Abstract – More and more ac drive installations are requiring manufacturer’s to improve line side harmonics to ultimately meet IEEE Harmonic Std 519-1992 on site [1]. This paper reveals several patented transformer topologies for such an effort. Compared with other harmonic solutions, auto and isolated transformers possess advantages as being simple, reliable, minimal line resonance problems and relatively cost effective. The proposed nine and twelve-phase auto-transformers can be viewed as a polygon winding type, where besides achieving an improved input current harmonics, junction points among various windings along the polygon can be wired out for step-down, unity and step-up voltage transfers. When electrically isolated primary windings are added, unlimited transfer ratio is available for every application. Application of these new industrial transformer devices, along with simple power diode energy conversion methods, result in a robust and reliable system that provides good DC bus regulation for AC drives utilizing a common DC bus configuration. The proposed topologies also provide a high AC input power factor and minimize harmonic currents to the Utility Interface. The paper provides technical analysis and field site data on the new topologies, as well as per unit metric comparison to other harmonic mitigation techniques versus horsepower size.

I. INTRODUCTION

Standard AC drive topologies utilize AC-DC-AC power conversion with a three phase rectifying bridge for the AC-DC function. A three-phase diode or SCR bridge generates 6 pulse type current that is ~ 32% rich in total harmonic current distortion [2]. As ac drives proliferate, equipment system specifications limiting the amount of harmonic current injected into the grid are becoming more common and thus solicit cost effective harmonic mitigation solutions.

System specifications are often written so measured total harmonic distortion at the Point of Common Coupling (PCC) in Fig. 1 complies with the maximum low voltage total harmonic distortion levels (THD$_{v}$) and system classification of IEEE 519 Table 10.2 and current distortion limits of Table 10.3. The PCC is usually at the power metering point (PCC1) where other customers connect to the common line voltage but may also be at (PCC2) or (PCC3) within a plant where linear and non-linear loads are connected. System classification and (THD$_{v}$) options are Special Application @ 3%, Dedicated System @ 10 % and most specified option of General System @ 5%. Current harmonic distortion (THD$_{i}$) of a single non-linear load is defined as the square root of the sum of the squares of all harmonic currents divided by the fundamental component of the non-linear load. However, Table 10.3 defines total harmonic current distortion limits in a system as Total Demand Distortion (TDD). TDD limiting values are dependent on the ratio of short circuit current ($I_{sc}$) at the PCC to the maximum demand load current ($I_{L}$) supplied by the user. There are five classifications of ($I_{sc}/I_{L}$), but worst case TDD limit of 5% for an ($I_{sc}/I_{L}$)< 20 is often used.

Fig. 1 One line showing various harmonic distortion measurement points

\[
TDD = \sqrt{\frac{\sum I_{h}^{2}}{I_{L}}} \quad \text{Eq. (1)}
\]

Fig. 2 shows THD$_{i}$ of available solutions applied at PCC3. Only the 18 pulse, active filter and synchronous convertor front end solutions are able to meet IEEE TDD limit of 5% at PCC3 and PCC1. The passive LC type has a typical THD$_{i}$ ~9% and is regarded as cost effective [3]. However, it is well known to have problems of resonance and leading power factor at no-load condition [4]. The LC filter requires a detailed harmonic analysis to determine if a TDD limit of 5% is possible at PCC3 in the installation. Active shunt, series and even hybrid filters are promising but remain expensive and questionable in reliability [5]. Analysis of Harmonic Canceling Reactors [6] or Line-side Inter-phase Transformer (LIT) [7] shows their effectiveness but does not prove their cost competitiveness.

An Auto-transformer solution is investigated in this paper as a preferred embodiment because it does not introduce resonance in power system, is reliable and relatively cost effective. Integrating power switching devices with an auto-transformer may reduce size, but sacrifices the optimum cost target [8]. Traditional pure-passive auto-transformers may be potentially more cost effective, but they also pose a problem in sharing bridge currents in such multi-pulse application.[9]

In this paper, various patented topologies [10-12] of new auto and isolation transformers are proposed for harmonic mitigation, that inherently solve the diode current balancing, and are proven with test results and product in the field.
II. PRIOR ART OF MULTI-PULSE TRANSFORMER CIRCUITS

18-pulse isolation transformers that convert three-phase to nine-phase AC power are well known but have several shortcomings. First, isolation transformers must be rated for the full power required on both primary and secondary windings. Second, as a result of separate primary and secondary windings, isolation transformers are relatively large. When isolation between a utility supply and a rectifier is not required, employing an auto-transformer, consisting of a plurality of series and common windings, may advantageously reduce the size, weight and cost of the 3-phase to 9-phase converter.

Fig. 3 shows an exemplary 3-phase to 9-phase auto-transformer topology [13]. Three phase AC input lines are linked to three input nodes (1,2,3) and nine output nodes (1-3, A-F) provide voltage to three separate six pulse bridges. 18-pulse operation is obtained with +/- 20 degree phase shift around nodes 1,2 and 3. One problem is an inherent impedance mismatch in the topology since one bridge is fed directly form the line and the other two bridges are fed through the short transformer windings which are characterized by a certain amount of leakage reactance. This results in looping currents among the 3 bridges, which further requires relatively bulky and expensive inter-phase transformer hardware to correct. Secondly, current-sharing problems among the three bridges is exacerbated when irregular and unpredictable pre-existing AC line harmonics occur as different source harmonics that substantially change bridge current sharing.

One solution to the looping and sharing current problems is to provide an autotransformer that equally spaces output voltages in phase. Thus, where nine outputs are required, the outputs can be phase shifted from each other by 40 degrees each. In Fig. 4a this is accomplished in a step-down autotransformer with three coils, having serial windings that form a delta and stub windings magnetically coupled with the serial winding from the same coil [14]. Three phase AC inputs are linked to the apex nodes (11,12,13). Direct output nodes (14,17,19) and indirect output nodes (15,16,18,19,21,22) all have identical voltage magnitude vectors with the required 40-degree phase shift. The 6 leaf secondary windings solely process secondary power.

Fig. 4 shows other nine-phase step-down autotransformer configurations investigated. A step-down version is needed to compensate for a 14% increase in dc bus voltage that occurs from 3-phase to 9-phase conversion. Fig. 4b and Fig. 4c contain even more secondary leaf windings. Fig. 4d uses only 3 secondary leaf windings resulting in more efficient usage of...
material. However, the calculated step-down ratio may be difficult to achieve. Fig. 4e has main windings in Y connection, Y connected leaf windings and a separate non-power isolated delta winding loop needed for circulating non sinusoidal currents.

Fig. 5 shows other nine-phase unity-gain autotransformer configurations. A 6-pulse drive guarantees 460V Output with 480V AC input. A unity-gain autotransformer version, with an inherent 18-pulse higher DC bus voltage value, is sometimes desirable for applications requiring 460V Output under low line conditions of the 480V AC input.

While staggering the transformer outputs by 40° essentially eliminates the looping and sharing current problems, the stub winding requirement in each of the prior art renditions results in increased kVA requirements, increased winding and core material and increased physical size.

Thus, the next section proposes 3-phase to 9-phase autotransformer solutions that do not have looping and sharing current problems, are relatively inexpensive to construct, that can be utilized as step-down or unity gain and that can have an optional primary winding to accommodate any voltage transfer ratio desired.

III. PROPOSED MULTI-PULSE TRANSFORMER CIRCUITS

A. 9-Phase Step-down & Unity Phase Shifting Autotransformer

One design objective is to develop a single auto transformer topology that can be utilized as a step-down or unity-gain transformer. This feature enables a manufacturer to reduce design and manufacturing cost as one transformer is used for two different applications. Fig. 6 shows a nine-phase autotransformer topology incorporated in a step down ac-dc power conversion system [10]. The transformer is wound on a regular three-pole core with 15 windings, where each phase has five windings. For example phase \( R \) consists of windings \( R1-R5 \). On each pole all windings are wound such that their polarities are in the same direction. This polarity alignment assures inductance in each winding is added up along the magnetic path length.

A second design objective is to provide 18-pulse performance at lowest cost. To this end, the proposed autotransformer only includes serial windings and does not require leaf windings, which solely process one side power. These results in better material utilization than prior art designs for the same transformation results. The plurality of the series windings is arranged to form a polygon.

The step-down transformation objective of Fig. 6 has winding junction points \( H1-H6 \) and \( X1-X9 \) wired for input/output, respectively. Since \( X1-X9 \) has equal magnitude and equal 40° phase shift, they serve as a nine-phase voltage output for rectification and DC output. Such DC output has 18-
pulse low ripple performance. Utility line RST input power connections, with their 120° phase shift set, can be connected to two sets of nodes; either $[H1,H2,H3]$ or $[H4,H5,H6]$ for a same step-down ratio.

A third design objective is to eliminate the looping and sharing current problems. This is accomplished by the equal $X1$-$X9$ secondary voltage magnitudes which are separated by equal 40° phase shift angles.

The step-down magnitude between primary and secondary voltages can be analyzed by Fig. 6 as a voltage plane where distance between nodes represents voltage magnitude. Lines can be drawn between nodes and the Origin (O). The angle between two lines represents a phase shift angle of two node voltages. For example, the phase angle between nodes $X1$ and $X2$ is 40°. A nine-phase autotransformer requires nine output nodes $X1$-$X9$ whose voltages are identical and spaced apart 40° on the dotted unit line circle of Fig.6. Nodes $X1$-$X9$ serve as output secondary voltages. It is seen that the voltage magnitudes at the step-down input set ($H1,H2,H3$) of Fig. 6 are greater than the voltage magnitudes at the output set ($X1$-$X9$). Step-down voltage magnitude will be proportional to the distance between primary and secondary output nodes.

Fig. 6 topology also meets the unity voltage transfer design objective when RST are connected to either one of $[X1,X4,X7], [X2,X5,X8]$ or $[X3,X6,X9]$ sets of nodes. It is seen the output voltage vector lengths and magnitudes are identical on the unit circle with the required 40° phase shift angle, while the input voltage vector magnitudes are identical in length to the output voltage vectors.

### B. 9-Phase Step-up & Unity Phase Shifting Autotransformer

Winding re-arrangement of the 15 nine-phase auto-transformer windings in Fig. 6 gives an alternate in Fig. 7a, capable of unity and step up with a ratio of $\frac{x1}{h6} \approx 1.28$ [11]. Unity three phase to nine phase voltage transformation is realized by connecting the primary three phase source to either node sets of $[X1,X4,X7], [X2,X5,X8]$ or $[X3,X6,X9]$ while the secondary output nine phases are taken from $X1$ to $X9$. There are three sets of parallel windings. One phase set in Fig. 7a consists of $R1$ through $R5$. Thus, each phase set has five windings wound on one pole of a conventional three-pole magnetic core.

When either set of $[H1,H2,H3]$ or $[H4,H5,H6]$ nodes are used to connect to the primary power source, this topology is capable of step-up voltage transformation. The ratio is defined by the trigonometric relationship as:

$$\frac{V_{sec}}{V_{pri}} = \frac{X1}{H6} \approx 1.28$$ \hspace{1cm} Eq.7

Again, each winding turns can be calculated in lengths:

$$R1 = R2 = \left( \frac{\cos(50\degree)}{\sin(30\degree)} \right) \frac{X1}{H6} = 0.5077 \times X1$$ \hspace{1cm} Eq.9

$$R3 = R5 = \left( \frac{\tan(30\degree)}{\sin(50\degree)} \right) \frac{X1}{H6} = 0.6940 \times X1$$ \hspace{1cm} Eq.10

Consequently,

$$R1 : R2 : R3 : R5 : R5 = 1:1:0.5321:1.3472:0.5321$$ \hspace{1cm} Eq. 12

Possible turns for each winding are summarized in Table 2.

#### Table 1

<table>
<thead>
<tr>
<th>Combination #</th>
<th>$R1$</th>
<th>$R2$</th>
<th>$R3$</th>
<th>$R4$</th>
<th>$R5$</th>
<th>Max Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15</td>
<td>15</td>
<td>8</td>
<td>20</td>
<td>8</td>
<td>0.77 %</td>
</tr>
<tr>
<td>2</td>
<td>28</td>
<td>28</td>
<td>15</td>
<td>38</td>
<td>15</td>
<td>0.31 %</td>
</tr>
<tr>
<td>3</td>
<td>32</td>
<td>32</td>
<td>17</td>
<td>43</td>
<td>17</td>
<td>0.07 %</td>
</tr>
<tr>
<td>4</td>
<td>43</td>
<td>43</td>
<td>23</td>
<td>58</td>
<td>23</td>
<td>0.25 %</td>
</tr>
</tbody>
</table>

Fig. 6 topology also meets the unity voltage transfer design objective when RST are connected to either one of $[X1,X4,X7], [X2,X5,X8] \text{ or } [X3,X6,X9]$ sets of nodes. It is
C. 9-Phase Polygon Secondary for Isolation Transformer

The autotransformer topology of Fig. 6 or Fig. 7a can be utilized as a secondary of an isolation transformer. Addition of three more windings electrically isolated from the fifteen polygon windings, shown delta connected in Fig. 7b, converts the entire topology into an isolation transformer with arbitrary voltage transfer ratio. The delta primary winding can be added to Fig. 6 in a similar manner.

With electrically isolated primary windings, unlimited voltage transfer ratio is available for every application, such as medium/low voltage transformation with medium voltage feeders to eliminate the need for an interface step-down utility transformer. For example, an 800 HP isolation transformer with 4.2 kV primary / 600 V step-down polygon secondary was manufactured and installed. This eliminated the need for a 1.5 MVA 4.2 kV primary / 600 V step-down utility transformer that would normally have fed a 600V/600V polygon autotransformer design.

D. 12-Phase Step-down/up & Unity Phase Shifting Autotransformer

Fig. 8 shows a twelve-phase auto-transformer configured as step-down in a 24-pulse ac-dc conversion system [12]. A twelve-phase 24-pulse rectifier system requires 30 degree phase shift between the 12 output voltage nodes to eliminate circulating and sharing current problems.

There are eighteen windings are arranged into a hexagon where all winding junctions can be utilized for various voltage transfer functions. These 18 windings are divided into three groups wound on three magnetic poles of a transformer core. Each pole phase has six windings that are interconnected with the same polarity. The polarity alignment assures inductance in each winding is added up along the magnetic path. Each phase consists of six windings (R1-R6 for phase R). Secondary voltages are supplied from equal magnitude points X1 to X12. Voltage transformation is determined by the trigonometry illustrated in Fig. 8. Figure 8 can be viewed as a voltage plane where distance between nodes represents voltage magnitude.

The voltage vector of each output phase is represented by a line from the origin node to its output node, such as X1. This line length represents voltage magnitude of the output phase. It is desirable for all output phases to have equal voltage magnitudes, so all output nodes X1 to X12 are on a circle with phase difference between phases of 30°. The twelve secondary outputs are connected to two six-phase rectifiers and their results are summed for a much lower ripple DC output.

Step-down autotransformer operation occurs when primary voltages RST are connected to a set of [H1_H2_H3] or [H4_H5_H6]. The step-down ratio is thus 0.8966.

\[
\frac{V_{sec}}{V_{pri}} = \frac{\sqrt{7}}{2} \frac{\cos(30°)}{\cos(15°)} = 0.8966 \quad \text{Eq. 13}
\]

Unity-gain autotransformer operation occurs when primary voltages RST are connected to a set of [X1_X5_X9], [X2_X6_X10], [X3_X7_X11] or [X4_X8_X12].

Step-up autotransformer operation occurs when primary voltages RST are connected to a set of [Y1_Y2_Y3] or [Y4_Y5_Y6]. The step-up ratio is thus 1.035.

\[
\frac{V_{sec}}{V_{pri}} = \frac{\sqrt{7}}{5} = \frac{1}{\cos(15°)} \approx 1.035 \quad \text{Eq. 14}
\]

The turns ratio among set R1 – R6 is thus:

\[
\frac{R1}{R2} : \frac{R3}{R4} : \frac{R5}{R6} = 1: 1.733 : 1: 1.733 : 1 \quad \text{Eq. 15}
\]

E. 9-Phase / 12 phase Autotransformer kVA Rating, Size & Cost

An equivalent autotransformer VA rating assists in comparing cost and size of the autotransformer topologies to that of a conventional isolated transformer. Equivalent rating is based upon the sum of all products of the sinusoidal equivalent voltage across the windings and relevant rms current through the windings [18]. Winding voltage is near sinusoidal but current waveforms are not. The VA rating was computed with simulation waveforms. Subsequent kVA rating calculation with respect to the DC output is 2.3 for a conventional isolated 18 pulse transformer, 0.84 for the 18-pulse nine-phase auto-xfmr.
and 0.74 for the 24-pulse twelve-phase auto-xfmr. These calculations verify the cost and size advantages of the new auto-xfmr topologies in Fig. 9 and Fig. 10 over existing isolation transformer methods. Fig. 11 shows an 18-pulse auto-xfmr and Rectifier Bridge is about ½ the cubic volume of the 500 HP inverter.

IV. HARMONIC PERFORMANCE OF MULTI-PULSE CIRCUITS

A. 9-Phase 18-pulse Autotransformer Simulation & Test Results

Fig. 12 shows a test setup used to test a 100 hp 18-pulse phase shifting step-down autotransformer. Load to the AC drive motor was a dc motor connected to the shaft.

Fig. 13 shows harmonic mitigation performance of 18-pulse autotransformer with test and simulation results. The RST input harmonic spectrum of 100 hp 18-pulse phase shifting step down auto-xfmr from simulation & test.
current waveform of Fig. 13(a) is nearly sinusoidal with a measured \(THD_I=4.8\%\). The simulated \(RST\) current waveform of Fig. 13(b) has a calculated \(THD_I=3.5\%\). Simulated harmonic current spectrum results in Fig. 13(c) show the classic dominant 18 +/- 1 (17th & 19th) harmonics at ~ 2% of fundamental, with the 5th, 7th 11th and 13th virtually eliminated. Tested harmonic current spectrum results in Fig. 13(c) show agreement with the (17th & 19th) harmonics, but contain a 3rd, 5th, 7th 11th and 13th components. The reason is attributed to unbalanced input line voltages. Presence of unbalanced negative sequence voltage in the power source does not effect multi-pulse dc output but causes a third harmonic in the converter line current [18]. A similar reason is attributed to the 5th and 7th components that appear only in measurement.

Fig. 14 shows simulated \(Phase\ R\) input line current along with secondary \(X_1- X_9\) line currents. Discrete positive and negative rectifier conduction pulses of current in each line is seen line with current magnitudes that are perfectly balanced. The discrete line pulse magnitudes indicate there is no current sharing problem and also no circulating current problem.

B. 12-Phase 24-pulse Autotransformer Simulation & Test Results

Fig. 15 shows harmonic mitigation performance of Fig.8 24-pulse autotransformer with test and simulation results. The \(Phase\ R\) input current waveform of Fig.15(a) is also nearly sinusoidal with a measured \(THD_I=4.1\%\). The simulated \(RST\) current waveform of Fig.15(b) has a calculated \(THD_I=2.4\%\).

C. 18-pulse AutoXFMR Comparison to Other Mitigation Techniques

Input current and voltage THD of 75 hp, 250 hp and 650 hp drives is compared for various front-end topologies:

- 6-pulse drive with 6 SCR Bridge converter attached to PWM inverter
- 12-pulse phase shift autotransformer with diode bridge & PWM inverter
- 18-pulse phase shift autotransformer with diode bridge & PWM inverter
- 6-pulse drive with hybrid harmonic tuned filter [3]

The drives utilize the same inverter and control board. Loading was similar to the test dyne setup of Fig.12. Tests were performed at different hp test cells on the manufacturing floor depending on drive size tested. Fig. 16 & Fig. 17 data is presented as providing insight on different harmonic mitigation techniques and not absolute since harmonic currents and voltages are largely dependent on system impedance’s within the power distribution system.

V. METRICS OF NEW MULTI-PULSE AUTOTRANSFORMERS

In a similar fashion other metrics are investigated in Table 3 with the various front-end topologies of Section IV.C. These include power factor, displacement factor, \(K\)-factor and efficiency.
Table 3

<table>
<thead>
<tr>
<th>Category</th>
<th>6-Pulse</th>
<th>12-Pulse</th>
<th>18-Pulse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current THD</td>
<td>30 – 35 %</td>
<td>6.5 – 9.5 %</td>
<td>4.5 – 5 %</td>
</tr>
<tr>
<td>Power factor</td>
<td>0.92 – 0.95</td>
<td>0.97 – 0.98</td>
<td>0.98 – 0.99</td>
</tr>
<tr>
<td>Displacement Factor</td>
<td>0.95 – 0.97</td>
<td>0.96 – 0.98</td>
<td>0.98 – 0.99</td>
</tr>
<tr>
<td>K – factor</td>
<td>3.0 – 5.0</td>
<td>2.0 – 3.0</td>
<td>1.0 – 2.0</td>
</tr>
<tr>
<td>Efficiency</td>
<td>96.5 – 97.5 %</td>
<td>97.0 – 98.0 %</td>
<td>97.5 – 98.0 %</td>
</tr>
</tbody>
</table>

A. Power Factor

Definitions are in order when discussing power factor of non-linear converters.

**Total Power Factor (pf total):** the ratio for the total power input, in watts to the total volt-ampere input to the converter.

**Displacement Power Factor (pf disp):** the displacement component of power factor. The ratio of the active power of the fundamental wave, in watts, to the apparent power of the fundamental wave, in volt-amperes.

**Distortion Power Factor (pf dist):** the ratio of the root-mean-square of the harmonic content to the root-mean-square of the fundamental component, expressed as a percent of fundamental.

For Three-Phase, Non-Sinusoidal, Balanced Systems

(The following approximations apply when V(THD) ≤ 5%)

<table>
<thead>
<tr>
<th></th>
<th>6-pulse</th>
<th>12-pulse</th>
<th>18-pulse</th>
</tr>
</thead>
<tbody>
<tr>
<td>True Apparent Power</td>
<td>S = V*I_{total} (kVA)</td>
<td>S1 = V*I_{fund} (kVA)</td>
<td></td>
</tr>
<tr>
<td>Real Power</td>
<td>P = V*I_{real} (kW)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>True Reactive Power</td>
<td>Q = V*sqrt(I_{react}^2 + I_{harm}^2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reactive Power</td>
<td>Q = V*I_{react} (kVAR)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Harmonic Power</td>
<td>D = V*I_{harm} (kVAR)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>sqrt(P^2 + Q^2 + D^2) = sqrt(P^2 + Q_t^2)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

pf total = true pf = pf disp * pf dist = I_{real} / I_{total} = P/S

pf disp = cos (angle between I_{real} and I_{fund}) = I_{real} / I_{fund} = P/S_1

pf dist = cos (angle between I_{fund} and I_{total}) = I_{fund} / I_{total} = S_1/S

THID = I_{harm} / I_{fund}

pf dist = sqrt(1/(1+THD_I^2))

I_{total} = sqrt((I_{real}^2 + I_{react}^2 + I_{harm}^2))

I_{true react} = sqrt(I_{react}^2 + I_{harm}^2)

These relationships are best visualized by the power cube representation in Fig. 18 [19]. Fig. 19 plots the pf dist equation. This plot can be used with the THDI values in Table 3 to generate Table 3 displacement factor for various multi-pulse topologies or filter with known THDI values.

Fig. 18 Power Cube relationship of power factor definitions

Fig. 19 Distortion power factor vs. THDI

Fig. 20 Simulation of 480V 18-pulse nine-phase step-down autotransformer line-neutral 400 Vpk voltage and phase R line current of 400 A pk. Total power factor approaches unity.

Fig. 20 shows the proposed 18-pulse autotransformer topology has a near unity total power factor from simulation, as also shown Table 3. Fig. 21 shows measured total power factor of the proposed 18-pulse autotransformer compared with the other various front-end topologies. Fig. 22 shows measured displacement power factor of proposed 18-pulse auto-xfmr compared with the other various front-end topologies.

Fig. 21 Total power factor at input terminals for various front-end topologies under varying load

Fig. 22 Displacement factor at input terminals for various front-end topologies under varying load
B. K - Factor

K – Factor is a calculation used to determine transformer derating in the presence of excessive current harmonic heating in the primary/secondary coils [20-22]. K – Factor is defined as:

\[ k = \frac{h_{\text{max}}}{\sum_{h=1}^{n} I_{h}^{2} h^{2}} \quad \text{Eq.17} \]

where \( I_{h} \) = rms current at harmonic \( h \), in per unit of rated rms load current

Table 3 shows the 18-pulse and 24 pulse autotransformer topologies have the lowest value. Larger K-factor means larger size and cost.

Thus, due to the lower fundamental input current with total \( p_f \approx 1 \) and lower harmonic currents, there is capital equipment savings in the feed transformer cost with 18-p and 24-p systems that offset original purchase cost. Also, $ cost savings is similar for cables, fuses and breakers. These are also an operating $ savings in power factor penalty cost for very large kVA systems with dedicated 18 pulse inputs with \( p_f \approx 1 \).

C. Efficiency

This section calculates the input-output efficiency of a nine-phase autoxfmr, 18 diode rectifier, pwm inverter and ac motor compared to a 6 SCR rectifier, DC link choke, pwm inverter and ac motor. Fig. 24 shows that 18-pulse system efficiency may be equal or better than for a 6-pulse system. Some differences may be the SCR forward voltage drop at higher input current vs. a diode drop at lower input current in the 18-pulse system. DC link power and output kVA to the motor were made equal in Fig. 23 in both cases. Table 4 data for rated 100 hp load shows measured results with a FLUKE 41 Power Analyzer that measured \( V_{LL} \) and \( I_{line} \).

<table>
<thead>
<tr>
<th>Drive</th>
<th>Eff Conv</th>
<th>Vout</th>
<th>Iout</th>
<th>kVAout</th>
<th>kWout</th>
<th>Eff. inv</th>
<th>Eff drive system</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 pulse</td>
<td>97.0%</td>
<td>460</td>
<td>138</td>
<td>109.8</td>
<td>97.74</td>
<td>99.6%</td>
<td>96.8%</td>
</tr>
<tr>
<td>18 pulse</td>
<td>98.1%</td>
<td>460</td>
<td>138</td>
<td>109.8</td>
<td>97.74</td>
<td>99.6%</td>
<td>97.8%</td>
</tr>
</tbody>
</table>

Fig. 23 Loss model of AC Drive system to calculate input-output efficiency

![Fig. 23 Loss model of AC Drive system to calculate input-output efficiency](image)

Table 4

<table>
<thead>
<tr>
<th>Drive</th>
<th>Vin</th>
<th>Iin</th>
<th>kVA in</th>
<th>kWin</th>
<th>PF</th>
<th>THDv</th>
<th>THD I</th>
<th>Vdc</th>
<th>Idc</th>
<th>kWdc</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 pulse</td>
<td>480</td>
<td>129.6</td>
<td>107.6</td>
<td>101.1</td>
<td>0.94</td>
<td>1.5</td>
<td>32.6</td>
<td>648</td>
<td>151.4</td>
<td>98.11</td>
</tr>
<tr>
<td>18 pulse</td>
<td>480</td>
<td>121.6</td>
<td>100.98</td>
<td>99.9</td>
<td>0.99</td>
<td>1.2</td>
<td>4.5</td>
<td>670</td>
<td>146.4</td>
<td>98.09</td>
</tr>
</tbody>
</table>

Fig. 24 Efficiency comparison of nine-phase auto-xfmr with 6-pulse system

![Fig. 24 Efficiency comparison of nine-phase auto-xfmr with 6-pulse system](image)

VI. MULTI-PULSE OPERATION WITH NON-IDEAL INPUT POWER

Non-ideal power source characteristics may cause current unbalance (up to 80% seen) and increased \( THD \) in prior art Auto-XFMR circuits with parallel bridge converters.

Pre-existing voltage harmonics is one contributor to current unbalance. Pre-existing 5th harmonic voltage induced on the desired PCC connection may be due to 6-pulse VFD (5th, 7th dominate) operation at a distant location in Fig.1 plant one-line diagram. A pre-existing 5th harmonic voltage of 2.5% is used for analysis based on best field data to date.

Utility source voltage unbalance is another contributor to current unbalance. ANSI C84.1-1982 [23] defines 3-phase % voltage unbalance in Eq. 18. A value of 1% covers ~ 70% of all field sites according to [23] and is thus a worst case design criteria.

\[ \% V_{\text{unbalance}} = \frac{3(V \text{max} - V \text{min})}{V_a + V_b + V_c} \times 100 \quad \text{Eq.18} \]

\( THD_i \) comparison at the input terminals to a drive with an 18-pulse phase-shifting Autotransformer was simulated with a 300 kVA 480V line under the following Type I – Type III combinations of utility Power Source input conditions.

Type I - Balanced Input Line Voltage & No pre-existing Harmonics

Type II - Imbalance (1%) Input Line Voltage & No pre-existing Harmonics

Type III - Imbalance (1%) Input Line Voltage & 2.5 % 5th Harmonic Voltage

Test - Obtained on test Floor

Fig.25 shows a Type I power source results in a \( THD_i = 3.25\% \) at full load and just over 5% at 1/4 load. Type II power, with 1% line unbalance, raises \( THD_i \) to 4.8% at full load and 9% at 1/4 load. However, IEEE-519 TDD limit of 5% at full load is still met at drive input terminals. Test floor 1% unbalance conditions match Type II simulation results very well with load. Type III power with 1% unbalance lines and 2.5 % pre-existing 5th harmonic voltage causes the highest \( THD_i \) at 7% for full load. Higher THD is a result of the 5th harmonic voltage phase angle causing a slight dc voltage unbalance in the rectifier output and thus some current unbalance, as explained in [18]. However, converter bridge and autotransformer can still operate continuously under this condition. Also, if the 18-pulse \( THD_i \) of 7% is combined with even a small linear load at the PCC, then IEEE-519 TDD limit of 5% may still be met.

Pre-existing 5th harmonic condition was tested by removing the dc drive isolation transformer in Fig.12, so that the dc drive 6-pulse current harmonics presented a \( THD_i \) of 7.4% at the 18-pulse autotransformer line inputs as shown in Fig.26. The resulting current waveform simulation and test results of Fig.26 also show general agreement.

![Fig. 25 Harmonic mitigation performance of 18-pulse VFD with phase shifting Auto-xfmr under different input line conditions](image)
The proposed nine- and twelve-phase auto-transformers can be sharing problems. Topologies utilizing these transformers were shown to not have current as well as small physical size. The proposed AC/DC converter other solutions, autotransformers possess such advantages as being transformer considerations for adjustable frequency drives,” PCIM 2000 proceedings, October 2000, pp. 432-438.


ANSI C84.1-1982, “American National Standard voltage ratings for electric power systems and equipment” 1430 Broadway, New York, NY