IMPACT OF VOLTAGE HARMONIC DISTORTION ON ENERGY EFFICIENCY

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ABSTRACT

The intent of this paper is to bring out the salient energy efficient technologies that can be adopted to suppress / control the voltage harmonic distortion.

Harmonic currents spawned by the non-sinusoidal loads can cause problems in the power systems and in equipment like distribution transformers, Motors, Generators, etc. as they are susceptible to overheating and premature failure lead to plunging of the efficiency of power system thereby resulting in greenhouse emissions. The existence of harmonics clearly upset the operational parameters such as temperature, core losses, etc. in transformers. The efficiency of a typical distribution transformer is in excess of 98% with 2% resulting in losses which will further increase with non-sinusoidal loads. These losses are far from negligible and anything that can be done to reduce them has the potential to deliver large savings. Hence, efficiency improvements with electrical machines can have a very large impact on energy consumption. The key challenges to increased efficiency in systems driven by electrical machines lie in three areas:

1) *To extend the application areas of variable-speed electric drives through reduction of power electronic and control costs.*
2) *To integrate the drive and the driven load to maximize system efficiency.*
3) *To increase the efficiency of the Transformer with non-sinusoidal loads.*

Application of Phase Shifting Transformers, Zigzag Transformers, K-Factor Transformers for Harmonics are analysed with few case studies. This dissertation provides a detailed analysis using E-TAP and PS-CAD software's in confronting non-sinusoidal loads, conspicuous technologies which are not only for reducing the harmonic distortion but also to improve the efficiency of power systems.

INTRODUCTION

Harmonics are voltages and currents which appear on the electrical system at frequencies that are integral multiples of the fundamental frequency. Harmonics are a mathematical way of describing distortion to a voltage or current waveform. For the purpose of a steady state waveform with equal positive and negative half-cycles, the Fourier series can be expressed as follows:

$$f(t) = \sum A_n \sin\left(\frac{n\pi t}{T}\right) \qquad (1)$$

Where
f (t) is the time domain function,
n is the harmonic number (only odd values of n are required,
A_n is the amplitude of the nth harmonic component,
T is the length of one cycle in seconds.

The ratio of the root-mean-square of the harmonic content to the root-mean square value of the fundamental quantity, expressed as a percent of the fundamental is Total Harmonic Distortion (THD).

$$THD = \sqrt{\frac{(I_3^2+I_5^2+I_7^2 \ldots\ldots)}{I_1^2}} \qquad (2)$$

Where, I_3, I_5, I_7 are harmonic currents at 3rd, 5th & 7th harmonics, I_1 is the fundamental current.

Harmonics of sinusoidal AC voltages and currents appear on the electrical system at frequencies that are integral multiples of the fundamental frequency. Voltage harmonics are mostly caused by current harmonics. The voltage provided by the voltage source will be distorted by current harmonics due to source impedance. The mathematical equation V = RI shows that any current flowing within a resistance (impedance) generates voltage at the terminals. As transformers also have impedance, voltage distortion appears at the transformer's secondary terminals when harmonic currents flow through it. Therefore, to reduce voltage distortion two factors can be modified: the level of harmonic currents and transformer impedance. Harmonic currents and voltages can have adverse effects on electrical equipment such as transformers, motors, DG sets which are subjected to higher heating losses and resulting in poor efficiency due to harmonic currents generated by non-linear loads. However, this dissertation deals with the efficiency of Transformers only.

Effect of Harmonics on Transformer losses

When a transformer is utilized under non-sinusoidal voltages and currents, it leads to increase of loss and, as a result, increase of temperature and so its output power decreases. Transformer temperature rise under non-sinusoidal loads is very high compared to its operation under sinusoidal load and so do the losses. Hence, if the same core is to operate under non-sinusoidal loads, it would be operating at higher loss and dissipates twice as much heat which ultimately results in emission of CO_2 (due to increase in fuel consumption for the generation). Moreover, when the harmonic current frequencies include harmonic orders having multiples of three (3, 6, 9, etc.), zero sequence currents flow in the neutral and overheating the neutral.

Harmonics such as the 7th, which "rotate" with the same sequence as the fundamental, are called positive sequence. Harmonics such as the 5th, which "rotate" in the opposite sequence as the fundamental, are called negative sequence. Triplen harmonics which don't rotate at all because they are in phase with each other are called zero sequence as shown in fig 1. Sequence especially matters when we're dealing with AC motors, since the mechanical rotation of the rotor depends on the torque produced by the sequential "rotation" of the applied 3-phase power. Positive-sequence frequencies work to push the rotor in the proper direction, whereas negative-sequence frequencies actually work against the direction of the rotor's rotation. Zero-sequence frequencies neither contribute to nor detract from the rotor's torque. An excess of negative-sequence harmonics (5th, 11th, 17th, and/or 23rd) in the power supplied to a three-phase AC motor will result in degradation of performance and possible overheating. Since the higher-order harmonics tend to be attenuated more by system inductances and magnetic core losses, and generally originate with less amplitude anyway, the primary harmonic of concern is the 5th, which is 250 Hz in 50 Hz power systems.

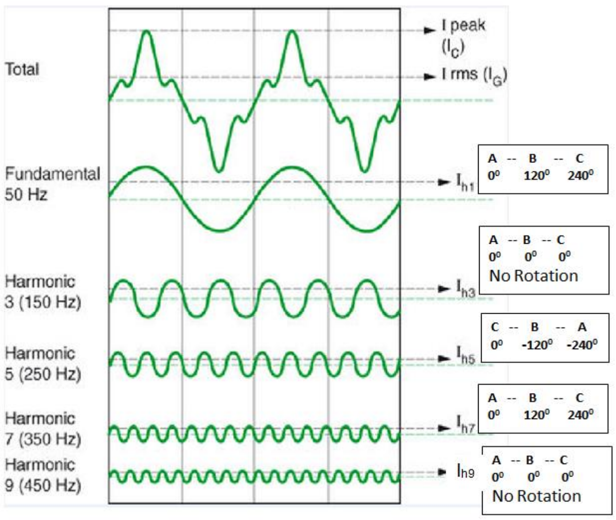

Fig.1 Harmonics Phase Sequence

Phase shifting transformers and zig-zag transformers are used to minimize the distortion on the primary side by providing an angular displacement between two three-phase outputs to cancel the harmonic currents and voltages. Hence, the following 3 options are discussed herewith in detail.

a) Phase Shifting Transformers
b) Zig-zag transformer
c) K-Factor Transformer

CASE STUDY

The following case studies have been performed for a steel plant with conveyors that are used to feed the stock house and also the blast furnace which are fed from single source i.e. 690V. These conveyors are provided with Variable Voltage & Variable Frequency (VVVF) drives as per the process requirement. From past experience of steel plants, it is observed that due to these non-sinusoidal loads, harmonics injected in to the source reduces the power factor & efficiency of the system. The following cases have been analysed and simulated in PSCAD software (version. 4.5).

Presently 4MVA, 6.6/0.72kV, DYyn11, conventional step-down transformer is being used in the system. However, the voltage harmonic distortion is high on both primary and secondary side of transformer. The main objective here is to evaluate the mitigating technologies which are not only for reducing the harmonic distortion, isolate the main electrical system i.e. 6.6kV from the harmonics but also to improve the efficiency of the power system. Hence, Phase Shifting Transformers, Zig-Zag Transformers and combination of Phase shifting transformers, Zig-zag transformers with harmonic filters are the most economical solutions.

Zig-zag and Phase Shifting transformers are merely used to isolate the main electrical system from the harmonics generated by non-sinusoidal loads are present on the secondary side of these transformers.

Phase Shifting Transformer

A Phase Shift Transformer is a distinct kind of transformer that has a special winding that changes the angular displacement between primary and secondary, also commonly called Harmonic Mitigating Transformers. Unlike a K-rated transformer, which only prevents the transformer and neutral conductor from overheating, a Phase-Shift Transformer uses a technique known as "phase shifting" to displace harmonic currents so that they cancel each other out. Harmonic treatment is provided entirely by electromagnetic flux cancellation; no filters, capacitors, or other such devices are used. Hence, an angular displacement of

a. 60° is required between two three-phase outputs to cancel the 3rd harmonic currents
b. 30° is required between two three-phase outputs to cancel the 5th and 7th harmonic currents
c. 15° is required between two three-phase outputs to cancel the 11th and 13th harmonic currents.

The Case study as shown in Fig. 2 illustrates the application of phase shifting transformer for mitigating the harmonics of Variable Voltage and Variable Frequency Drives (VVVF's), which contains the two most corruptive harmonics i.e. 5th and 7th order harmonics within the waveform. Voltage distortion Characteristics of the VVVF's are tabulated in Table I.

A delta-star step-down transformer was initially used to feed the VVVF's however; the non-sinusoidal voltages and currents have led to increase in losses as a result increase of temperature and so its efficiency decreases. Harmonic distortion at the primary and secondary side of transformer is 15.3% disturbing the power factor and life of distribution system. Hence, Phase shifting Transformer is introduced here with a phase shift of +30º and -30°.

TABLE I. Harmonic Voltage Distortion

Harmonic order	Voltage U_h (V)	U_h/U_{LV} (%)	V_{THD} (%)	As per IEEE-519
1	627	-	15.3	5%
5	62.6	10.0		
7	37.7	6.0		
11	25.4	4.1		
13	35.7	5.7		
17	8.7	1.4		
31	14.2	2.3		
35	14.2	2.3		

Harmonic spectrum on the secondary side of transformer is shown in Fig.3. The phase shifting transformer shifts the 5th harmonic to 150° and shifts the 7th harmonic to 210° when the shifted harmonics return back onto the line, the shifted 5th will be approximately 30° away from a perfect 180° with respect to the non-shifted 5th. Likewise the shifted 7th will be 30° from 180° with respect to the non-shifted 7th. Now, within the electrical distribution system, the shifted 5th harmonics are opposite in phase and cancel with each other, as do the shifted 7th harmonics. With a phase shifting transformer it is observed that the 5th and 7th harmonics are cancelled and the voltage harmonic distortion on the primary side is less than 5% as shown in Fig.4. It is important to note that harmonic currents still flow on the secondary windings

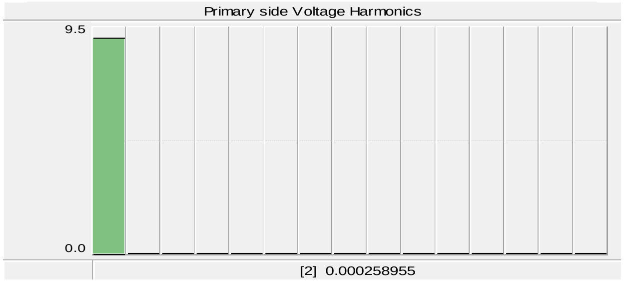

Fig.4 Harmonics on 6.6kV side with Phase Shifting Transformer

Zig-zag Transformer

A Zigzag Vector Phase Shift Transformer is designed to trap triplen harmonic currents (3rd, 9th, 15th, 21st, etc.) and also called as interconnected star connection. This connection has some of the features of the Y and the Δ connections, combining the advantages of both connections. The Case study as shown in Fig. 5 illustrates the application of Zig-zag vector phase shifting transformer for mitigating the harmonics of VVVF's which contains the two most corruptive harmonics i.e. 5th and 7th order harmonics within the waveform as shown in fig 1.

Harmonic distortion at the primary and secondary side of transformer is 15.3% as discussed in the above case. Hence, Zig-zag vector Phase shifting Transformer is

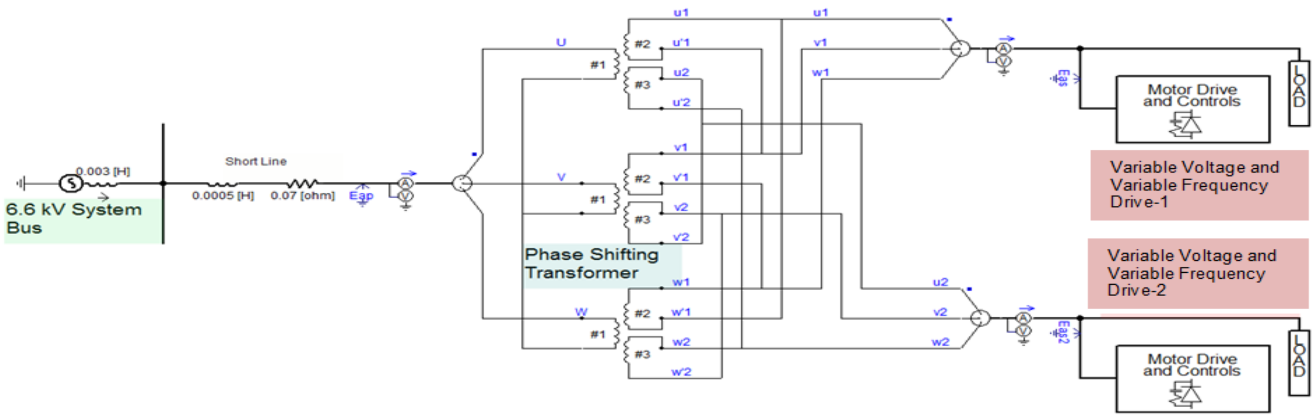

Fig.2 Case Study of Phase Shifting Transformer

as the phase difference of +30° cancels the 5th & 7th harmonics only on the primary side.

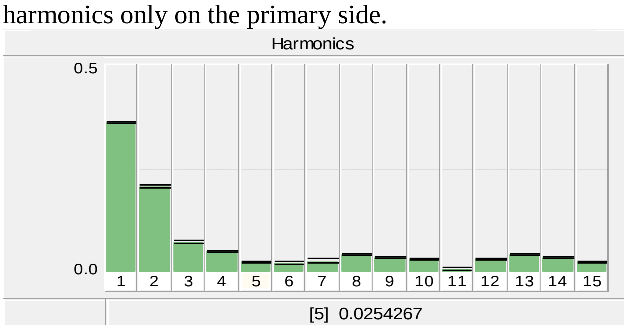

Fig.3Harmonics on 690V side with Phase Shifting Transformer

introduced here with a phase shift of +30º.

Harmonics flowing in the secondary cannot be ignored as the equipment life will be degraded after certain period of time resulting in breakdown. Hence a passive filter can be provided on the secondary side to reduce the harmonics which is explained in further chapters of this dissertation.

The Zig-zag vector phase shifting transformer has cancelled all the triplen harmonics (3rd, 9th, 15th, 21st, 27th, etc.) on the primary side with a phase shift of 30° between primary and secondary. Harmonic spectrum on the secondary side of transformer is shown in Fig.6. Hence, this zig-zag transformer modelled in this case study has the capability to cancel 3rd, 5th, 7th, 9th, 15th, 21st, etc.). With a Zig-zag vector phase shifting transformer it is observed that the 5th and 7th harmonics are cancelled and the voltage harmonic distortion on the primary side is less than 5% as shown in Fig.7.

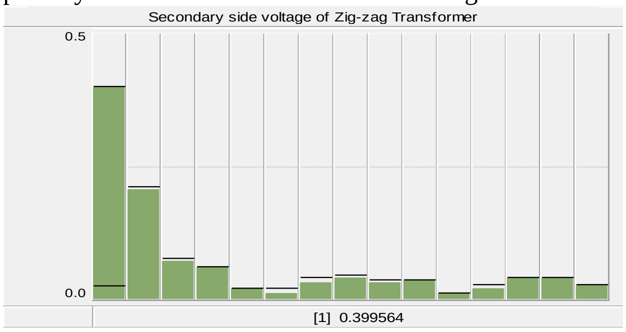

Fig.6 Harmonics on 690V side with Zig-zag Transformer

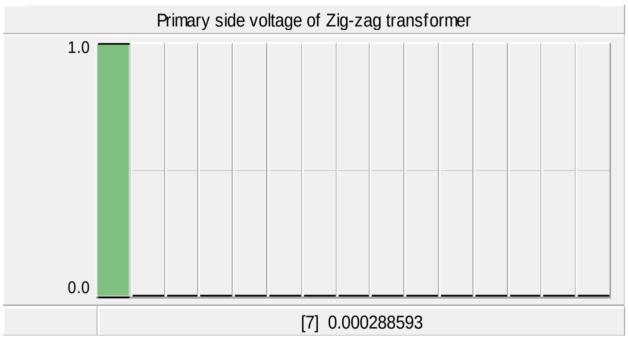

Fig.7 Harmonics on 6.6kV side with Zig-zag Transformer

However, it is to be noted that the zig-zag transformer cancels the harmonics only on the primary side of transformer and the secondary side harmonics remain. These harmonics flowing in the secondary cannot be ignored as the equipment life will be degraded after certain period of time resulting in breakdown. Hence a passive filter can be provided on the secondary side to reduce the harmonics which is explained with a case study below.

Combination of Phase Shifting Transformer & Harmonic Filter

In both the cases, it is observed that the Total Harmonic Distortion (THD) remains as it is on the secondary side. In addition to the phase shifting transformer, a suitable harmonic filter was introduced to maintain the THD levels below 5%. Single-tuned passive filter has been sized and placed near the VVVF to reduce the harmonics on the secondary side of transformer. With the introduction of a harmonic filter 5th order harmonic is completely nullified and also the Individual Harmonic Distortion (IHD) of other harmonic orders are reduced as shown in Fig. 8. Total Harmonic Distortion at the transformer secondary is reduced to 3.4% which is as per IEEE-519, 1992. The details of the harmonic filter are listed in Table II.

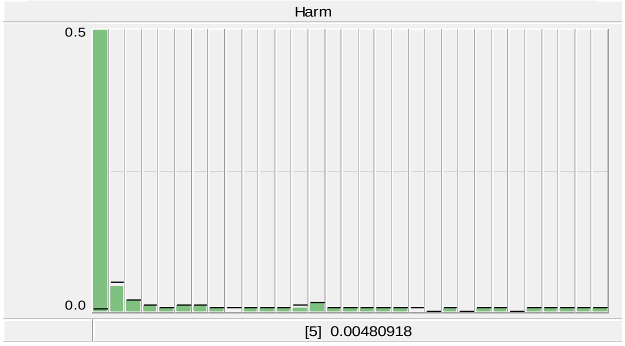

Fig. 8 Voltage spectrum with Harmonic Filter on 690V side with Phase Shifting Transformer

TABLE II. Passive Filter Details

Capacitance (1-phase)	1000µF
Rated kV	0.69kV
K-Factor	5
Inductance	0.0073H
Maximum current	400A
Desired power factor	0.95
Load	1.8MVA

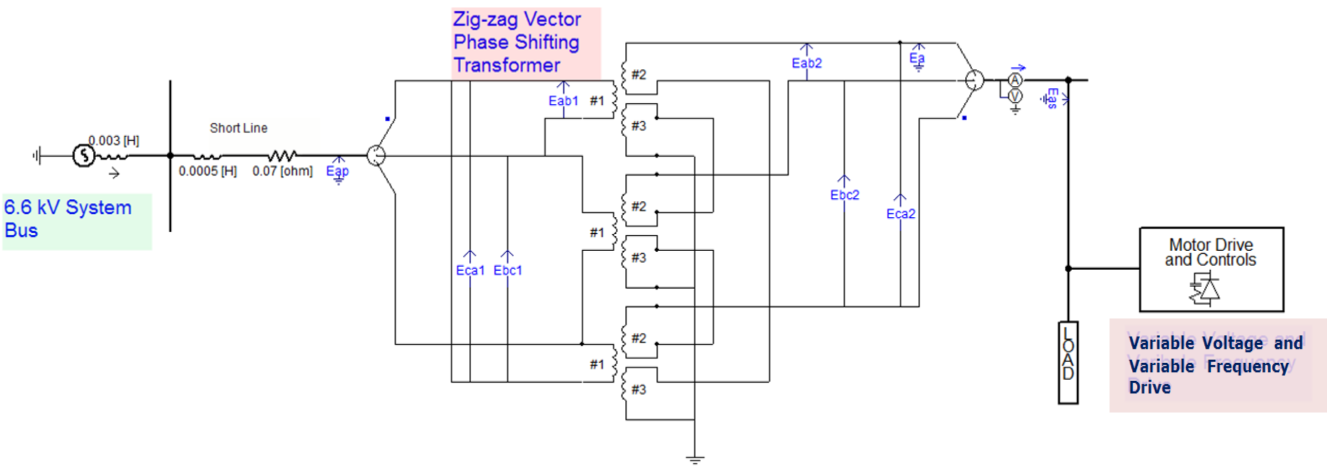

Fig. 5 Case Study of Zig-zag vector Phase Shifting Transformer

K-Factor Transformer

These specialized transformers feature conductors capable of carrying the harmonic currents of non-linear loads without exceeding the temperature rating of the insulation system. The core and coil design manages the flux caused by triplen harmonics that can cause core saturation, voltage instability and overheating in a standard transformer. Some of the constructional features are:-

a. Specially designed core and coils have reduced induction levels, resulting in a reduction in stray losses.
b. Reduced core flux density prevents core from saturation and overheating from voltage distortions caused by harmonic currents.
c. High grade, non-ageing, silicon steel with high magnetic permeability provides reduced core induction levels.
d. Neutral bus sized and configured to accommodate at least 200% of the rated current compensates for increased neutral currents found in non-linear loads, thus reducing heat.

Harmonic analysis was performed with over-sized conventional transformer and losses due to non-sinusoidal loads are worked out with the harmonic loss factors as per IEEE C57.110-1998. Voltage distortion Characteristics of the VVVF's are as per Table I.

The harmonic order at which the maximum distortion occurs has been analysed. It is observed by over sizing the transformer that even though the transformer is over-sized to reduce the overheating and premature failures, the losses are still on higher side. Hence, a K-factor transformer of 5 is selected based on the above case studies. Harmonic analysis was performed with K-5 Transformer and it is found that the losses are less than that of conventional transformer and operating at higher efficiency.

With the combination of K-factor transformer & single-tuned passive harmonic filter, the total harmonic distortion at the PCC level is reduced to 3.8% which is as per IEEE-519, 1992 as Tabulated in Table III. Also, the total Harmonic distortion on the primary side of transformer is reduced to 0.34% with the overall power factor improved to 0.956.

TABLE III. Harmonic Voltage Distortion

Harmonic order	Voltage U_h (V)	U_h/U_{LV} (%)	V_{THD} (%)	As per IEEE-519
1	627	-	3.8%	5%
5	8.1	1.3		
7	5.7	0.9		

With a K-factor transformer, substantial energy savings can be achieved over a period of time as the losses are less than that of de-rated transformer. K-factor transformer yields energy savings of 1.2 times of conventional transformer. Payback period will be 2 years approximately. Combination of k-factor transformer & harmonic filter yields huge energy savings of 1.4 times of conventional transformer as per Table IV. Payback period will be 3 years approximately.

TABLE IV. Comparison of K-5 transformer with and without harmonic filter

Description	K-5 Transformer		Conventional Transformer
	Without filter	with filter	
Losses (kW)	28.2	25.2	34.8
Power factor	0.8	0.95	0.8
Energy losses (MWh)	2470	2207	3052

CONCLUSION

Using latest cost effective technologies in all the energy segments forms an important part of policy and strategy. Mitigating Harmonics is one such small yet imperative stride in establishing an efficient energy system. Proper management of greenhouse gas emissions is a key indicator of environmental profile of the industry.

The intent of this paper is to bring out the salient energy efficient technologies prevailing today. Depending upon the system requirement and usage, the appropriate and most suitable methodology, can be adopted which doesn't affect the system and hamper the main objective of the use of Transformer

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