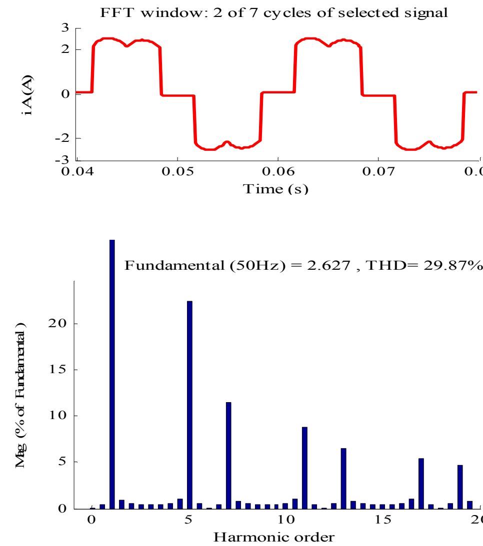

Fig. 5. FFT analysis of the line current, i_A at the ac utility for resistive load.

pulses each of 3.333ms thus accounting for the six-pulse dc voltage output. Fig. 5 depicts the fast fourier transform (FFT) of the ac utility line current. Harmonics up to the 20th have been considered. The THD of the input current of the rectifier also the ac utility line current is 29.87%.

2) Rectifier feeding inductive load: The waveforms of the line currents of the ac utility directly connected to the six-pulse rectifier feeding an inductive load are shown in Fig. 6. Comparison of these waveforms with those pertaining to resistive load in Fig. 3 clearly shows that the currents are flat topped in the former. This is because of the predominance of inductance in the load for waveforms in Fig. 6. The dc link voltage and the associated load current are shown in Fig. 7.

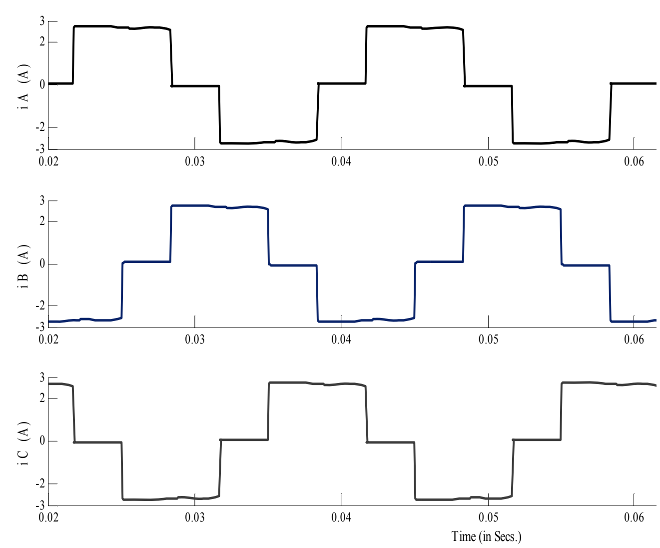

Fig. 6. Line currents of ac utility directly connected to a three-phase diode bridge rectifier feeding an inductive load.

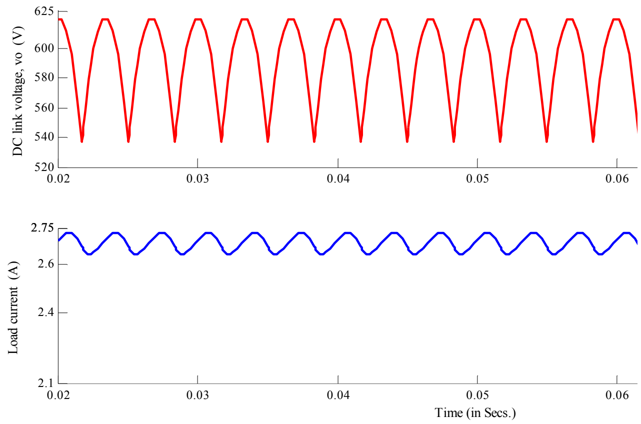

Fig. 7. DC side voltage and current at the ac utility directly connected to a three-phase diode bridge rectifier feeding an inductive load.

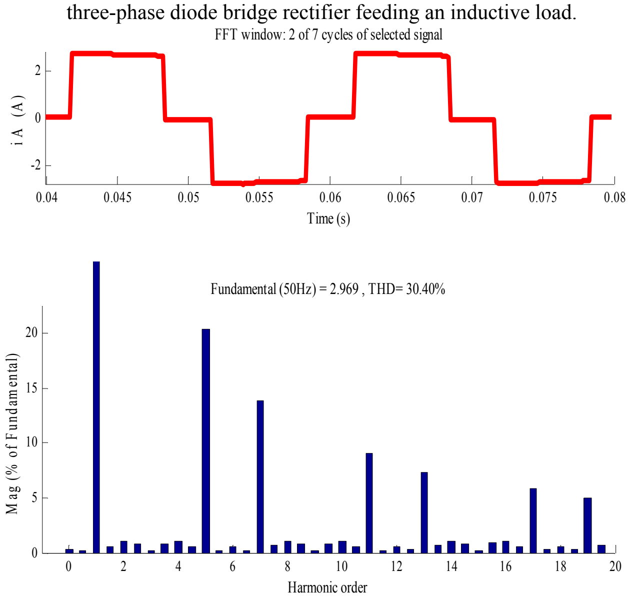

Fig. 8. FFT of the line current, i_A at the ac utility for inductive load.

The dc link voltage is identical with that for the resistive load shown in Fig. 4 and from the waveforms it is clear that the peak line voltage is √2 times the r.m.s. value of 440V i.e. 622.25V. The load current, however, expectedly differs from that pertaining to the resistive load in that the ripple content is substantially reduced. The THD of the ac utility line current is obtained to be 30.40% and the relevant FFT is is shown in Fig. 8. The marginal increase of 0.53% in THD of the line current for this case vis-à-vis the previous case can be attributed to the change in the wave shape of the line currents because of the inductance in the load.

B. *Power Quality for AC Utility Connected via Dy1 Transformer to 3-phase Rectifier*

1) Rectifier Feeding Resistive Load: Figs. 9 and 10 show the currents drawn from the ac utility that are also the primary delta winding line currents and the phase currents in the delta winding respectively. The peak value of the line currents in Fig. 9 is 3.03A while that of the phase currents in Fig. 10 is 1.54A. The secondary wye currents that are also the rectifier input currents shown in Fig. 11, are in phase with the currents in Fig. 10, and have a peak value of 2.525A that is almost √3 times that of the latter.

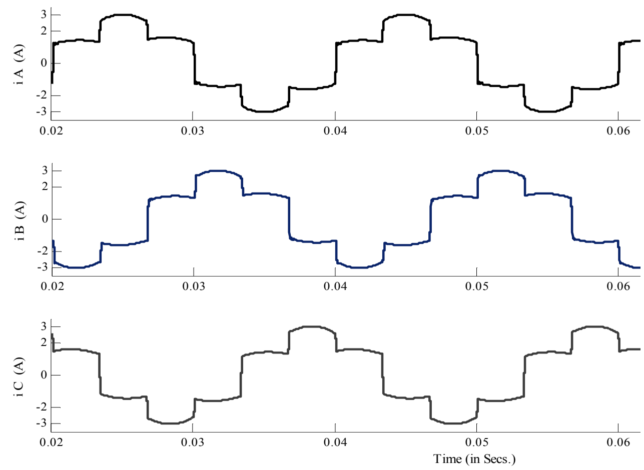

Fig. 9 Line currents of an ac utility connected via delta-wye (Dy1) transformer to a 3-phase diode bridge rectifier feeding a resistive load.

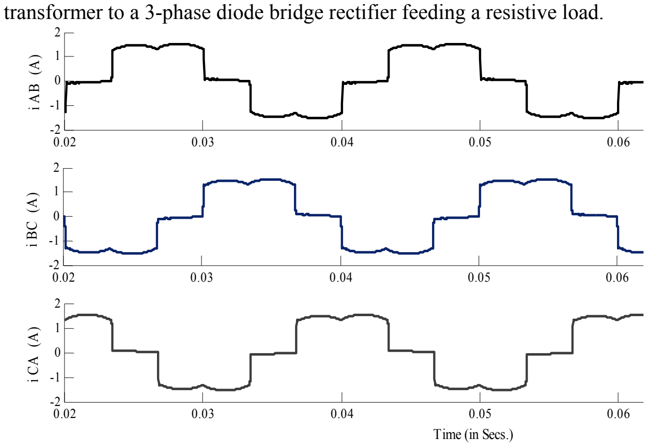

Fig. 10 Phase currents of the delta connected windings of a delta-wye (Dy1) transformer coupled to a 3-phase diode bridge rectifier feeding a resistive load.

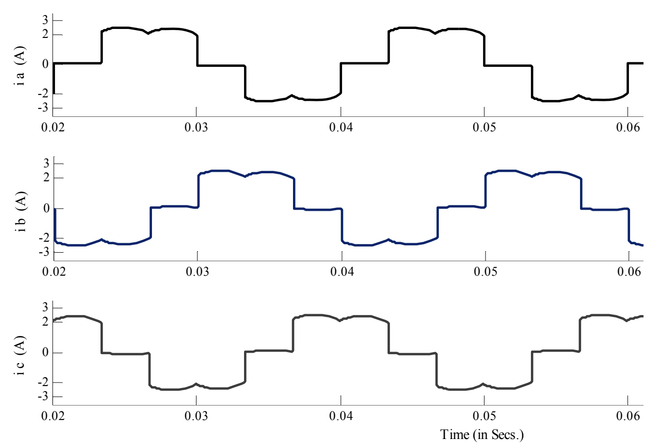

Fig. 11 Input currents of a 3-phase diode bridge rectifier, feeding a resistive load, coupled to an ac utility via delta-wye (Dy1) transformer.

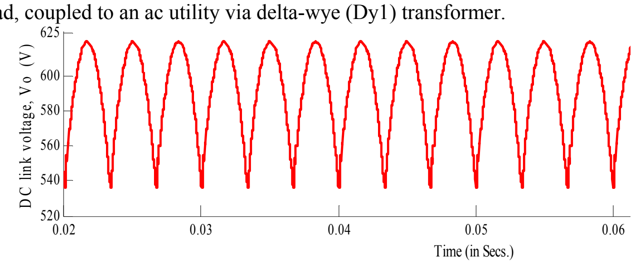

Fig. 12. DC link voltage of a three-phase diode bridge rectifier, feeding a resistive load, coupled to an ac utility via delta-wye (Dy1) transformer.

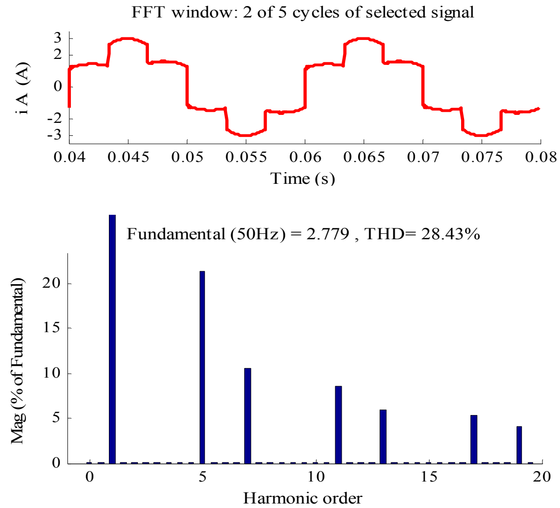

Fig. 13. FFT analysis of the line current, i_A, at the ac utility connected via Dy1 transformer to a 3-phase diode bridge rectifier feeding a resistive load.

The line currents on the delta side must theoretically have the same peak value of 2.525A as the wye side since the voltage ratio (of the line voltages) is 1:1, however, the discrepancy of 0.505A (3.03A – 2.525A) is because of the magnetizing current of the transformer. The dc link voltage shown in Fig. 12 comprises six complete pulses for the 20ms time period corresponding to the 50Hz fundamental frequency rather than those obtained without the Dy1 transformer shown in Figs. 4 and 7. The FFT of the ac utility line current is shown in Fig. 13, wherein, it is clear that a THD value of 28.43% is obtained that is an improvement of 1.44% over the 29.87% value for resistive load without the Dy1 transformer as indicated in Table I.

2) Rectifier Feeding Inductive Load: The waveforms of the line and phase currents on the Δ- connected primary winding, line currents on the Y-connected secondary winding and dc link voltage for the topology shown in Fig. 2 are similar to those shown for the same topology feeding a resistive load except that the currents are flat topped. The line currents on the Δ-side and the corresponding FFT indicating a THD of 28.69% are shown in Figs. 14 and 15 respectively.

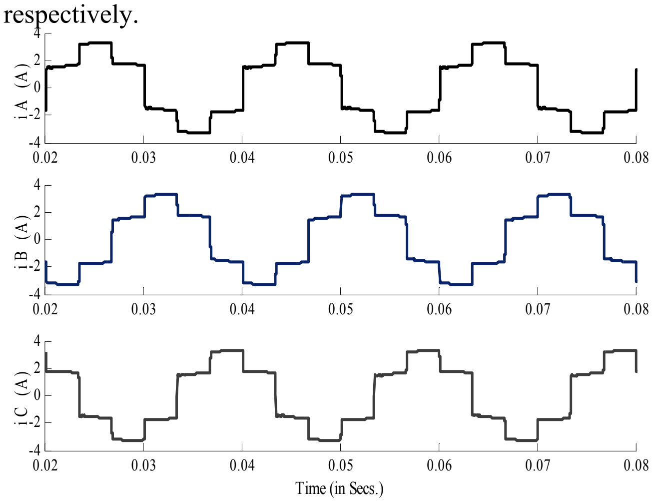

Fig. 14. Line currents of ac utility connected via delta-wye (Dy1) transformer to a three-phase diode bridge rectifier feeding an inductive load.

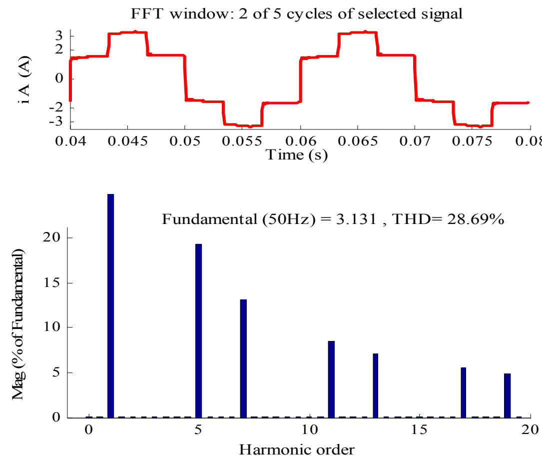

Fig. 15 FFT of the line current, i_A, at the ac utility connected via Dy1 transformer to a 3-phase diode bridge rectifier feeding an inductive load.

Table I indicates that the THD value of the line current at the ac utility is lower than the 30.40% obtained for a identical inductive load without the Δ/Y transformer by 1.71%. The line current, for a level magnitude of I, in Fig. 14 can be expressed in a Fourier series as:

$$i=\frac{4\sqrt{3}}{2\pi}I\left[\sin\omega t+\frac{\sin 5\omega t}{5}+\frac{\sin 7\omega t}{7}+\frac{\sin 11\omega t}{11}+\frac{\sin 13\omega t}{13}+\frac{\sin 17\omega t}{17}+......\right] \quad (2)$$

while that in Fig. 6 can be expressed as:

$$i=\frac{4\sqrt{3}}{2\pi}I\left[\sin\omega t-\frac{\sin 5\omega t}{5}-\frac{\sin 7\omega t}{7}+\frac{\sin 11\omega t}{11}+\frac{\sin 13\omega t}{13}-\frac{\sin 17\omega t}{17}-......\right] \quad (3)$$

VI. Experimental Results

The simulation results were experimentally verified for resistive load by fabricating a 0.5kW prototype comprising of a 415V/190V, (Dy1) delta-wye transformer and a three-phase bridge rectifier compatible with three-phase, 110V, 50Hz input. A rheostat was used as a resistive load. The Dy1 transformer was fed by a 3-phase autotransformer to obtain the appropriate primary voltage to obtain the 110V voltage level required by the diode bridge. The measurements were taken using the Fluke PD345 clamp meter. The experimental set up is shown in Fig. 16.

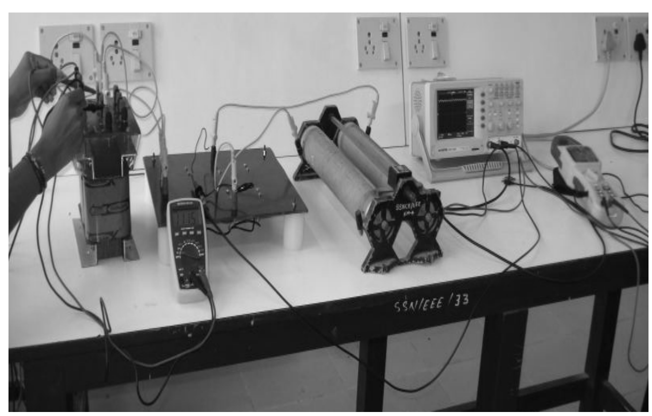

Fig. 16 Experimental set up.

1) With Dy1 transformer at the ac interface: The experimental data pertaining to the condition wherein the three-phase diode bridge rectifier is fed via the Dy1 transformer are shown in Table II.

TABLE II
EXPERIMENTAL DATA WITH DY1 TRANSFORMER FEEDING THE RECTIFIER

Primary voltage/current	Secondary voltage/current	DC voltage	Load current	Load resistance
242 V 0.61 A	110 V 1.08 A	147.5 V	1.42 A	100 Ω
245.6 V 1.12 A	106.6 V 2.32 A	140.5 V	2.87 A	49 Ω

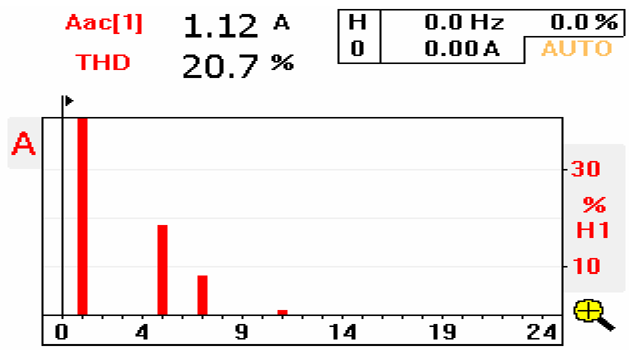

Fig. 17 FFT of the line current at the ac interface with diode bridge fed via Dy1 transformer.

Fig. 17 shows the FFT (Fast Fourier Transform) of the line current at the ac interface with the Dy1 transformer feeding the three-phase, diode bridge rectifier connected to a resistive load with parameters corresponding to the second row of Table II i.e. a load current of 2.87A. From the Fig. it is clear that the 5^{th} and 7^{th} harmonics are the predominant harmonics typical of a six-pulse rectifier. The THD is measured to be 20.7%.

2) *Diode bridge directly fed by the ac utility:* The data corresponding to the condition wherein the 3-phase rectifier is fed directly by the ac utility are shown in Table III.

TABLE III
EXPERIMENTAL DATA FOR AC UTILITY DIRECTLY FEEDING THE RECTIFIER

Input voltage/current	DC voltage	Load current	Load resistance
110 V/1.14 A	147.5 V	1.44 A	100 Ω
110 V/2.34 A	145.4 V	2.87 A	50 Ω

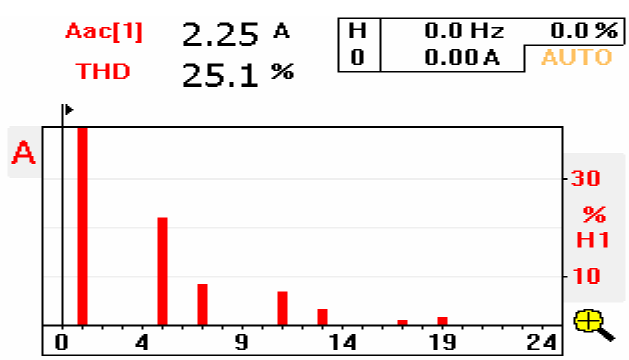

Fig. 18 FFT of the line current at the ac interface with diode bridge fed directly by the ac utility..

Fig. 18 shows the FFT (Fast Fourier Transform) of the line current at the ac interface for the condition wherein the diode bridge rectifier feeding a resistive load is directly coupled to the ac source (i.e. without the Dy1 Transformer). The load parameters in this case correspond to those indicated in the second row of Table III. From the Fig. 18 it is seen that the THD of the line current at the utility for this condition is 25.1%. It is noteworthy that the THD of the line current at the utility drawn by the six-pulse diode bridge rectifier connected to a resistive load and fed via the Dy1 transformer is significantly less compared to the condition when the same rectifier connected to the same resistive load is fed directly by the ac utility.

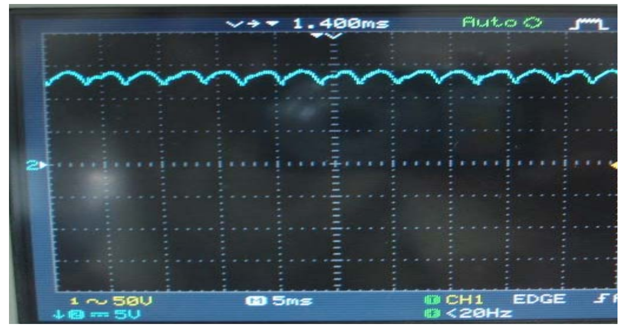

Fig. 19 DC output voltage of the six-pulse diode bridge rectifier.

Fig. 19 shows the dc output voltage waveform of the three-phase, diode bridge rectifier.

VII. CONCLUSION

The harmonic content in the line currents of the generic six-pulse diode bridge topology are much higher than modern power quality stipulations, however, its connection to the ac utility via a delta-wye (Dy1) transformer, intrinsically a line current triplen harmonic filter, renders it amenable to certain distortion mitigation techniques.

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