Harmonic Analysis of Power Transformer Vector Groups

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Abstract: Transformer is an important element of the power system. It has several applications in the industry. For example, it is used to change the voltages from one level to another level and it also used to isolate one circuit from another circuit. There are many factors affecting the performance of the power system. The harmonics are the one of those factors. Harmonics are caused by the circulating current at the secondary windings of the power transformers, when unsuitable vector groups are used in order to connect the two or more transformers in parallel. Consequently distortion in the current and voltage wave form is occurred. This can lead to heating up of transformer and may result in insulation failure. This reduces the life of transformer as well. Vector groups are used to detect the suitable connection of the transformer, when they are connected in parallel. In this work experiments are carried out by using various types of vector groups of the transformers to analyze the harmonics. The total harmonic distortion (THD) values are taken by using the Power Quality Analyzer. The results of various transformer vector groups are taken and then comparison analysis is done. The models of the different vector groups are drawn by using the MATLAB software. The transformers are connected in parallel and then different vector groups are used to analyze the harmonic behavior of the transformer.

Keywords: *Transformer, harmonics, harmonic distortion, Matlab and power system*

1. Introduction

For the generation, transmission and distribution of the power; three phase system has been implemented all over the world. This is why three phase transformer should be used to step up or step down the voltage level in the system. Transformers are one of the main apparatus to transmit and to distribute electrical energy [1].The differentiation in the phase/angular displacement between primary and secondary winding is determined by using transformer vector groups [2]. There are several ways to connect three phase transformer windings depends on characteristics that transformer needed. Usually the manufacturers indicate the vector group on the name plate of the transformer. We can also define it as a means of identifying. Which combination of three-phase transformer connections (delta-delta, wye-delta, delta-wye etc) will allow 3-phase transformers to be paralleled with each other, as some combinations cannot be paralleled [4].

1.1 Issue related with vector Groups of Transformer

Vector groups are much essential while two or more transformers are being connected in parallel. A difference in phase angle and a large circulating current will be produced, if the transformers connected in parallel are of the dissimilar vector groups. Imbalanced loading conditions are caused by the circulating current and it might be impracticable to obtain the collective full load outputs from the parallel connected group without one of the transformers becoming extremely hot. This is why, it is incredibly very essential to stay away from the current that circulate and other disorders of the system.

1.2 Three Phase Transformer

These days' three phase power systems have become mandatory for the generation, distribution and transmission of the power. Three phase transformer is the very important part of the three phase power system. So it is necessary to understand, where the three phase transformers can be used. Three phase transformers can be constructed in two ways. The one is by taking the 3-single phase transformers and to connect them in a bank. The other one is by wrapping 3 sets of winding over the three limbs of the transformer core. Fig. 1(a) and Fig.1(b) are given below. The latter one transformer construction is preferred today because it is cheaper, lighter, smaller and efficient. The former construction also has an advantage that in case any of the transformers is damaged it can be replaced easily but this is not better than the single three phase transformer in many applications.

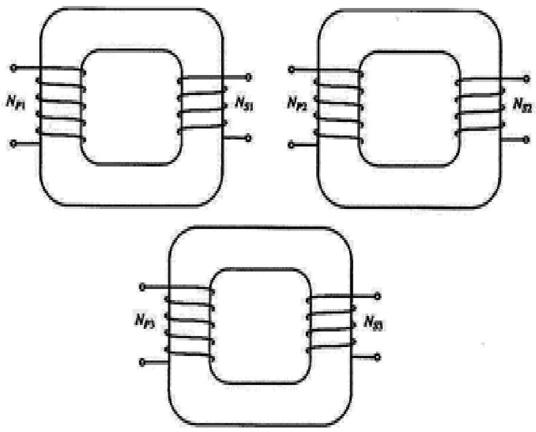

Figure. 1(a): A bank of three Single phase transformer

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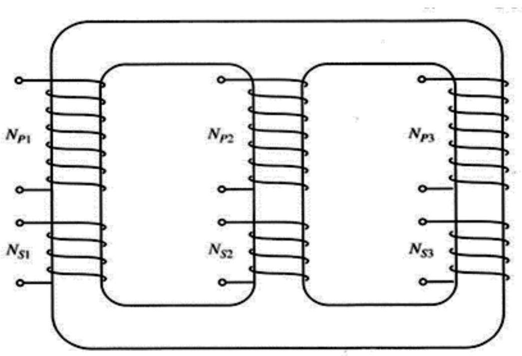

Figure.1(b): A three limbed core 3-phase transformer

The voltage developed by a transformer is shown as in equation (1);

$$E = 4.44 \times f \times N \times B_{max} \times A_{core} \quad (1)$$

E = coil rated voltage

f = operated frequency

N = winding turns no.

Bmax = Core flux density (maximum)

Acore = Area of cross section of core

Together, with voltage equation, in transformer design, another equation of power elaborating the rating of current in terms of other input parameters also used. Exclusively the equation formed is;

$$V_A = 4.44 \times f \times N \times B_{max} \times A_{core} \times J \times A_{cond} \quad (2)$$

In the Equation (2), the terms *f, N, Bmax, Acore* are already mentioned. Here *J* shows density of current. *Acond* indicates cross-sectional area of coil in the core window. *J* is dependent on the cooling and thermal dissipation.

2.3 Transformers operating in parallel

In any industry the transformers operating in parallel is very common. Operation of this type is often needed. The adequate performance when two or more transformers operating in parallel have following parameters:

a) Voltage-ratio must be identical

b) Similar impedance in per unit

c) Polarity should be similar

d) Similar phase sequence and zero relative phase displacement

From the above mentioned parameters ‘c’ and ‘d’ are very important & state ‘a’ must be fulfilled to a close degree value. There is more flexibility with situation ‘b’, but almost this is true; the load-division will be better between a numbers of transformers:

a) Voltage Ratio: In order to avoid circulating current at no load equal voltage ratio is necessary; if not it may result to a redundant loss. Transformer impedance is so small, hence a little percentage voltage dissimilarity might be adequate to flow a significant current and result further I^2R losses.

While secondary are loaded, the circulating current may likely to create imbalanced loading condition and collective full-load output from the parallel-connected group may not be possible to take, unless any of two transformers become extremely hot.

b) Impedance: Ratio of resistance to reactance (i.e. impedances) of two transformers can vary in quality and in magnitude and to make differentiation between numerical and per-unit impedance is necessary. For example taking two transformers having ratio 2:1; when the current is doubled, the earlier must possess impedance half of the later for the similar regulation.

For the parallel operation regulation must be the same, the situation being imposed by connecting in parallel. Thus the currents carried by two transformers are relative to their ratings, if the numerical and ohmic impedances of these transformers are not directly proportional to their ratings and they have identical per unit impedances.

c) Polarity: This might be right or wrong. If it is wrong it leads to a short circuit called dead short circuit.

d) Phase Sequence: It is related with poly-phase transformer. If there is phase–displacement between the secondary voltages of the two transformers then they are not proposed for parallel operation. For two transformers connected in parallel, the phase sequence, in which phases may reach their maximum +ve voltages, must be the same; otherwise for some length of cycle each couple of phases would be short-circuited.

e) Phase/Angular displacement: The characteristic of a three phase transformer according to which the primary and secondary voltages become out of phase with each other is termed as angular or phase displacement of the T/F. As shown in Fig.2.

f) Magnetizing current: The magnetizing current is the current that flows in the primary when the secondary is unloaded. It is also called exciting current.

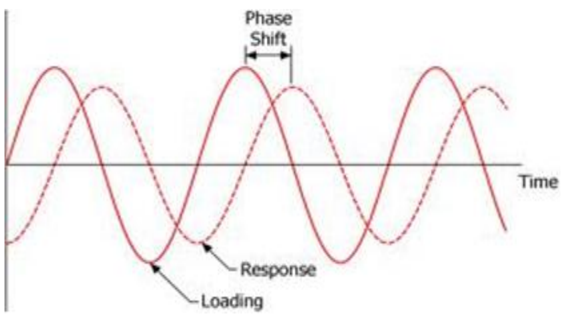

Figure. 2. Phase shift/displacement

2.4 Vector Groups

The vector group defines phase/angular displacement between the voltages of primary and secondary windings. There are so many way to connect the three phase transformer windings. The vector group can be determined from the connection of the winding. It is sometimes also indicated on the name plate of the transformer. These vector groups are especially necessary while two or more transformers to be parallel connected. In a condition if the two transformers are connected in parallel having difference in phase/angular displacement then there will be a large circulating current on the secondary of the transformers; which is very harmful.

2.4.1 Standard code for transformer vector groups

IEC (International Electro-technical Commission) has formulated the standard code in order to determine transformer vector group. The IEC code consists of two or more letters followed by 1 or 2 digits.

The letter that comes first is capital letter which might be D, Y or Z, (Delta, Star or Interconnected star respectively), which stands for High voltage side. The letter that comes second is a small letter that might be y, d or z (star, delta, or interconnected star) windings respectively; which stands for low voltage. The letter that comes third is a number that shows the phase/angular difference between low voltage and high voltage sides.

2.4.2 Phase rotation

The arrangement according to which phase voltages attain their peak values is called phase rotation. This could be A – B - C or C – A - B, in the 3-phase system interchanging two phases on both windings will drift to the original position. Accordingly, minute hand shows phase voltage at transformer's HT side which set at 12 O'clock position (reference point) and hour hand of the clock in Fig.3, shows the phase voltage at low voltage side of the transformer. The hour hand moves freely. Angular rotation is anticlockwise all the time.

The phase displacement angle is represented by hour indicator.

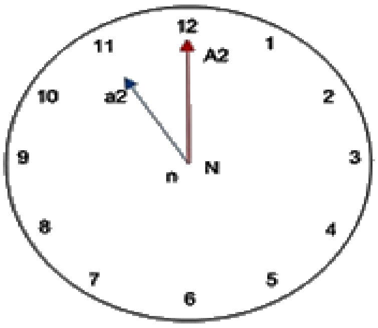

Figure.3.Clock showing phase displacement

Since clock consists of 12 hours, a circle is of 360^0, so the every hour shows 30^0.

Therefore; $12=360^0$ or 0^0, $6=180^0$, $3=90^0$, $2=60^0$ and $1=30^0$.

The phase voltage of HV winding is replaced by minute hand which is maintained on 12 O'clock.As rotation is counter-clockwise, 1 = 30^0 lagging (LV lags HV with 30^0) and 11 = 330° lagging or 30° leading (LV leads HV with 30°)

3. Basics of harmonies

At the frequencies of 50 or 60 Hz, power systems are designed to function. Though, some type of loads draw frequencies of currents and voltages that are integer multiple of 50 or 60 Hz. These larger frequencies lead to electrical pollution also called power system harmonics. Harmonic distortions are shown in the Fig.4.

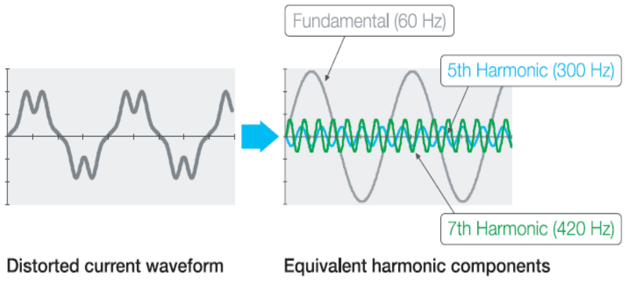

Figure.4. Distortion in the current wave form is shown

As the size and rating of transformer increases because of the supplies to the transformers are sinusoidal. Harmonic current effects are shown below:

1. Extra copper losses caused by harmonic current
2. Core loss will increase
3. Electro-magnetic intervention with communication circuits is increased

While the harmonic voltage will lead to:

1. Dielectric stress on insulation is increased
2. Electro-static intervention with communication circuits
3. Resonance between reactance of winding and capacitance of feeder

Harmonics are nothing but a method to define disturbance to current or voltage wave form. Also, the harmonic is an element of wave form which takes place at the integer multiples of the frequency (fundamental) in order to get steady state wave form with the same +ve & –ve half cycles, the series in equation (3), is called Fourier series.

$$f(t) = \sum_{n=1}^{\alpha} A_n . \sin(\frac{n\pi t}{T}) \quad (3)$$

Whereas, *n* is number of harmonics *f (t)* time domain function, *An nth* harmonic component amplitude *T* one cycle length in seconds.

It is not important to understand mathematics of Harmonics. The important thing is to know that harmonics are steady-state phenomenon and recur with every 50Hz cycle. Spikes, dips, impulses, oscillations or other transient forms make harmonics confusing [9]. THD or total harmonic distortion is a common term in relation to harmonics. The term THD almost expresses current or voltage distortion & it is given in the equation (4).

$$THD(\%) = ID_1^2 + ID_2^2 + \dots ID_n^2 \quad (4)$$

In equation (4) *IDn* refers to *nth* harmonics magnitude as a %age of the fundamental individual fundamental distortion. THD is also used in the place of distortion factor.

3.1 Causes of Harmonics

Mostly the non-linear loads are the main cause of the harmonics; these are the loads that change a sinusoidal wave form into non-sinusoidal wave form. The following wave forms show the change in instantaneous current with respect to time for two dissimilar loads, the supply of these two loads is from a sinusoidal voltage source.

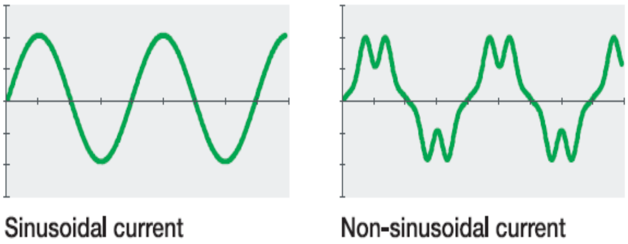

Figure.5. The sinusoidal and non-sinusoidal current wave form

As shown in the Fig.5, the instantaneous current for each load with respect to time is zero. The magnitude of the current first increases until it reaches to maximum value and the decreases to zero.

From this point the current appears to reverse and the maximum to zero value condition recur in the negative direction. This situation continued until the device is energized, generating waveforms that hold on a common time period.

3.2 Types of harmonics

There are two types of harmonics.

1. Even Harmonics
2. Odd Harmonics

3.2.1 Even harmonics

Even multiple of fundamental frequency i.e. fundamental frequency = 50Hz, 2nd harmonic is = 2*50=100Hz. 100Hz is even harmonic of 50Hz.

3.2.2 Odd harmonics

Odd multiple of fundamental frequency i.e. fundamental frequency = 50Hz, 3rd harmonic is = 3*50=150Hz. 150Hz is odd harmonic of 50Hz.Harmonic Order can be calculated by: n=k*p±1.

Where, n= harmonic order, K= an integer and P= no. of pulses

3.2.3 Total harmonic distortion

It is ratio of root mean square value of input current for all harmonics to r.m.s value of fundamental current. Mathematically, THD is given in Equation (5).

$$THD = \sqrt{\frac{A_2^2+A_3^2+A_4^2+A_5^2 \ldots\ldots A_n^2}{A_1^2}} \quad (5)$$

$$THD = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \cdots + V_n^2}}{V_1} \times 100\%$$

Equation (5), is in terms of voltage. The final result is in percentage dividing the harmonics component and the fundamental component of voltage or current.

4. MATLAB Simulator

We shall introduce our computation, modeling, simulation environment in the MATLAB. The word MATLAB is the abbreviation of Matrix Laboratory. Actually, MATLAB was made to endow with an easy approach to software known as matrix made by LINPACK (Linear system package) and EISPACK (Eigen system package) projects. The MATLAB is software of technical computing for excellently performing visualization and numeric computation. It contains matrix computation, numerical analysis, graphics, and processing of signal in an approach that is very simple to work on; where the problems and their solutions are given just like they are written mathematically- without traditional programming. [10]

5. Results and Discussion

5.1 Experimental Setup

There are various vector groups used for experimentation in this research work. Vector groups are more important when two transformers are connected in parallel. The harmonics on various vector groups are critically observed and analyzed. The experimentation is carried out during work with the help of power quality analyzer. The PQA captures THD, wave form and Power Transformer's power factor on various vector groups. The experimental arrangement is shown in Fig.6.

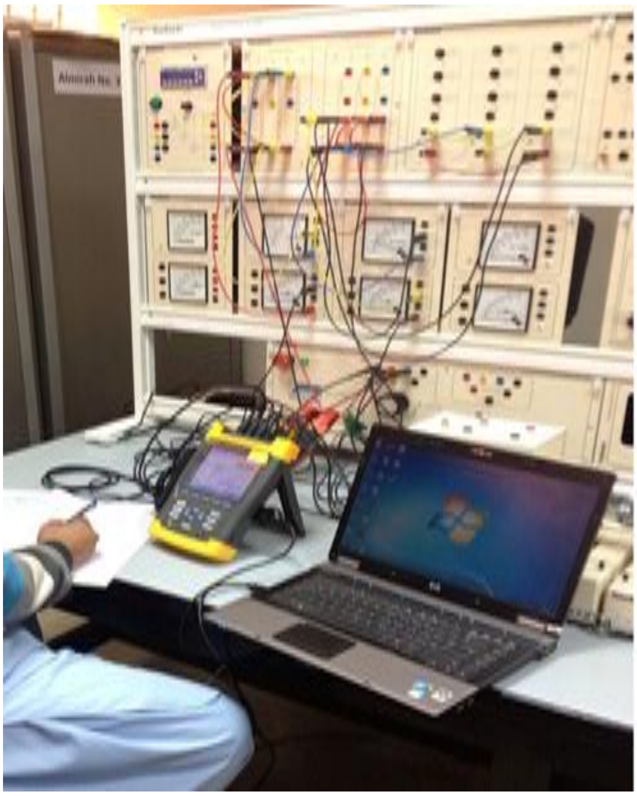

Figure.6. Experimental setup

5.2 Connection of 3-Phase Transformer

There are four main basic connections of connecting three phase transformers for three phase circuits are delta-delta, star-star, star-delta and delta-star connections (as shown in the Fig.7). Delta-delta connection could be advantageous in case, if a transformer is out of order or is detached from the circuit, remaining transformers can be connected in open delta connection. In star-star connection, the line voltage is reduced to 57.7% and delivers to all phases. [11-12] the star-star connection is rarely used.

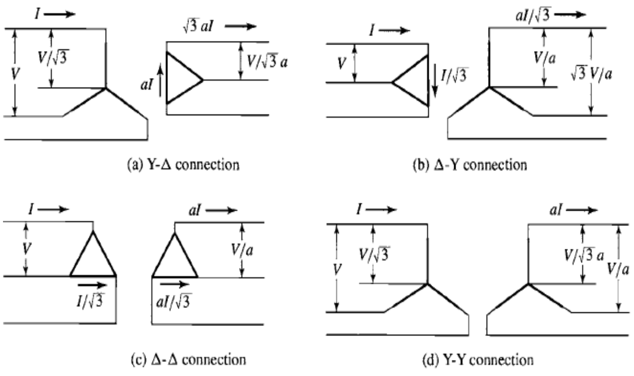

Figure. 7. Basic four transformer connections

5.2.1 Wave form of 3-Phase Supply Voltage

The Fig.8 shows the wave form of the three phase voltages of the supply voltage. The wave form shows the three phase voltages, the red line shows the voltage between lines BC, the black line shows the voltage between AB, the blue line shows the voltage between CA.

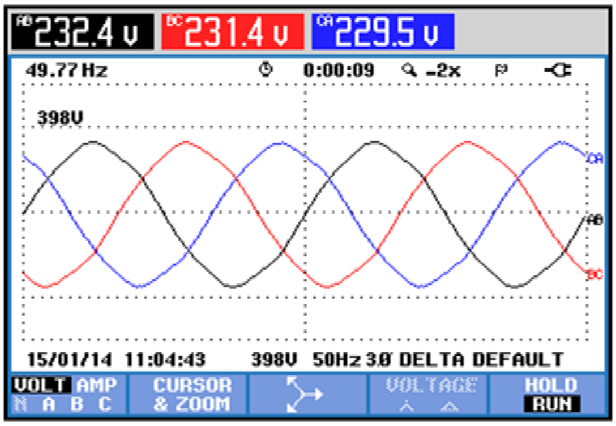

Figure.8.Wave form of 3-phase supply voltage

5.2.2 Harmonic analysis of delta-delta (dd0) transformer vector groups

The Fig.9 is taken during the experiment on the delta-delta transformer vector group. Fig.6 indicates the harmonic spectrum of the current on the delta –delta connection. It is being observed that the 3rd harmonics are greater than the 5th and 7th harmonics but still they are not so harmful because they are not in a sufficient value.

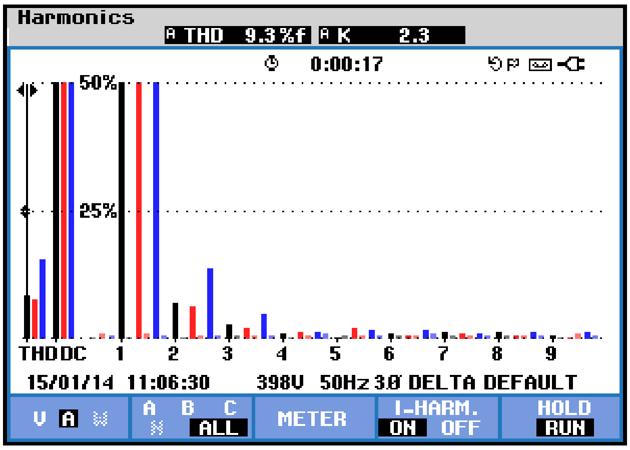

Figure. 9. Harmonic spectrum of current

5.2.3 Harmonic analysis of stat-star (yy0) transformer vector groups

The Fig.10 shows the harmonic spectrum of the star-star transformer vector group. The total harmonic distortion (THD) is also given which is 12.2%. The voltage supplied is 230 V stars connected.

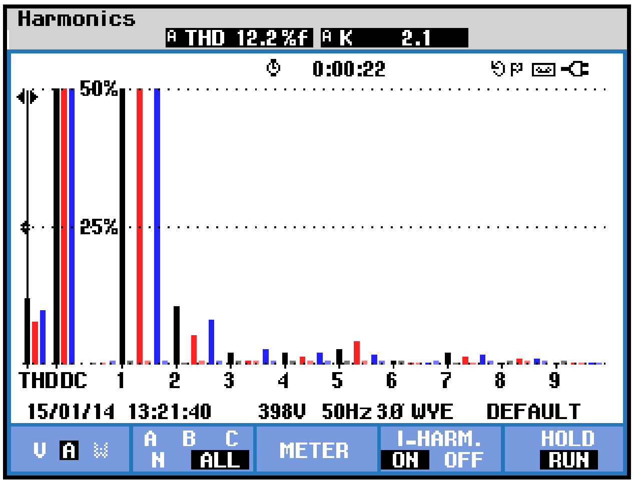

Figure. 10. Harmonic spectrum of current

5.2.4 Harmonic analysis of star-delta (yd11) transformer vector group

The Fig.11 is of the star-delta connection of the transformer vector group. Here it is shown that there is fewer amounts of 3rd harmonics due to the star is grounded which suppress the 3rd harmonics. So the Total Harmonic Distortion (THD) given is 13.9 on the voltage of 230 v and 50 Hz frequency which constant.

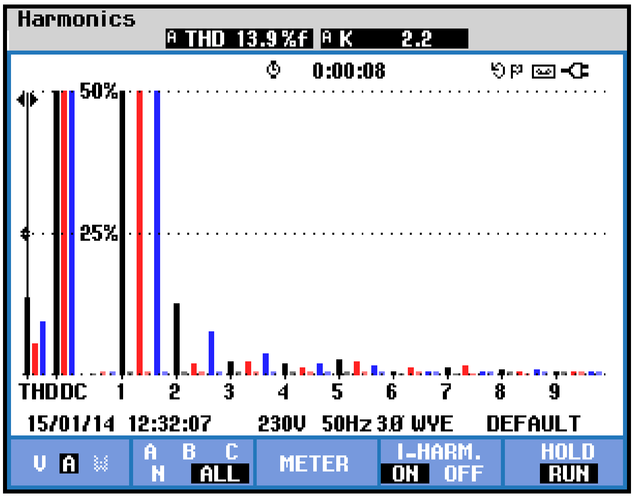

Figure. 11. Harmonic spectrum of current

5.2.5 Harmonic analysis of delta-star (dy11) transformer vector groups

The Fig.12 is taken from the experiment done on the power transformer having connection delta-star. In this figure there are great amount of total harmonic distortion; it is because the transformer's high voltage and low voltage windings are delta & star connected respectively. Mostly harmonics produced at LV winding transmit to the HV winding but due to delta connection the harmonics circulate in the delta hence remain there and increased.

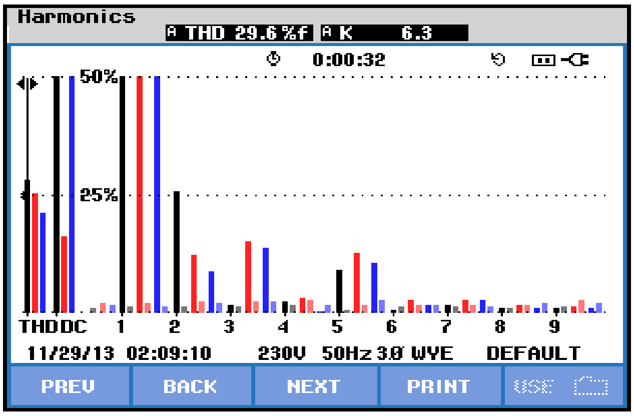

Figure.12. Harmonic spectrum of current

5.2.6 Harmonic analysis of delta-zigzag (dz1) transformer vector groups

Here the connection given is the delta-zigzag connection of the transformer vector group. The Fig.13 shows the harmonic spectrum of the current on the delta-zigzag transformer vector group. The total harmonic distortion given here is 33.3%. This is also detrimental.

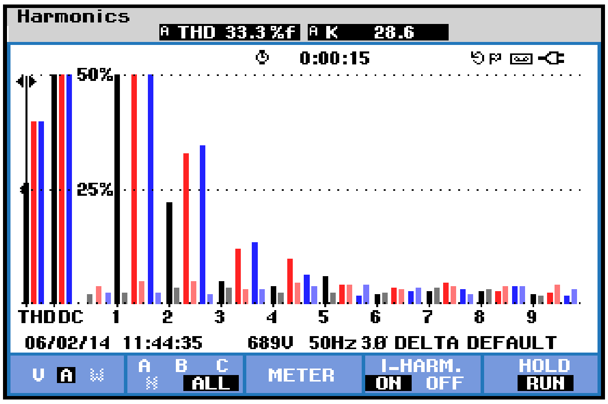

Figure. 13. Harmonic spectrum of current

5.2.7 Harmonic analysis of star-zigzag (yz1) transformer vector groups

The Fig.14 shows the harmonic spectrum of the current on the star zigzag connection of the transformer. Here this would be observed that there are fewer harmonic than delta-zigzag transformer. The total harmonic distortion shown is 31.4%. All the results are collectively shown in the Table 4.1.

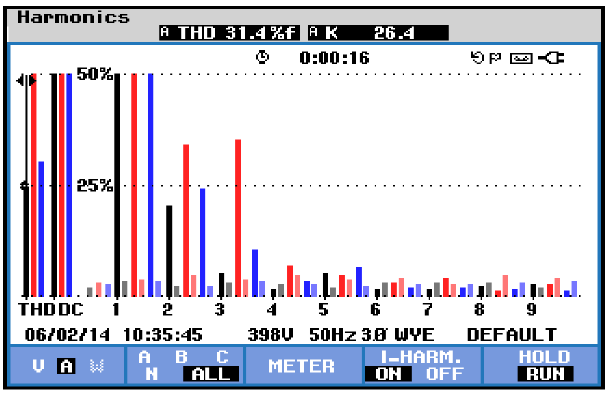

Figure. 14: Harmonic spectrum of current

Table 4.1. Comparison between different vector groups

S.No	Vector group	THDi
1	Delta supply-delta load	9.3
2	Star supply-star load	12.2
3	Star supply-delta load	13.9
4	Delta supply-star load	29.6
5	Delta-zigzag	33.3
6	Star zigzag	31.4

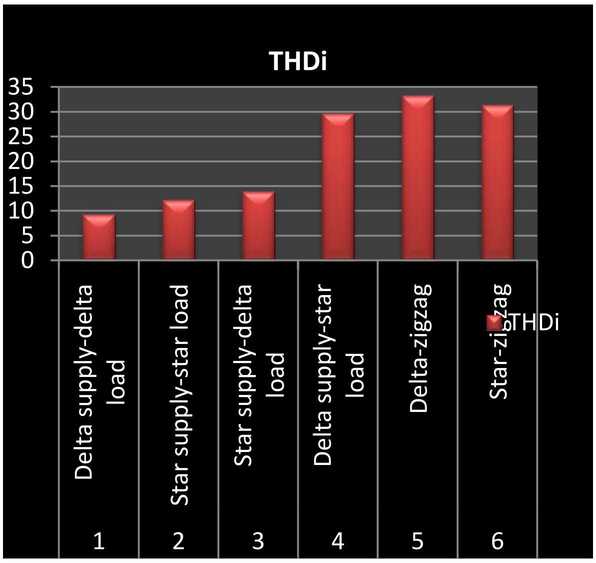

Figure.15. Graphical representations of the experimental results

The bar graph in Fig.15 shows the comparison analysis of the various vector groups of the power transformer on the basis of harmonics. In the bar graph it is clear that the delta-delta has the minimum value of the THD and the star-zigzag has the maximum value.

5.3 Simulated Model and Their Results when Transformers are connected in parallel

5.3.1Group 1: zero phase displacement (yy0, dd0)

In order to analyze the harmonic characteristics of the Yy0-Dd0 connection of the transformer a simulated model is designed, which is shown in Fig.16, a three phase voltage source is being connected on the primaries of the two wye-wye connected transformers. The simulated model also connected a voltage measurement block to which a line to line voltage from primary side as well as from secondary side is taken and compared. A three phase voltage measurement is also being attached to the secondary of the two parallel transformers, in order to compare the wave forms of the two transformers connected in parallel. The r.m.s value is also use to determine the zero sequence currents that's why an r.m.s block is connected. In star-star line voltage is 57.7% but line current is fully supplied. Star-star is the rarely used connection.

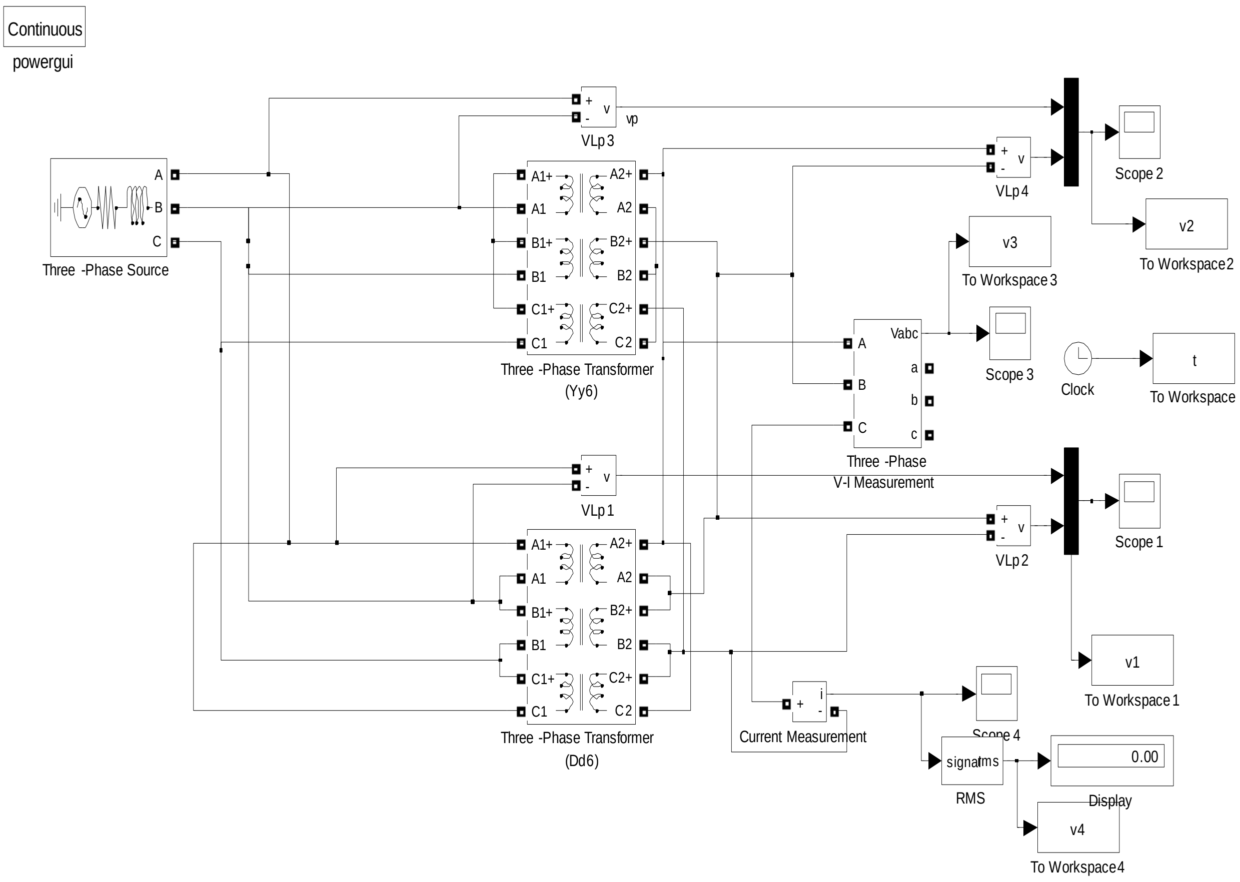

Figure.16. Shows a simulated model of zero phase displacement

6. Conclusion

The detail study of transformer vector groups and its harmonic effects were carried out. The harmonic distortion of various vector groups of transformer was analyzed. From the experimental results the increase of the harmonic elements of the electric current causes increase in the transformer losses. The simulation models of various vector groups were developed in MATLAB software. From the simulated results it is concluded that the transformers having similar group could be parallel connected very easily. Transformers of group 1 & 2 could not be connected in parallel with 3 & 4 groups. Also, it is not possible to parallel transformers of group 1 & 2, since there is 180^0 phase displacement b/w the secondary windings; only through altering the internal connection this could be resolved.

If the transformers having unsuitable vector groups are parallel connected then angular difference will occur b/w the secondary of the transformer that cause a large circulating current which is very harmful. When the transformers of groups 3 & 4 will be connected then the phase difference will be 60^0 b/w secondary windings. So through the modification to the external connection phase difference could be made zero. Thus, by external change in the connection the transformer of group 3 & 4 could be run in parallel.

Dd0 winding on the high voltage side is connected in delta and also the winding on low voltage side is also connected in delta. Zero phase difference b/w high voltage and low voltage.

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