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RESEARCH ARTICLE

MODELING OF HARMONIC REDUCTION WITH TRANSFORMER CONNECTED MULTILEVEL INVERTER

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ABSTRACT

This paper proposes a Harmonic Reduction with Transformer Connected Multilevel Inverter arrangement employing a series connected transformer to suppress 7th, 11th &13th order harmonics (generated by non-linear loads).In the proposed scheme sinusoidal PWM signal generation technique is used for three phase multilevel VSI in conjunction with series connected transformer .The proposed model eliminates the need of output filter inductor. With this control strategy harmonic components of output voltage and switching losses can be minimized considerably. A simulation result verifies the proposed concept and indicates that the transformer is capable of reducing the harmonics in the line. In multilevel inverter development for 3-phase applications, total number of transformer in the circuit can be reduced by using of cascaded 3-phase transformer circuit instead of single-phase transformer circuit. In the scheme, total number of switching components in the circuit is still a drawback to achieve lower cost and smaller size of the inverter compared with conventional multilevel inverter. This paper includes a challenging method to reduce total switching components in the multilevel inverter by adopting common-arm structure.

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INTRODUCTION

In many industrial fields, multilevel inverters have been received great attention. The most valuable advantage of them is to synthesize high voltage outputs with low switching frequency. Hence they are considered as a substitute of conventional PWM inverters. Harmonics are undesirable always whether it is current harmonics or voltage harmonics. With increase dependency on non-linear loads it is necessary to use some arrangement which can suppress, reduce, mitigate or eliminate the harmonics by which power quality and system efficiency could improve. When nonlinear loads are considerable part of the total load in the facility (more than 25%) there is a chance of harmonic problem. There are two main affects of harmonic currents on a distribution system. The first is that harmonic currents add to the RMS value of the fundamental .This additional current will increase losses in bus bars, wire and power factor correction capacitors used in the distribution system. The second affect is the additional heating caused by each of the harmonic currents. The higher order harmonics do not contribute to real work done. So these are always undesirable. Harmonics are the byproducts of modern electronics. They occur frequently when there are a large number of personal computers; uninterrupted power supplies (UPS), variable frequency drive (AC and DC) or any electronic device using solid state power switching. Multilevel power inverter has become extremely popular in recent years considering the advantages over traditional inverters. Amongst the available multilevel topologies the cascaded multilevel has distinct advantages due to compounding effect of the voltage levels. Multilevel voltage source inverter have been paid attention in medium-voltage and high power applications due to low switching losses, low voltage stress on switch devices and low harmonic distortion in output voltage. Therefore, many recent works with different multilevel inverter topologies have widely used in manufacturing factories recently because of their good performance of for the industry applications. According to this when two multilevel inverters are cascaded through the load connection, the result is an operation with an equivalent no. of levels that is the product of the two inverters. Typically each inverter requires an isolated power source. This leads to difficulties in applications where high power density required.

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Proposed Transformer Arrangements with Inverter Topology

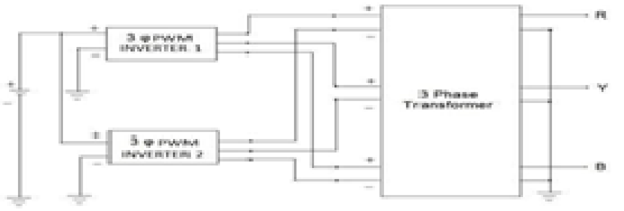

Fig. 1. General model of proposed system

Transformer as a Harmonic Filter (Basic Concept and Theory)

The clock frequencies and ultrahigh speed operation of today‘s electronics would seem like science fiction to engineers a few decades ago. But because of the high clock rates associated with modern microprocessors and the high switching frequencies associated with switching power supplies, PCs and other equipment are guilty of generating and kicking back massive amounts of distortion into the line. Effective noise rejection filters should pass the 50-Hz or 60-Hz fundamental and remove all higher frequencies. However, the line source impedance, combined with the impedance of the actual load, is low (ranging from 1 V to 100 V at 50 Hz or 60 Hz). Therefore, for optimum attenuation, the impedance of the filter should be low as well. In reality, however, this would require impracticably large and expensive capacitors and inductors. Therefore, there may be some power or performance limitation imposed by current handling capability of the series inductor as it must grow in size, weight and thermal dissipation to accommodate higher power devices. In addition, the high-pass shunt capacitors from line and neutral to ground increase system leakage current to ground. This becomes a significant factor where low levels of leakage current are demanded, such as in medical applications in patient care devices. A more practical approach is to start filtering noise at frequencies above 1 kHz, where most of the unwanted noises are found and where such interference causes malfunction of electronic equipment. The filter should be of the low pass type with second- or higher-order slopes. The internal inductance of the transformer with externally connected capacitors can be used to create the desired filter. Common solutions the installation of an off-the-shelf line filters, which is available in a variety of configurations from various companies. Leakage inductance between the primary and secondary windings in all transformers already functions as a first order low-pass filter. Its corner frequency is high—20 kHz for EI-transformers and 200 kHz for toroidal transformers (due to the toroid‘s inherent low leakage inductance).

The two techniques

1. Increasing internal series inductance, and
2. Phase cancellation

Satisfy different attenuation requirements. Simply adding leakage inductance has the affect of inserting a series inductor and removing any current handling limitations. The increased leakage inductance is the prime factor in the performance of the design. The combination of the leakage inductance with the transformed capacitance from secondary to primary (C) and the primary dc-resistance (R) acts as a second-order low-pass filter. The corner frequency of the filter is determined by the combination of the L, C and R elements along with the load impedance Z_L.

Harmonic Cancellation

The non-linear currents from two or more three-phase load panels can be phase-shifted from one another through various types of three-phase transformer connections so that their aggregate distortion is less distorted than each of the original‘s waveforms. This reduces the distortion of current flowing into the primary power.

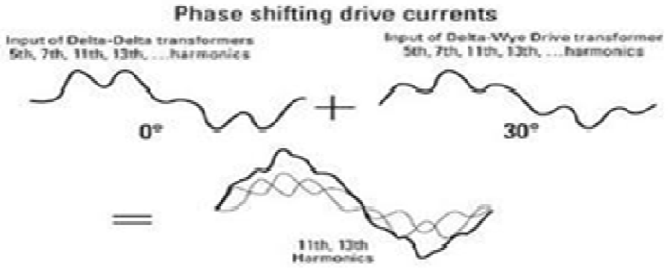

Fig. 2. Resultant wave of phase shifting arrangement

In response to the increasing use of adjustable frequency drives in industrial facilities, IEEE 519-1992 has set guidelines for maximum current distortion present at a building service entrance. These guidelines are intended to prevent one factory from affecting the service of another, and to protect utility equipment. The determining factor in meeting IEEE 519-1992 current distortion limits is the percent of the service capacity that is used for serving non-linear loads. Typically, an industrial facility can load up to five percent of its total service capacity with six-pulse variable frequency drives without exceeding recommended limits. Beyond that, some form of harmonic abatement may be necessary. Motor drive current distortion can be reduced using filters, 12-pulse or higher drives, line reactors, drive isolation transformers or harmonic canceling transformers. Both line reactors and drive isolation transformers use reactive harmonic attenuation effects to reduce the actual current distortion at the input terminals to the drives. This practice alone can increase the six-pulse drive load by 20 percent or more of service capacity without exceeding guideline distortions. The effectiveness of reactive harmonic attenuation varies, depending on other system characteristics. Careful system analysis is always a good idea before applying any harmonic abatement solution to ensure the intended results. Harmonic abatement using filtering and/or 12-, 18- or 24-pulse drive technology is becoming increasingly popular, but these are relatively expensive solutions. Using transformers for harmonic cancellation can be an attractive alternative, particularly for users who incorporate isolation transformers for their drives anyway. The simplest cancellation method is to provide Delta-Delta connected transformers for some drive power, and Delta-Wye connected transformers for the remaining drives. If the sum of drive loads on each type of drive isolation transformer is balanced, current distortion into the primary system can be reduced significantly. The largest distortion components by far in six-pulse drive current are 5th and 7th harmonics. Eliminating these can significantly improve point of common-coupling current waveform distortion. The 5th and 7th harmonic cancellation effects brought about by the 30-degree phase shift between Delta-Delta and Delta-Wye connected transformers will depend on load balance. For continuous torque applications, where loads are fairly constant, close load balance is easier to achieve. On the other hand, process control applications, such as punching, stamping or motion control, make it difficult to maintain consistent balance of multiple drive loads at any given time. In some cases, Delta-Delta connected drive isolation transformers are undesirable because the secondary cannot be grounded in a balanced way. Ungrounded power can adversely affect the operation of some drives, and can cause drives to trip on surges and impulses coupled from the primary service. For these applications, Delta-Zigzag connected transformers are available. The zero-phase shifting acts like a Wye source for the drive, providing a balanced neutral point for grounding. At the same time, they substitute for Delta-Delta transformers, providing the same harmonic abatement when used in combination with Delta-Wye connected transformers serving other drive loads on the same service, as in Figure 4. Of course, when voltage change is not required, the use of line reactors on half the load along with Delta-Wye connected loads on the other half also can be used. Since standard drive isolation transformers can be effectively used as harmonic canceling transformers, the term ‗harmonic canceling transformer' becomes somewhat ill-defined. In general, that special term is attributed to transformer products with special connections that can address 11th, 13th and even higher harmonics in drive loads. These can be single transformers with multiple secondary's, or sets of transformers feeding multiple loads. The basic principles are the same, except that 15-degree phase shift is required to address 11th and 13th harmonics. The benefits of this additional step in harmonic reduction are dubious, however, because 11th and 13th harmonic components contribute to less than one-fifth of the total distortion in service entrance currents. The difficulties of obtaining precise balance of loads will almost always leave enough residual 5th and 7th harmonic distortion to minimize the benefit of any higher harmonic treatment. Filtering is a much more cost-effective method for addressing upper order (11th and higher) harmonics compared to special harmonic cancellation' transformers.

Theory of HMT (Harmonic Mitigating Transformer) or Phase Shifting Transformer

In addition to improved system reliability and reduced maintenance costs, HMTs also have excellent energy-saving characteristics. With the cost of electricity continuing to increase around the world, there is an ever-increasing interest in energy-efficient products. Because HMTs are intended to be installed HMTs is in systems that contain high levels of nonlinear loads. HMTs are an economical solution in the battle against the harmful effects of harmonics. Whenever the HMT is energized, it will provide harmonic treatment. Harmonic mitigating transformers are commonly referred to as ¯phase-shifting‖ transformers. The HMT has three-wire connected primary windings and four-wire connected secondary windings. The fundamental changes to the orientation of the transformer winding allow a transformer to be designed in a wide variety of different phase-shifts (–15°, 0°, +15°, 30°). In standard delta-wye transformers, including K-factor rated transformers, triplen harmonics are passed from the secondary windings, into the primary delta windings, where they flow and cause substantial watt loss. In HMTs, the electromagnetic flux cancellation created by the zigzag winding configuration prevents 3rd and other triplen harmonics from being transmitted into the primary delta winding. Harmonic treatment is provided entirely by electromagnetic flux cancellation; no filters, capacitors, or other such devices are used. It is important to remember that the harmonic currents still flow to the secondary windings. Phase shifting involves separating the electrical supply into two or more outputs, each output being phase shifted with respect to each other with an appropriate angle for the harmonic pairs to be eliminated. The concept is to displace the harmonic current pairs in order **to** bring each to a 180" phase shift so that they cancel each other out. Positive sequence currents will act against negative-sequence currents, whereas zero-sequence currents act against each other in a three-phase system. Recall that triplen harmonics are zero-sequence vectors; 5th, 11th and 17th harmonics are negative-sequence vectors, and 7th, 13th and 19th harmonics are positive-sequence vectors. Hence, an angular displacement of: 1) 60" is required between two three-phase outputs to cancel the 3rd harmonic currents;2) 30" is required between two three-phase outputs to attenuate the 5th and 7th harmonic current pairs; 3)15" is required between two three-phase outputs to cancel the 11th and 13th harmonic current pairs.

Zig-Zag Transformer

The three-phase four-wire distribution power systems have the problems of harmonic pollution, load unbalance and over-load of neutral conductor. In order to ensure high "Power Quality" for low tension consumers, it is necessary to treat harmonics. So the Zig-Zag transformer's can be used to attenuate the neutral current and zero-sequence harmonic current on the utility sites due to the advantage of low cost, high reliability.It is an effective way to reduce harmonics by using a zig-zag transformer. A zig-zag transformer cancels the fifth and seventh harmonics as well as triplen (third order) harmonics. The third, fifth and seventh are the most prevalent harmonics so eliminating them results in a major reduction of the total current distortion. It is important to note that the spectrum of the harmonic distortion created varies depending on the type of nonlinear load. The added benefit of the zig-zag transformer is that it will also reduce the fifth and seventh harmonic as well as reduce the effect voltage distortion on the output caused by the current distortion.

Isolation Transformer

Since input circuit reactance is a major determining factor for the magnitude of harmonics that will be present and flowing to an individual load, isolation transformers can be used effectively to reduce harmonic distortion. The leakage inductance of isolation transformers can offer appropriate values of circuit impedance so that harmonics are attenuated. The typical configuration of isolation transformer, for power quality purposes, is delta primary and wye secondary. Like a reactor, the inductive reactance is low enough at the fundamental frequency to easily pass fundamental current, but increases proportionately for harmonic frequencies and can achieve performance similar to that of a line reactor. Additionally, the isolation transformer can be supplied with an electrostatic shield between the primary and secondary windings. Due to the capacitive coupling between each winding and the shield, a low impedance path is created to attenuate noise, transients and zero sequence currents. The shield helps to mitigate the common mode disturbances to their originating side (primary or secondary) of the transformer.

Connection A

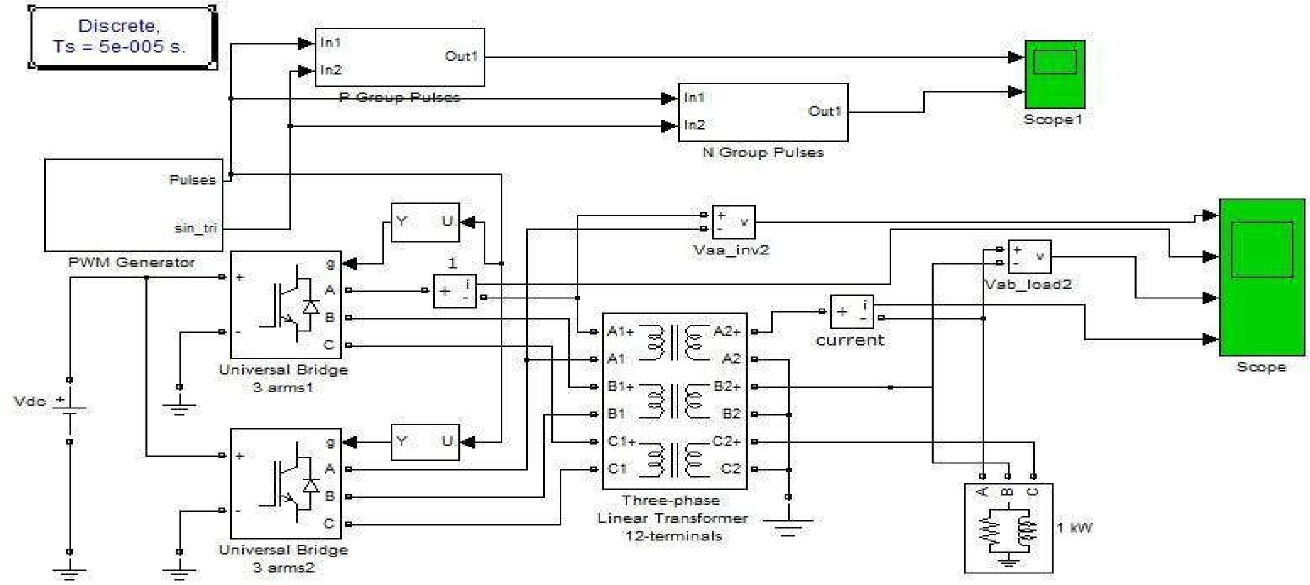

Fig. 3. Simulink model of Connection type A

A.1 FFT analysis of connection

Voltage and current harmonics before transformer

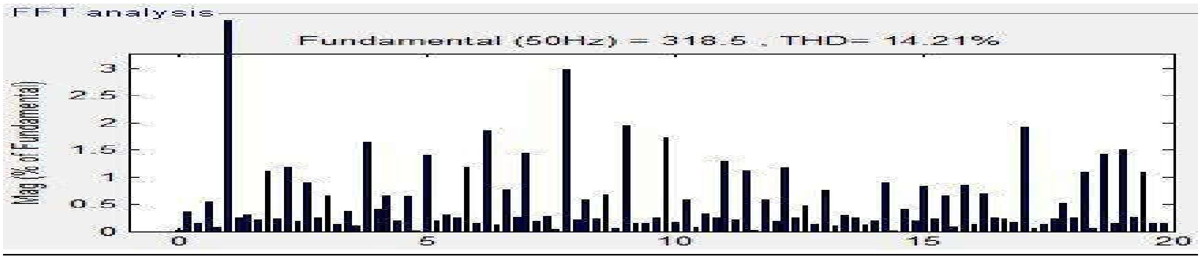

Fig. 4. Voltage harmonics before transformer for Connection A

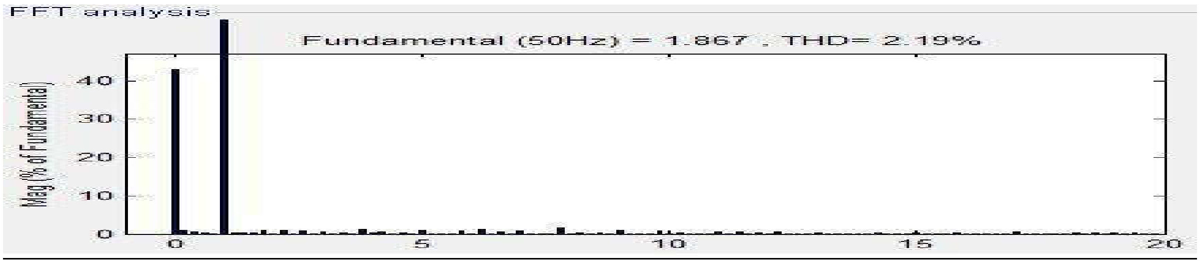

Fig. 5. Current harmonics before transformer for Connection A

Voltage and current harmonics after transformer

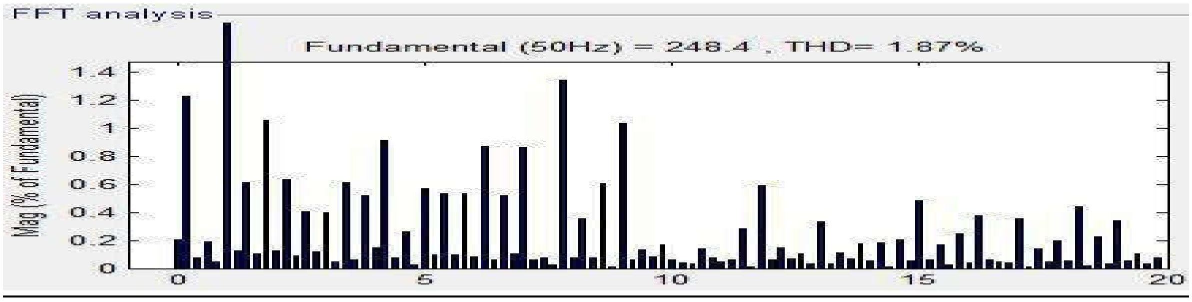

Fig. 6. Voltage harmonics after transformer for Connection A

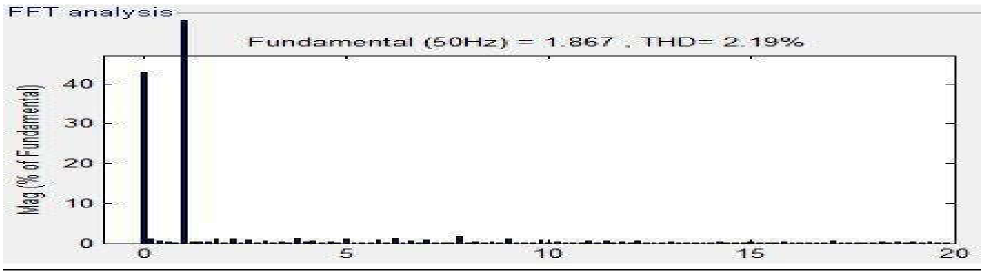

Fig. 7. Current harmonics after transformer for Connection A

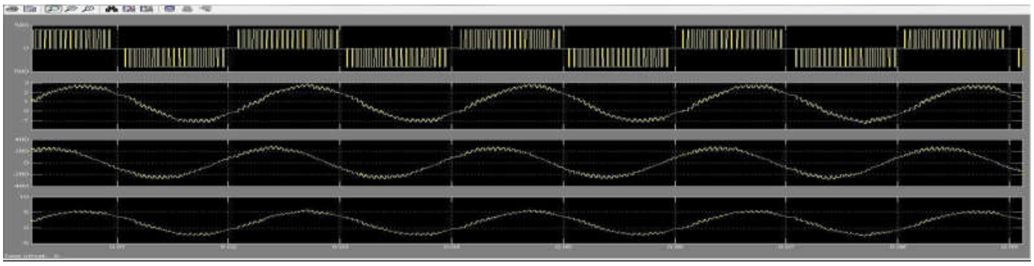

Fig. 8. Scope output of connection A

Connection B

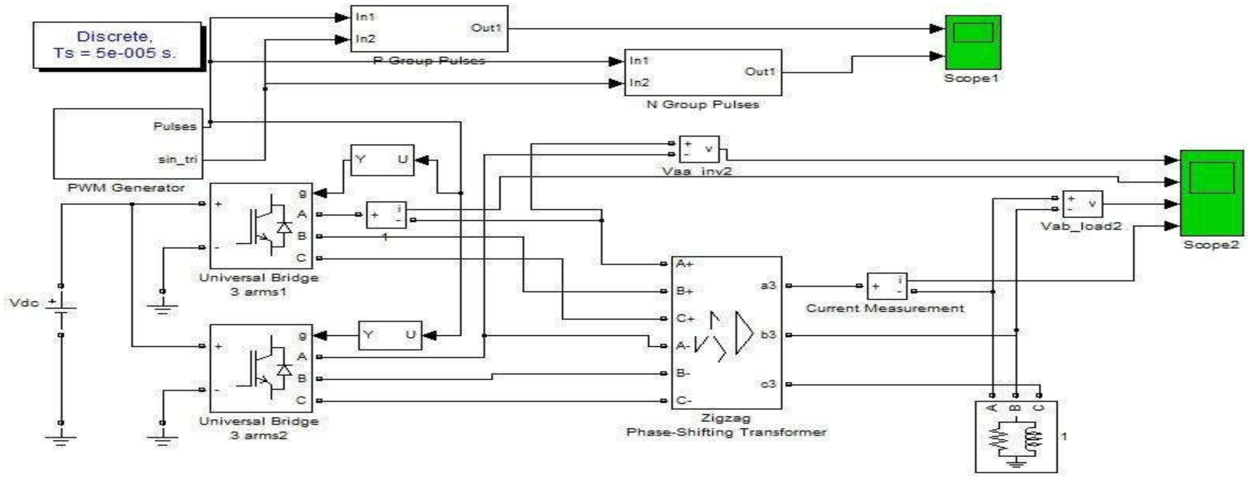

Fig. 9. Simulink model of Connection type B

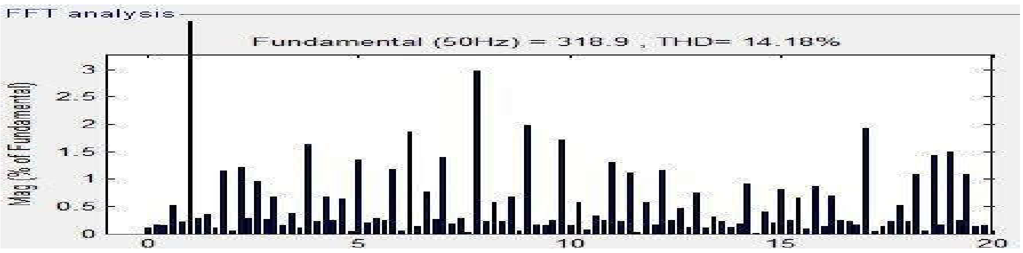

Fig. 10. Voltage harmonics before transformer for Connection B

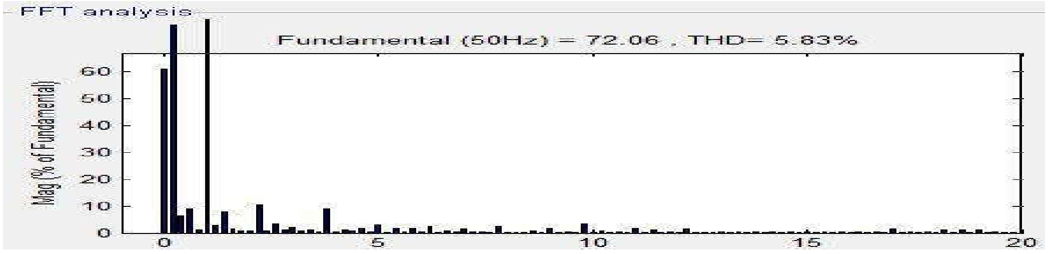

Fig. 11. Current harmonics before transformer for Connection B

Voltage and current harmonics after transformer

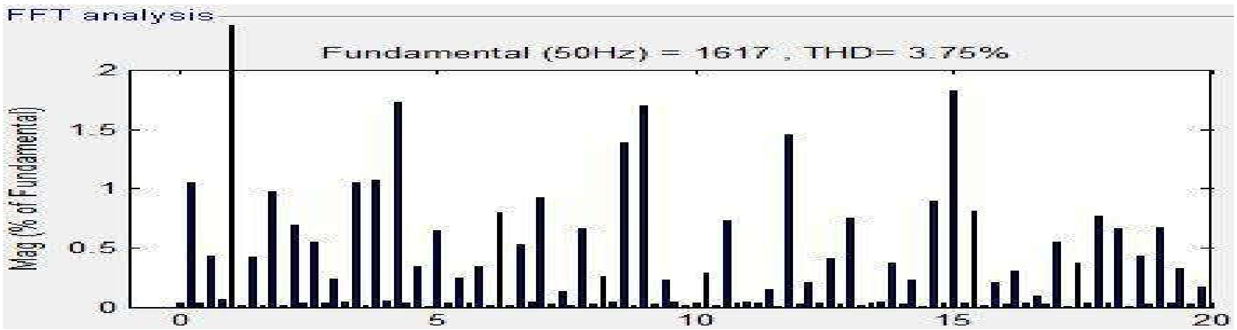

Fig. 12. Voltage harmonics after transformer for Connection B

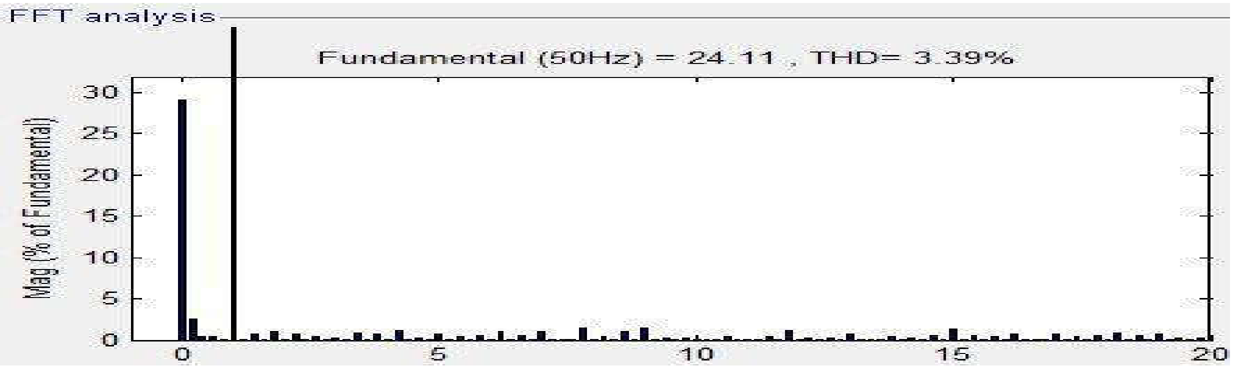

Fig. 13. Current harmonics after transformer for Connection B

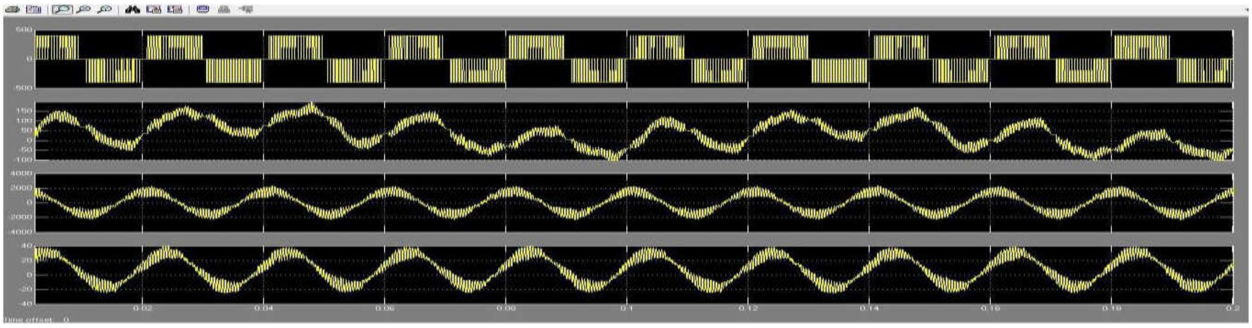

Fig. 14. Scope Output of Connection B

Connection C

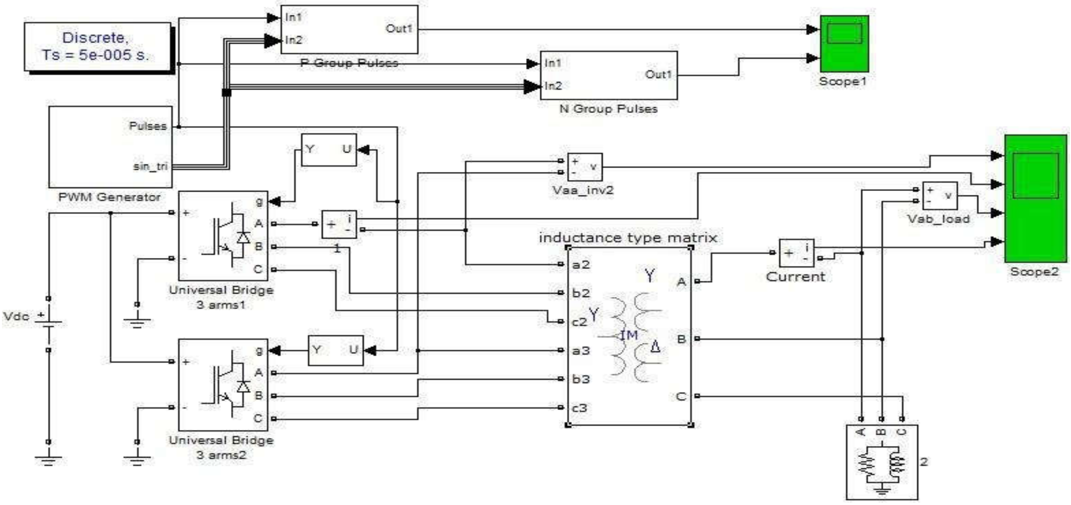

Fig. 15. Simulink model of Connection type C

C.1 FFT analysis of connection:

Voltage and current harmonics before transformer

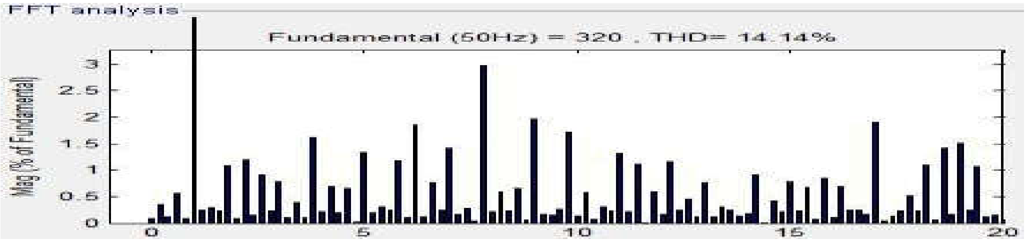

Fig. 16. Voltage harmonics before transformer for Connection C

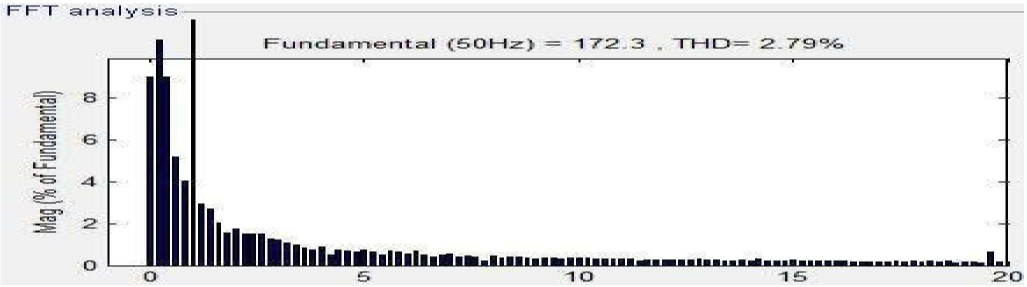

Fig. 17. Current harmonics before transformer for Connection C

Voltage and current harmonics after transformer

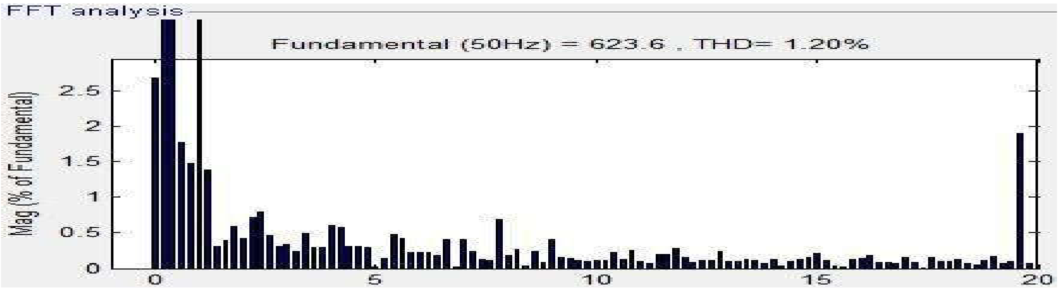

Fig. 18. Voltage Harmonics after Transformer for Connection C

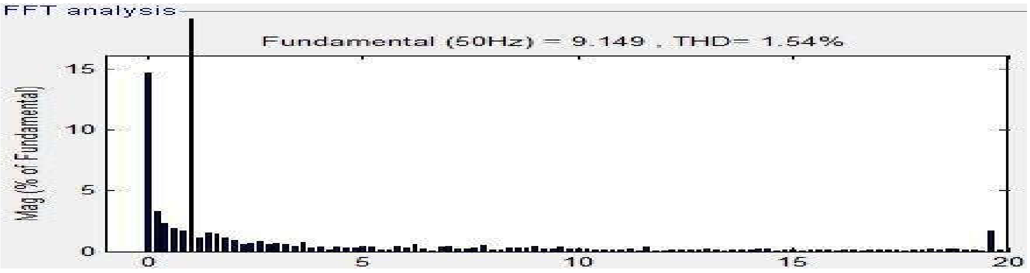

Fig. 19. Current harmonics after transformer for Connection C

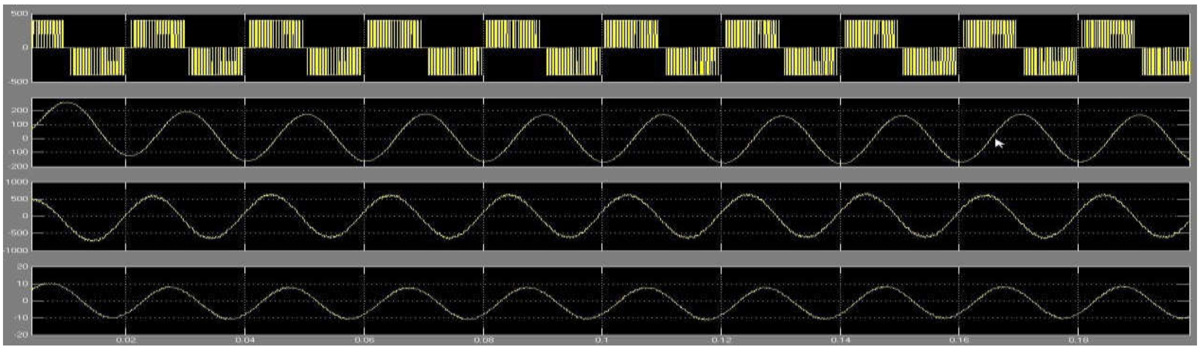

Fig. 20. Scope output of Connection C

Connection D

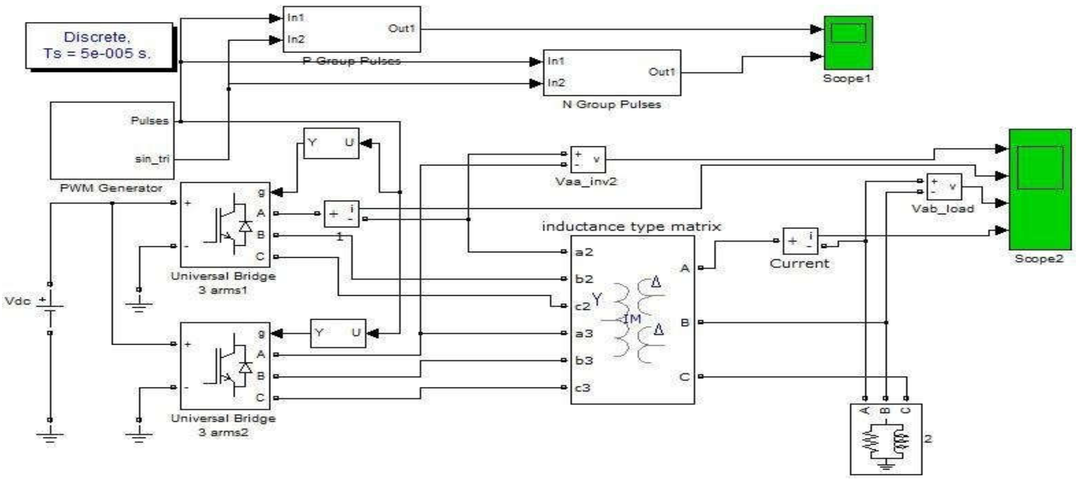

Fig. 21. Simulink model of Connection type D

D.1 FFT analysis of connection D:

Voltage and current harmonics before transformer

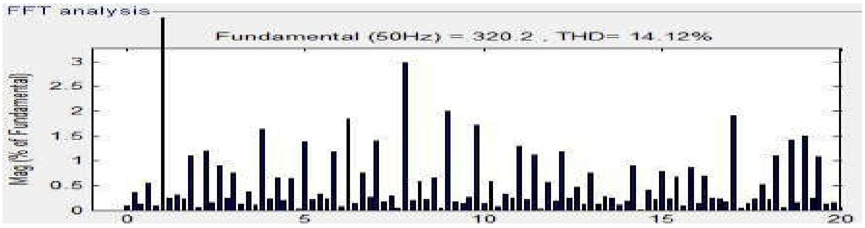

Fig. 22. Voltage harmonics before transformer for Connection D

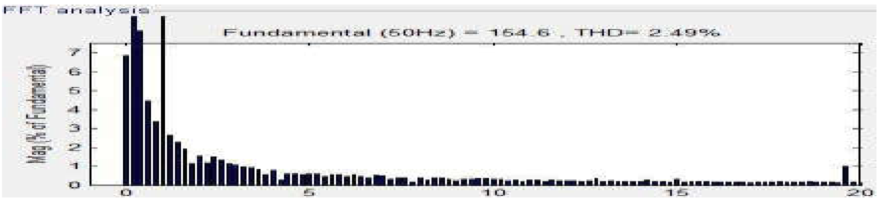

Fig 23. Current harmonics before transformer for Connection D

Voltage and current harmonics after transformer

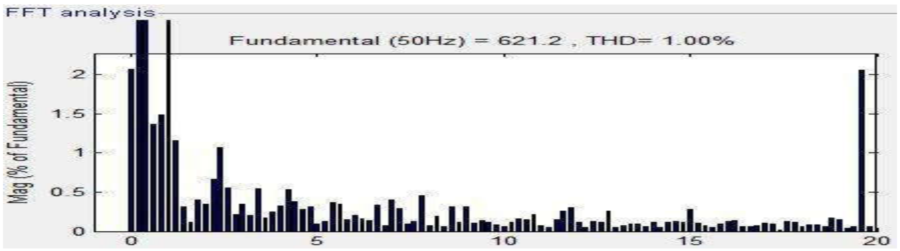

Fig. 24. Voltage harmonics after transformer for Connection D

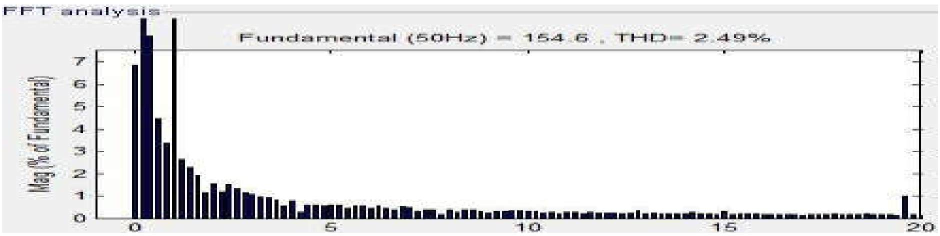

Fig. 25. Current harmonics after transformer for Connection D

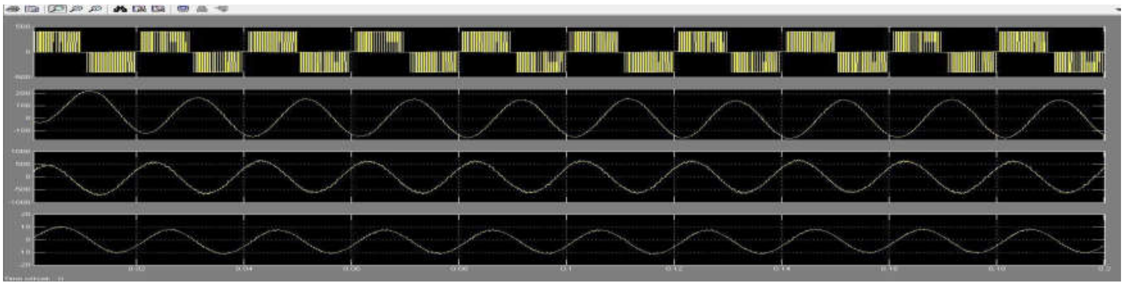

Fig. 26. Scope output of Connection D

Without transformer connection

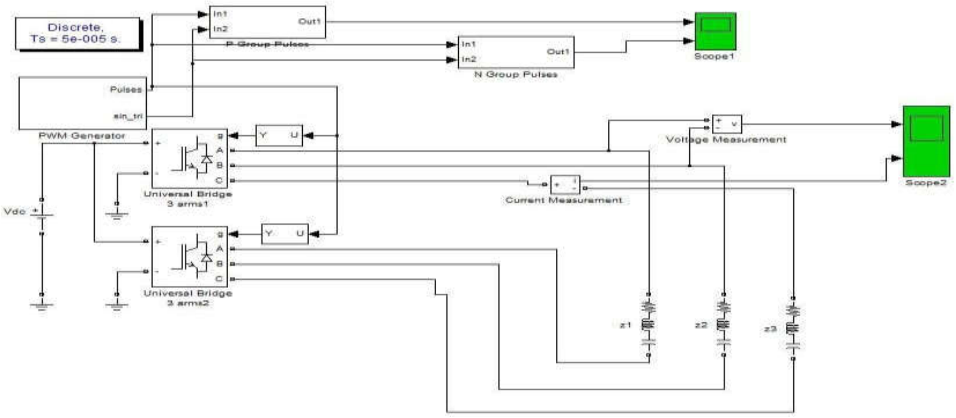

Fig. 27. Simulink model without transformer connection

Voltage and current harmonics

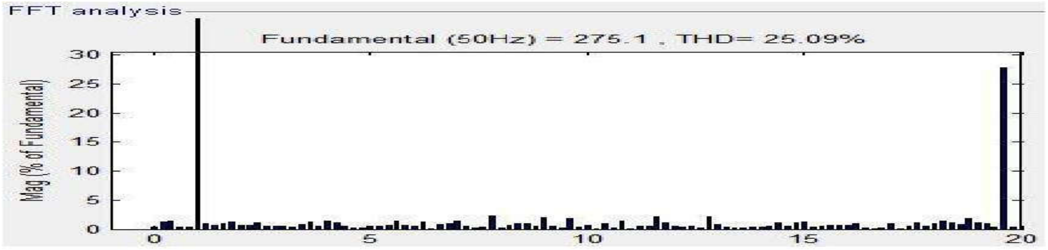

Fig. 28. Voltage harmonics for without transformer connection

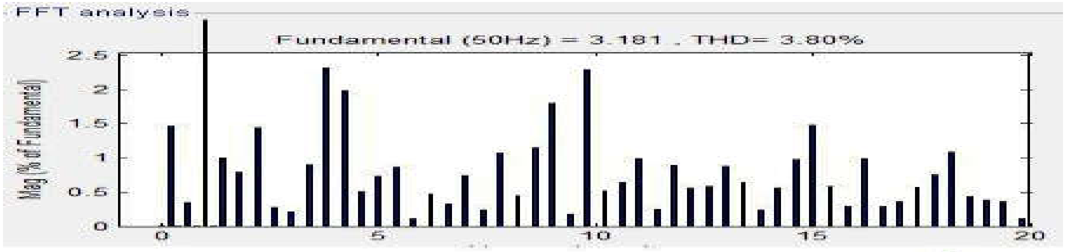

Fig. 29. Current harmonics for without transformer connection

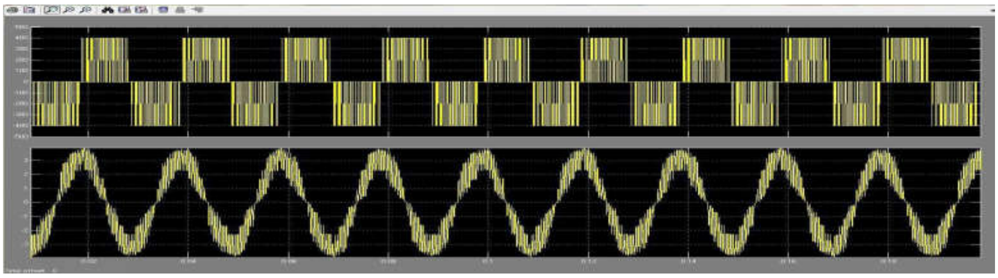

Fig. 30. Scope output of without transformer connection

Table -1 Comparison of THD in different connections (for P=1000W Q_T=500 VAr)

MI	Without Transformer	CONNECTION A (THD V&I) %		CONNECTION B (THD V&I) %		CONNECTION C (THD V&I) %		CONNECTION D (THD V&I) %	
		Before transformer	After transformer	Before transformer	After transformer	Before transformer	After transformer	Before transformer	After transformer
0.9	19.85 3.22%	13.42%, 2.15%	1.74%, 2.15%	13.40%, 5.35%	3.31%, 3.03%	13.35%, 2.98%	1.02%, 1.42%	13.34%, 2.81%	1.00%, 1.53%
0.8	25.09, 3.80%	14.21%, 2.19%	1.87%, 2.19%	14.18%, 5.83%	3.75%, 3.39%	14.14%, 2.79%	1.20%, 1.54%	14.12%, 2.49%	1.00%, 1.45%
0.7	27.62, 4.32%	16.62%, 1.97%	1.44%, 1.97%	16.58%, 5.88%	3.51%, 3.22%	16.53%, 2.81%	1.23%, 1.35%	16.52%, 2.66%	1.05%, 1.18%
0.6	30.26, 5.19%	18.15%, 1.92%	1.73%, 1.92%	18.12%, 6.34%	5.10%, 4.29%	18.05%, 2.86%	1.32%, 1.43%	18.02%, 2.45%	1.17%, 1.29%
0.5	41.34, 5.52%	23.87%, 2.34%	1.82%, 2.34%	23.80%, 6.20%	5.13%, 4.34%	23.69%, 2.61%	1.19%, 1.67%	23.66%, 2.27%	1.03%, 1.61%

The wye secondary transformer has the capability of providing a new electrical ground for the load circuit. An isolation transformer is a transformer with physically separate primary and secondary windings. These windings are typically separated by an electrostatic shield, which is a sheet of nonmagnetic conducting material (copper or aluminum) connected to ground which acts as a shield to prevent the noise of one system from passing through the transformer to sensitive equipments. Shielded isolation transformers are very popular power-conditioning devices. They isolate sensitive loads from transients and noise caused by the utility. They can also keep harmonics produced by end-user non linear equipments from getting onto the utility‘s system. They especially eliminate common - mode noise.

Inductive Filtering Connection

The existing new transformer connection, the primary side is wye wiring, and the two group windings of second side adopt delta wiring, which formed the 30° phase differences. Its secondary winding adopts prolonged-delta wiring. The secondary prolonged winding and the common winding of the new converter transformer adopt self-coupling connection, which is similar to the series winding and the common winding of autotransformer .It can realize the goal that once the harmonic current flows into the prolonged winding, the common winding will induct the opposite harmonic current to balance it by the zero impedance design of the common winding.

SIMULATION AND RESULTS

In order to verify proposed arrangement simulation analysis (Fig. 3, 11, 17 & 23) was performed with different modulation indices varying from 0.5 to 0.9. Voltage and current waveforms before and after transformer for different suggested connections as well as FFT analysis of proposed system (with modulation index= 0.8) also done and showed in subsequent figures. It is observed that THD of all arrangements are in permissible limit which is enviable. It can be observed that the output of transformer has reduced harmonic pollution with practical load attached with transformer. FFT analysis also shows the harmonic spectrum before and after transformer. Above table shows the THD variation with different connection at different modulation index. From the table it can be deduced that on decreasing the modulation index, THD of system increases with same load with different connections. Performance of Connection C and D is better than A and B. Without transformer connection and performance of FFT analysis also have done and data are shown in table.

Conclusion

These days electrical system has been trended in smaller, low cost, and lighter. In this paper, a cascaded multilevel inverter adopting a common-arm configuration to reduce the number of switching devices is proposed. The proposed configuration has achieved smaller system by reduction of switching components and its gating drivers. When we use the proposed inverter scheme, the scheme generates higher current rating than conventional circuit. Fortunately, disadvantage of the current rating in the proposed circuit can be compensated by advantage of the size effect by reduction of switching component and gating drivers. Valuable advantages of the proposed approach are summarized as follows:

1) Efficient and economical circuit configuration to synthesize multilevel outputs by using three-phase transformers.
2) Increase of utilization rate and decrease of volume by using three-phase transformers.
3) Possibility of using a single dc source by using isolated transformers.
4) Little transition loss of switch due to low switching frequency and reduced electromagnetic interference, which is suitable for high-voltage applications.

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