A Novel 24-pulse rectification system

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ABSTRACT A novel autotransformer configuration for 24-pulse rectification is proposed that not only maintains the desired power quality but also enables a reduction in autotransformer equivalent power capacity, therefore, lowering cost, volume and weight of the overall 24-pulse rectification system. The significances of the proposed autotransformer configuration are: easier implementation and have reduced windings per autotransformer core limb contrary to the established topology. The topology of the novel autotransformer is such that one of the four 3-phase rectifiers draws current directly from the input power supply instead of the autotransformer hence the power load on the autotransformer is significantly reduced. Higher pulse rectification systems are needed to be investigated because they comply with the stringent power quality standards defined by IEEE-519. The performance of the novel topology is compared with the well-established 24-pulse rectification system where the proposed system exhibit superior characteristics evaluated regarding power quality and simplicity. In this paper, the performance of both 24-pulse power converters is assessed through MATLAB simulations and validated through experimental prototypes.

INDEX TERMS Autotransformer, Power quality, Multi-pulse, Power converters.

I. INTRODUCTION

The vital role of power converters in a wide range of applications such as aerospace, automotive, motor drives, railway traction, renewable generation, distributed generation, communication systems, etc. have brought popularity to the power electronics technology [1]. With the advancements in technology, more stringent constraints regarding sizes, power quality, power factor, efficiency and reliability with cost minimization have been directed [2] [3] [4] [5]. In addition to the nonlinear nature of the power converter, the non-linear load generates current harmonics in the source side thus polluting the power source. These current harmonics result in low power quality, overheating effects, resonances and stability issues in the distribution network [6].

Different harmonic mitigation techniques have been proposed including active/passive harmonic filtering techniques and multi-pulse transformer based rectifiers [7] [8] [9] [10] [11] [12]. These mitigation solutions are implemented to comply with the international regulations, despite their addition to the complication and alleviation in the overall system cost and size. In case of active filtering, the feedback control with high-frequency switching aggravates high-order harmonics, which are responsible for the parallel and series resonance in the power systems [13]. Due to the mutual interaction between control systems and with passive components, the instability phenomenon may occur in different frequency ranges [14] [15]. Furthermore, harmonic instability may also be generated or magnified by the control of converters in interaction with harmonic resonance conditions, introduced by the high-order power filters for converters and parasitic capacitors of power cables [16] [17] [18]. Similarly, in passive filtering method, the use of DC link capacitors with uncontrolled rectifiers injects unacceptable harmonic current into the mains, affecting the power-supply system by causing vibration and overheating [19].

On the other hand, a multi-pulse technique for harmonic mitigation has gained the attention of researchers due to its simplicity, high reliability, elevated efficiency, and small size and weight along with the desired power quality results. Contrary to active filtering techniques, no electromagnetic interference (EMI) filter is required due to intrinsic lower order harmonic cancellation behavior of autotransformer. This avoids the use of capacitive phase displacement of the input voltage and current which also lowers the power factor [20].

Multi-pulse AC-DC converters offer low ripple dc voltages, hence there is no need of DC link filter, which could cause harmonic generation at the AC supply. The main power quality requirements demanded from AC-DC converters are...
fulfilled by multi-pulse converters, which enable the power factor close to unity [19]. Conventionally, isolation transformer was used to phase shifts the primary voltages of the AC supply, but it does not meet the requirements of low cost, small weight, size, and equivalent transformer capacity. Therefore, the trend has been shifted to autotransformer, which offers these desired qualities in multi-pulse rectification. The performance of the multi-pulse rectifier improves with the number of pulses by increasing the number of supply voltages. This task is done by the autotransformer in multi-pulse rectification by phase shifting the primary three-phase supply voltages by an angle of ±φ, thereby producing a m number of three-phase sets [21] [22]. This property is proved from the fact that the input current characteristic harmonics of the order 6km ± 1 are generated in the AC supply with amplitudes of 1 / (6km ± 1), where k is the positive integer, and m is the number of 3-phase rectifiers connected in parallel [23] [24] [25]. The general diagram for multi-pulse rectification is depicted in Fig. 1, where three-phase ac supply is converted into an n number of phases, each separated from the other adjacent phase by an angle of ±φ. These phases are fed to an n-phase rectification system where an m number of three-phase rectifiers are connected in parallel, directly or indirectly (through an Inter Phase Transformer (IPT)), depending upon the configuration of the autotransformer. Some configurations of autotransformer do not require the use of IPT, AC and DC filters, because they possess an intrinsic capability of current harmonic cancellation while maintaining equal current conduction through rectifiers so these components are depicted as optional here[26][27].

Six pulse rectifier, which is the basic building block of a multi-pulse conversion system, has been most commonly used in industries for decades as an AC-DC converter. Due to the advancement and the emergence of green power technology, stringency in IEEE-519 standards for the power quality has increased, which is not achievable by the 6-pulse rectification system. Typical THD value of a 6-pulse rectifier is around 30% of the fundamental harmonic, which is beyond the standard level [28]. Another multi-pulse rectifier which has been widely used is the 12–pulse rectifier having normal THD value around 15%, which does not comply with IEEE-519 standards, mentioned in Table II. However, there are some configurations of autotransformer in 18-pulse rectification systems, which have the property of intrinsically cancelling current harmonics while offering THD values within limits set by IEEE-519. Similarly, 24-pulse rectifiers also offer THD values within limits set by the same IEEE standards. These rectifiers are capable of suppressing the non-characteristic current harmonics of the input supply, provided the respective autotransformer to generate balanced voltages. In this paper, a novel configuration of an autotransformer is proposed for 24-pulse rectification and compared with the performance of a former well established 24-pulse rectifier to improve the power quality, size, weight, and transformer equivalent power capacity. The DC voltage ripple examines power quality, power factor and THD at input while size and weight are based on the transformer equivalent power capacity.

The organization of this paper is as follows: Section II discusses the designs and operation of the formerly available topology and the novel 24-pulse autotransformer topology. Section III describes the voltage and current analysis of the pre-mentioned rectifiers. Simulation and experimental results are depicted and discussed in section IV. Section V concludes the paper.

II. DESIGNS
In the case of 24-pulse rectification, the output DC voltage has 24 pulses in one cycle of the fundamental system frequency. It can be obtained by using 12 phases which are separated from each other by a phase shift of ±φ. These 12 phases are grouped in four sets of 3-phase rectifiers connected in parallel or series depending upon the topology of transformers used. This section discusses subsequently the designs of formerly available as well as the newly developed 24-pulse autotransformer topology.
A. 24-Pulse Autotransformer

The design of the established 24-pulse rectifier is based on symmetric differential star/wye configured autotransformer. Input power supply phases are shifted by angles of ±7.5° and ±22.5°, so that to split it into four sets of three phases as shown in Fig. 2a. The auxiliary phases generated, $U_{ABC(i)}$, $U_{ABC(2)}$, $U_{ABC(3)}$, and $U_{ABC(4)}$ have equal magnitudes as that of primary, but the primary supply voltages are not directly used in rectification. The connection diagram of this rectification system is depicted in Fig. 2b where input power is supplied by the three-phase system $U_{ABC}$ which is further converted into four sets of 3-phase supply namely $U_{ABC(1)}$, $U_{ABC(2)}$, $U_{ABC(3)}$ and $U_{ABC(4)}$. These voltage sets are obtained by adequately tapping the primary voltage windings. These sets supply power to the rectifiers which are connected in parallel as discussed in the next section. For effective harmonic suppression, phase shift maintained among voltages is according to the rule defined by [8] i.e phase shift = 60°/number of six-pulse converters. The full load power is therefore distributed among more numbers of rectifiers, and each rectifier carries 1/4th of the entire load power thereby reducing the power ratings of the rectifiers.

B. NEW 24-Pulse Autotransformer

The design of novel autotransformer for 24-pulse rectification is also based on a symmetric differential star/wye configuration. Contrary to the previously discussed configuration, this new idea utilizes the main 3-phase supply directly along with the auxiliary phases. The number of windings per limb of autotransformer reduces from 5 to 4, thus reducing the complexity and interconnections of the autotransformer. Three phase source is phase shifted by angles of +15°, +30°, and +45° to convert it into four sets of three phases as shown in Fig. 3a. The auxiliary phases generated, $U_{ABC(1)}$, $U_{ABC(2)}$, and $U_{ABC(3)}$ have equal magnitudes as that of primary $U_{ABC}$. The connection diagram of this rectification system is depicted in Fig. 3b where input power is supplied by the three-phase system $U_{ABC}$, which is further converted into four sets of 3-phase supply.

III. VOLTAGE AND CURRENT EVALUATION

A. Conventional 24-Pulse ATRU

The circuit diagram shown in Fig. 4a depicts a 24-pulse rectification system where the main component is
autotransformer. In Fig. 4b, all the \( K \) terms are representing the winding ratios relative to the primary winding, which is taken as unity. The values of the winding ratios are calculated in the figure using the vector resolution method. The primary set of voltages \( U_{ABC} \) is not directly connected to any of the rectifiers but is utilized in generating the phase shifted voltages. These generated voltages \( U_{ABC(1)}, U_{ABC(2)}, U_{ABC(3)} \) and \( U_{ABC(4)} \) feeds the four, three-phase bridge rectifier \( B_1, B_2, B_3, \) and \( B_4, \) connected in parallel through zero sequence blocking transformers (ZSBT). Here each bridge rectifier carries \( 1/4 \) of the load power. These ZSBTs are responsible for eliminating the inherent impedance mismatch and maintaining equal current conduction in all the rectifiers so that to suppress harmonics and obtain 24-pulse output dc voltage. However, this adds to the volume, weight, cost, and complexity of the design but the lower THD values and reduced ripples in output dc voltage makes it more attractive for applications with stringent power quality requirements. The auxiliary voltage, \( U_{dc} \) is generated by taking \( K_3 \) times \( A_1 \) with \( K_1 \) times \( C \) and \( K_2 \) times \( A_3 \) with \( K_4 \) times \( C \) respectively.

Taking the input line voltages as unity per unit (p.u) and considering the input phase voltage \( U_a \) at 0°, the winding ratios \( K_1, K_2, K_3, \) and \( K_4 \) can be derived using relations:

\[
\begin{align*}
U_{a1} &= K_1U_a - K_1U_C, U_{a2} = K_4U_a - K_4U_C \\
U_{a3} &= K_3U_a - K_3U_B, U_{a4} = K_4U_a - K_4U_B
\end{align*}
\]  

(1)

Solving by simple manipulation, the above equations for the unknowns \( K_1, K_2, K_3, \) and \( K_4 \) yields 0.151, 0.443, 0.916, and 0.703 respectively.

Representing the peak magnitude of the input phase voltage to the rectifier by \( U_{pk} \), and DC and RMS values of the output load voltage and current by \( U_{dc}, I_{dc}, U_{rms}, \) and \( I_{rms} \) respectively, the average load voltage is calculated from voltage waveforms in Fig. 4c as:

\[
\begin{align*}
U_{dc} &= \frac{12}{\pi} \int_0^{2\pi/3} U_{pk} \sin(\omega t) d(\omega t) \\
&= \frac{12}{\pi} U_{pk} \times \left[ \frac{\cos(\frac{\omega t}{2}) - \cos(\frac{\omega t}{3})}{\frac{\omega t}{2}} \right] \\
&= 1.71 U_{pk}
\end{align*}
\]  

(2)

Rectification ratio (R.R) is given by

\[
\sigma = \frac{U_{dc}}{U_{rms}} \text{ where}
\]  

\[
\begin{align*}
U_{rms} &= \frac{12}{\pi} \int_0^{2\pi/3} (U_{pk} \sin(\omega t))^2 d(\omega t) = 1.71 U_{pk} \\
I_{dc} &= \frac{U_{dc}}{\eta_{load}} = \frac{1.71 U_{pk}}{\eta_{load}} \times \eta_{load}
\end{align*}
\]  

(3)

Hence R.R = \( \sigma = 1 \).

Form Factor = \( F.F = \frac{U_{rms}}{U_{dc}} = \frac{1.71 U_{pk}}{1.71 U_{pk}} = 1 \)

(4)

Ripple factor = \( \frac{U_{rms} - U_{dc}}{U_{dc}} = 1 - 1 = 0 \)

(5)

Power Factor = \( \frac{U_{rms} \cos(\omega t)}{I_{rms}} = 0.991 \)

(6)

The total transformer power capacity (\( C_T \)) is expressed as:

Total kVA in \( K1 = 6 \times K1 \times U_{(L-N)out} \times I_{a1} \) 
Total kVA in \( K2 = 6 \times K2 \times U_{(L-N)out} \times I_{a2} \) 
Total kVA in \( K3 - K4 = 3 \times (K3 - K4) \times U_{(L-N)out} \times I_{a3} \) 
Total kVA in \( K4 = 3 \times K4 \times U_{(L-N)out} \times I_{a4} \) 
Total kVA in \( K5 = 3 \times K5 \times U_{(L-N)out} \times I_{a5} \)

(8)

Hence total transformer capacity is

\[
C_T = (6K_1U_{(L-N)out}I_{a1} + 6K_2U_{(L-N)out}I_{a2} + 3(K_3 - K_4)U_{(L-N)out}I_{a3} + 3K_4U_{(L-N)out}I_{a4}) + 3(K_1U_{(L-N)out}I_{a5})/2
\]  

(9)

The effectiveness of the autotransformer topology is indicated by the relative power term which is autotransformer equivalent power capacity (\( C_{eq} \)). It is the relative power term for the autotransformer power capacity with respect to the DC load power. The lower values of this term indicate, the better topologies.

\[
C_{eq} = \frac{C_T}{U_{dc}I_{dc}}
\]  

(10)

**FIGURE 4.** (a) Circuit diagram; (b) Voltage phasor diagram; (c) Rectifier input voltages and currents waveforms.
B. New 24-Pulse ATRU

The circuit diagram shown in Fig. 5a depicts a 24-pulse rectification system where Fig. 5b presents the autotransformer windings’ interconnections. All the K terms are representing the winding ratios relative to the primary winding, which is taken as unity. The values of the winding ratios are calculated from the figure using the vector resolution method. The additionally generated voltages \( U_{ABC(1)} \), \( U_{ABC(2)} \), and \( U_{ABC(3)} \) feeds the auxiliary bridge rectifiers B\(_1\), B\(_2\), and B\(_3\) while the primary bridge B\(_P\) is connected directly to the input supply. These generated voltages \( U_{ABC(1)} \), \( U_{ABC(2)} \), and \( U_{ABC(3)} \) along with the primary supply voltages \( U_{ABC} \) feeds the four 3-phase bridge rectifiers B\(_P\), B\(_1\), B\(_2\), and B\(_3\), which are connected in parallel through zero sequence blocking transformers (ZSBT), and each bridge rectifier carries 1/4\(^{th}\) of the load power. The ZSBTs in this topology serve the same purpose as that in the previously discussed topology. All the auxiliary voltages are generated by adequately tapping the autotransformer windings’ interconnections. All the other voltages are generated in this rectification system, each diode in all the bridge rectifiers conducts current for 15° altogether and 7.5° with another diode individually.

Taking the input line voltages as unity per unit (p.u) and considering the input phase voltage \( U_i \) at 0°, the winding ratios \( K_1 \), \( K_2 \), \( K_3 \), and \( K_4 \) can be derived using relations:

\[
\begin{align*}
U_{A1} &= K_4 U_A - K_4 U_B, \quad U_{A2} = K_4 U_A - K_2 U_B, \\
U_{A3} &= K_6 U_A - K_2 U_B
\end{align*}
\]

Solving by simple manipulation, the above equations for the unknowns \( K_1, K_2, K_3, K_4 \) and \( K_6 \) yields 0.3, 0.57, 0.815, 0.815, 0.59, and 0.3 respectively.

Representing the peak magnitude of the input phase voltage to the rectifier by \( \bar{U}_{pk} \), DC and RMS values of the output load voltage and current by \( U_{dc}, I_{dc}, U_{rms}, \) and \( I_{rms} \) respectively, the average load voltage is calculated from voltage waveforms in Fig 5c as:

\[
U_{dc} = \frac{24}{2\pi} \left( \frac{13\pi}{24} \sqrt{3} \bar{U}_{pk} \sin(\omega t) \right) d(\omega t) = \frac{127}{8} \bar{U}_{pk}
\]

Rectification ratio (R.R) is given by

\[
\sigma = \frac{U_{dc}}{U_{rms}} \quad \text{where} \quad U_{rms} = \sqrt{\frac{\sum d^{rms2}}{I_{rms}}}
\]

Hence R.R = \( \sigma = 1 \). For six-pulse basic rectifier under highly inductive load condition, the original side of the supply current pulse width is considered 120° square wave, which is calculated by Fourier series.

\[
I_A = \frac{2\pi}{\pi} i_{A1} \left( \sin(\omega t) - \frac{1}{2} \sin 5\omega t + \frac{1}{7} \sin 7\omega t + \frac{1}{11} \sin 11\omega t + \ldots \right)
\]

Every branch current is fed as the rectifier input. The input current of every branch has the same period and amplitude as compared to the rectifier input current \( I_A \), but with phase differences. The Fourier formula for new 24-pulse rectifier could be deduced similarly to that of the 6-pulse rectifier in the above equation. Considering phase A, for instance, one of the branches \( I_{A1} \) advance \( I_A \) phase current by 15° i-e

\[
I_A = \sum b_j \sin j(\pi t + \phi) = \sum_{j=1,3,5} \left( \frac{24}{\pi} \cos \frac{j\pi}{6} \right) \sin j(\omega t) \quad (19)
\]

\[
I_{A1} = \sum b_j \sin j(\pi t + \phi) = \sum_{j=1,3,5} \left( \frac{24}{\pi} \cos \frac{j\pi}{6} \right) \sin j(\omega t + \frac{\pi}{12}) \quad (20)
\]

Where \( I_{A1} \) is the 6-pulse rectifier output current. Similarly, \( I_{A2} \) is the 6-pulse rectifier output current. Similarly,

\[
I_{A2} = \sum_{j=1,3,5} \left( \frac{24}{\pi} \cos \frac{j\pi}{6} \right) \sin j(\omega t + \frac{\pi}{6}) \quad (21)
\]

\[
I_{A3} = \sum_{j=1,3,5} \left( \frac{24}{\pi} \cos \frac{j\pi}{6} \right) \sin j(\omega t + \frac{\pi}{3}) \quad (22)
\]

Moreover, the vice side currents are:

FIGURE 5. (a) Circuit diagram; (b) Voltage phasor diagram; (c) Rectifier input voltages and currents waveforms.
The currents in each phase of the network side are the combination of the corresponding vice side vectors and the main branch currents. The main branch currents $I_{AX}$ and vice side currents $I_{Cout}$ are derived using Fig. 6 (a, b, c, d, e, f) as:

\[
I_{B1} = \sum_{j=1,3,5} \left( \frac{4U_{P}}{j} \sin \left( \frac{\omega t - \frac{3\pi}{4}}{6} \right) \cos \left( \frac{\omega t}{6} \right) \right)
\]

(23)

\[
I_{B2} = \sum_{j=1,3,5} \left( \frac{4U_{P}}{j} \sin \left( \frac{\omega t - \frac{\pi}{4}}{6} \right) \cos \left( \frac{\omega t}{6} \right) \right)
\]

(24)

\[
I_{B3} = \sum_{j=1,3,5} \left( \frac{4U_{P}}{j} \sin \left( \frac{\omega t - \frac{9\pi}{4}}{6} \right) \cos \left( \frac{\omega t}{6} \right) \right)
\]

(25)

The currents in each phase of the network side are the combination of the corresponding vice side vectors and the main branch currents. The main branch currents $I_{AX}$ and vice side currents $I_{Cout}$ are derived using Fig. 6 (a, b, c, d, e, f) as:

\[
I_{Cout} = (U_{C2}\cos(45\cdot K_4), K_5, K_6) = (I_{C2}\cos(30\cdot K_4), K_5, I_{Cout} = (I_{C1}\cos(15\cdot K_4), K_5, I_{Cout} = (I_{C1}\cos(15\cdot K_4), K_5)
\]

(26)

Similarly, the output vice sides currents can be calculated as:

\[
I_{Cout} = (U_{C1}\cos(45\cdot K_4), K_5, K_6) = (I_{C2}\cos(30\cdot K_4), K_5, I_{Cout} = (I_{C1}\cos(15\cdot K_4), K_5, I_{Cout} = (I_{C1}\cos(15\cdot K_4), K_5)
\]

(27)

The total transformer power capacity ($C_T$) is expressed as:

\[
\begin{align*}
\text{Total kVA in } K1 &= 3 \times K_1 \times U_{(L-N)out} \times I_{A1} \\
\text{Total kVA in } K2 &= 3 \times K_2 \times U_{(L-N)out} \times I_{A2} \\
\text{Total kVA in } K3 &= 3 \times K_3 \times U_{(L-N)out} \times I_{A3} \\
\text{Total kVA in } K4 &= 3 \times (K_4 - K_5) \times U_{(L-N)out} \times \frac{I_{(K4-K5)A}}{L} \\
\text{Total kVA in } K5 &= 3 \times K_5 \times U_{(L-N)out} \times I_{K6A} \\
\text{Total kVA in } K6 &= 3 \times K_6 \times U_{(L-N)out} \times I_{K7A} \\
\text{Total kVA in } K7 &= 3 \times K_7 \times U_{(L-N)out} \times I_{K7A}
\end{align*}
\]

(28)

Hence the total transformer capacity is

\[
C_T = (3K_1U_{(L-N)out}I_{A1} + 3K_2U_{(L-N)out}I_{A2} + 3K_3U_{(L-N)out}I_{A3} + 3(K_4 - K_5)U_{(L-N)out}I_{(K4-K5)A} + 3(K_5 - K_6)U_{(L-N)out}I_{K6A} + 3(1 - K_6)U_{(L-N)out}I_{K7A})/2
\]

(29)

Moreover, the total transformer equivalent power capacity ($C_{eq}$) is calculated as:

\[
C_{eq} = \frac{C_T}{U_{dc}^{2}dc}
\]

(30)

IV. SIMULATION AND EXPERIMENT RESULTS

Simulation and experimental results of both the 24-pulse ATRUs are discussed in this section. The detailed models for both the rectification systems, with the circuit parameters given in Table I, were simulated in the MATLAB / Simulink environment using ode23tb (stiff/TR-BDF2) solver. The experimental setup for the novel 24-pulse rectification system is shown in Fig. 7 with all devices duly labeled. Experimental validation was carried out by developing their prototypes of 2kW using core materials of SD $32 \times 32 \times 100$ (0.1 m/m) (I). Operating frequency and the optimal flux density ($B_{01}$) of these core materials are 400 Hz and 0.971 Tesla respectively. Adjusting the number of windings per core leg such that the optimum current density ($J_0$) is set to the optimum of 270 A/cm². Results were measured using a data-acquisition system Gen7 from HBM, which were exported to MATLAB in CSV format for reconstruction.

FIGURE 6. Main branch currents and vice side currents vectors

The main branch currents $I_{AX}$ and vice side currents $I_{Cout}$ are derived as:

FIGURE 7. Experimental setup
Simulation and experimental results for formerly available 24-pulse ATRU are shown in Fig. 8 (a, b, c, d, e, f, g, h) while those of the newly developed 24-pulse ATRU are shown in Fig. 9 (a, b, c, d, e, f, g, h) respectively. For the sake of clarity, values of currents are drawn against the y-axis to the right of Figures. Total harmonic distortion (THD) of both the rectification systems were measured from the input line current of simulation as well as experimental setup, which are given in Table II along with their characteristics and non-characteristics odd harmonics. Since the waveform of input line current \( (I_L) \) does not have any DC component, and exhibits mirrored symmetry about the axis, therefore, the DC component and the even coefficients in the Fourier series representation are zero i.e even harmonics are zero. To make the comparison more accessible, the limits of harmonics set by IEEE-519 are also mentioned against each harmonic number.

### TABLE I

Circuit Parameters For The Two Rectification Systems

<table>
<thead>
<tr>
<th>ATRU</th>
<th>( U_{in} ) (RMS)</th>
<th>( C_{T, eq} )</th>
<th>( L_{dc} ) (mH)</th>
<th>( R_{dc} ) (Ω)</th>
<th>( K_1 )</th>
<th>( K_2 )</th>
<th>( K_3 )</th>
<th>( K_4 )</th>
<th>( K_5 )</th>
<th>( K_6 )</th>
<th>Phase Shift Angle</th>
<th>( U_{dc} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Old 24-pulse</td>
<td>115</td>
<td>0.68</td>
<td>4.37</td>
<td>1</td>
<td>30</td>
<td>0.151</td>
<td>0.443</td>
<td>0.916</td>
<td>0.703</td>
<td>N.A</td>
<td>N.A</td>
<td>±7.5° &amp; ±22.5°</td>
</tr>
<tr>
<td>New 24-pulse</td>
<td>115</td>
<td>0.75</td>
<td>4.37</td>
<td>1</td>
<td>30</td>
<td>0.3</td>
<td>0.57</td>
<td>0.815</td>
<td>0.815</td>
<td>0.59</td>
<td>0.3</td>
<td>+15°, +30°, +45°</td>
</tr>
</tbody>
</table>

### A. Conventional 24-Pulse ATRU

The phase shift of the auxiliary voltages from primary voltages by the angles of ±7.5° and ±22.5° having equal magnitudes as those of the primary makes the current conduction in each diode for a period of 15° as a whole. Every diode conducts for 7.5° with other diode and then the current is commutated to another diode which conducts current for the remaining 7.5° with the diode 1 as shown in (simulation) Fig. 8e and (experimental) Fig. 8f. Load voltages in Fig. 8a and 8b show a 3.38 % increase in comparison to the 6-pulse rectifier. Since this increase will account for voltage drops in lines, therefore, it is acceptable. As mentioned in Table II, the rectification ratio and ripple factor of the load voltage are approximately 1 and 0 respectively. Consequently, very small ripples are witnessed in load voltage and current waveforms. The slight phase difference of input line current with that of the input line voltage in Fig. 8c and 8d deteriorate the power factor to 0.991, but it is negligible. Input line current waveform depicts 24 steps in each cycle, hence proving 24-pulse rectification. However, there is small deterioration in the experimental waveform (8d) which is acceptable. Improvement in the power factor and (THD) is indicated in Fig. 8g. The THD reduces, however, power factor increases with the increase in percentage load from 10% to 100%, which is according to expectation. Similarly, the 3-D plot in Fig. 8h, presenting non-characteristic odd harmonics along with the characteristic harmonics 23rd and 25th shows a descending trend with the increase in percentage load. The THD levels from Table II (simulation = 2.31%, experimental = 2.52%) are within limits as per IEEE standards. The lower autotransformer equivalent capacity \( (C_{T, eq} = 0.68) \), THD value and acceptable load voltage level make it more desirable by the aircraft systems.
FIGURE 8. Simulation (a, c, e) and experimental (b, d, f) results of the Load voltage with current; Input line current with voltage; rectifier input currents with voltages; Power factor and THD relation with load variation (g) and 3-D plot of input harmonics (h) for old topology.

B. New 24-Pulse ATRU

The phase shift of the auxiliary voltages from primary voltages by an angle of +15°, +30° and +45° having magnitudes equivalent to the primary voltages, makes all the bridges (B_rP, B_r1, B_r2, and B_r3) conduct for equal periods. Each diode conducts current for 15° by mutual conduction of 7.5°, 7.5° with the other two diodes as shown in Fig. 9e (simulation) and Fig. 9f (experimental). Load voltage in Fig. 8a and 8b show a 3.99 % increase in comparison to a basic 6-pulse rectifier which will account for voltage drops in lines. As mentioned in Table II, rectification ratio and ripple factor of the load voltage are approximately 1 and 0 respectively, and the ripples witnessed in load voltage, and current waveforms are lower than those of the formerly available 24-pulse rectification hence, dominating regarding power quality. The phase difference of the input line current in Fig. 9c and 9d with that of the input line are almost negligible and the power factor therefore calculated is 0.9973. The 24 steps in one cycle of the input line current waveform depict 24-pulse rectification. With the increase in the percentage load from 10% to 100% in Fig. 9g, the power factor of the rectification system improves while THD reduces according to expectation. The presented 3-D plot in Fig. 9h shows a descending trend with the increase in percentage load for non-characteristic odd harmonics along with the characteristic harmonics 23rd and 25th. From Table II, the THD levels (simulation = 1.78 %, experimental = 2.1%) are within limits as per IEEE standards. Reduction in transformer equivalent power capacity (C_T, eq = 0.78), THD value and acceptable load voltage level make it more desirable by the aircraft systems.
FIGURE 9. Simulation (a, c, e) and experimental (b, d, f) results of the Load voltage with current; Input line current with voltage; rectifier input currents with voltages; Power factor and THD relation with load variation (g) and 3-D plot of input harmonics (h) of new topology.
TABLE II
SHOWING TOTAL HARMONIC DISTORTION (THD), RECTIFICATION RATIO (RR), RIPPLE FACTOR (RF) AND POWER FACTOR

<table>
<thead>
<tr>
<th>Harmonic No.</th>
<th>(I_s) (Input) (simulation)</th>
<th>(I_s) (Input) (experiment)</th>
<th>(V_{L-N})</th>
<th>(I_s) (Input) (simulation)</th>
<th>(I_s) (Input) (experiment)</th>
<th>(V_{L-N})</th>
<th>Limits for current</th>
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<td>1</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>-</td>
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<tr>
<td>3</td>
<td>0.91</td>
<td>0.93</td>
<td>0.01</td>
<td>0.81</td>
<td>0.92</td>
<td>0.00</td>
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<tr>
<td>5</td>
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<td>0.77</td>
<td>0.00</td>
<td>0.74</td>
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<td>0.00</td>
<td>0.45</td>
<td>0.40</td>
<td>0.00</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
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<td>0.11</td>
<td>0.00</td>
<td>0.02</td>
<td>0.01</td>
<td>0.00</td>
<td>1.11</td>
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<tr>
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<td>0.00</td>
<td>0.01</td>
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<tr>
<td>23</td>
<td>0.96</td>
<td>1.02</td>
<td>0.03</td>
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<td>0.02</td>
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<td>0.91</td>
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<td>0.59</td>
<td>0.7</td>
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VI. CONCLUSION
These power converters are considered as highly-reliable since they do not consist of many interconnected devices, which may lead to earlier failure of the system. The only devices involved are an autotransformer and three-phase rectifiers whose reliability is already high. Secondly, the reduced equivalent power capacities of these autotransformers make them capable of feeding higher power loads hence the overall cost, and the sizes of the systems are reduced. Both rectification systems discussed here are suitable for applications where high-power quality along with reliability, reduced size, weight, and cost are required such as aircraft systems. The harmonic levels are within limits specified by IEEE 519 (1992). Moreover, both topologies require the use of ZSBT, but their harmonic level of the input line current, DC link voltage ripples and the power factor are much lower. The former autotransformer topology based rectification system offer 32% decrease in kVA ratings, however, the novel autotransformer based rectification system offer 24% decrease in the kVA rating as compared to the double wound transformer based rectification system. This helps in system cost and size reduction by the same ratio. The equivalent autotransformer capacity of the formerly available topology is lower by the difference of 0.07 than that of the proposed topology, however, the comparison regarding power quality, reduction in complexity level and the number of windings per transformer core limbs to favor the newly introduced 24-rectification system.

REFERENCES


