Comparative Analysis of 18-Pulse Autotransformer Rectifier Unit Topologies with Intrinsic Harmonic Current Cancellation

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Abstract: With the evolution of the More Electric Aircraft (MEA) concept, high pulse converters have gained the attention of researchers due to their higher power quality. Among the high pulse converters, 18-pulse autotransformer rectifier unit (ATRU) offers better power quality level with small size, weight and medium complexity. The conventional topologies of autotransformers that require the use of extra elements such as Inter Phase Transformers (IPT) or Zero Sequence Blocking Transformers (ZSBT), adding to the complexity, weight and size of the overall system, are not considered in the analysis. For 18-pulse rectification, only those topologies of autotransformers which have the intrinsic current harmonic cancellation capabilities are presented here for comparison. These topologies offer current harmonic levels within limits specified by IEEE 519 with reduced weight and size as compared to the conventional multi-pulse converters. A comparison of different differential delta/fork configured 18-pulse autotransformer rectifier units is presented so as to come up with the best among available topologies with respect to weight, size and power quality. Experimental prototypes of each topology were designed and their results are displayed along with the simulation results for comparison.

Keywords: inter phase transformers (IPT); power quality; zero sequence blocking transformers; 18-pulse converters; autotransformers rectifier unit (ATRU)

1. Introduction

Power electronic converters have gained the attention of engineers due to their excessive use in electronic systems such as low-power computer systems, industrial machines and household appliances [1]. The demand for power converters has increased in a wide range of applications such as vehicular power systems, distributed generation, variable frequency drives, communication systems, renewable energy generations, photovoltaic systems, fuel cells and especially aircraft [2–4]. In aircraft, the concept of utilizing electrical systems instead of pneumatic and hydraulic systems is known as the “More Electric Aircraft (MEA)”. Variable speed electrical drives with associated power electronic converters are likely to be used for driving the main pumps designated for fuel and lubrication in the MEA approach [5–10]. Apart from advantages offered by the MEA concept, there are several issues that needs to be addressed such as interaction between source and loads due to an increase in power electronic loads, instability, and the generation of low-order current harmonics on the AC supply side.
Engineers have focused their attention on developing new control techniques and efficient power converters for obtaining high reliability and performance and to meet the IEEE-prescribed standards in power quality [11]. For low ripple output voltage and smaller total harmonic distortion (THD) at input supply current, multi-pulse AC/DC converters have proved to be the best since they rarely pollute the AC supply sources. By maintaining low total harmonic distortion (THD) at the AC side these converters consume less power comparatively. Power converters interfere with the existing power system through electromagnetic interference when active harmonic filtering techniques are used while in the case of passive harmonic filtering techniques, they interfere due to possible resonance with capacitive filters. Luckily, multi-pulse converters do not use high-frequency switching or capacitive filtering which may cause these problems. In multi-pulse converters, the idea of filtering relies on intrinsic cancellation of current harmonics rather than flux cancellation method and results in lower overall harmonics [12]. The idea of multi-pulse operation was developed by connecting two or more basic 6-pulse rectifiers (depending upon the number of phases generated by autotransformer) in parallel through IPT or directly to attain multi-pulse rectification system [13]. Improvement in performance is achieved by increasing the number of phases generated by autotransformers since input current harmonics introduced in multi-pulse converters have orders of $6mx \pm 1$ with amplitudes $1/(6mx \pm 1)$, where $x$ is the number of 3-phase rectifiers connected in parallel and $m$ is any positive integer [14–18]. However, the practical values of these harmonics are greater than the above mentioned mathematical calculations. This means 18-pulse ATRUs will have their characteristic current harmonics i.e., 17th and 19th with much smaller amplitudes and produce very little distortion, as compared to 6-pulse and 12-pulse converters, at the input supply. The general circuit diagram for multi-pulse rectifier system is shown in Figure 1 where IPT is an optional component, depending upon the type of auto transformer configuration used i.e., some configurations require its use while others have the intrinsic property of current balancing through rectifiers. All four topologies, symmetric differential delta, symmetric differential T-delta, asymmetric differential delta and step down differential fork, discussed here do not require any extra elements for filtering purposes and therefore small sizes and weights along with reduced equivalent power capacity.

### Figure 1. General circuit diagram for multi-pulse converters.

Comparison of the available 6-, 12- and 18-pulse power converters is given in Table 1 which shows that the 6-pulse and 12-pulse techniques are insufficient to meet the current distortion levels recommended in IEEE 519 (1992) for many large-power installations [19]. Among the contemporary available solutions are inter-phase transformers (IPT) or zero sequence blocking transformers (ZSBT) to reduce the non-characteristics’ low-order current harmonics at the AC supply side but these tools not only add to the cost of the overall system but are also heavy and bulky. To achieve superior harmonic performance, 18-pulse or higher-power conversion systems must be applied. Since the design of 24-pulse and higher-power converters are cumbersome and the labor involved plus complexity of the windings are daunting, 18-pulse auto-transformers are considered as the optimum

| Harmonic Order | 6-Pulse | 12-Pulse | 18-Pulse |
|----------------|---------|----------|----------|
| 5th            | -       | -        | -        |
| 7th            | -       | -        | -        |
| 11th           | -       | -        | -        |
| 13th           | -       | -        | -        |
| 17th           | -       | -        | -        |
| 19th           | -       | -        | -        |
| 23rd           | -       | -        | -        |
| 25th           | -       | -        | -        |
| 29th           | -       | -        | -        |
| 31st           | -       | -        | -        |
| 37th           | -       | -        | -        |
| 39th           | -       | -        | -        |
| 41st           | -       | -        | -        |
solution. A comparison of different differential delta/fork-configured 18-pulse autotransformer rectifier units is done to come up with the best among available topologies with respect to weight, size and power quality.

Table 1. Characteristic harmonics offered by different multi-pulse rectifiers.

| Characteristic Harmonics | 6-Pulse | 12-Pulse | 18-Pulse |
|--------------------------|---------|----------|----------|
| 5th                      | -       | -        | -        |
| 7th                      | -       | -        | -        |
| 11th                     | 11th    | -        | -        |
| 13th                     | 13th    | -        | -        |
| 17th                     | -       | -        | 17th     |
| 19th                     | -       | -        | 19th     |
| 23rd                     | 23rd    | -        | -        |
| 25th                     | 25th    | -        | -        |
| 29th                     | -       | -        | -        |
| 31st                     | -       | -        | -        |
| 35th                     | 35th    | -        | -        |
| 37th                     | 37th    | -        | 37th     |

The rest of the paper is organized as follows: Section 2 of the manuscript explains the 18-pulse rectifiers with different auto transformer configurations. Section 3 presents the analysis of the aforementioned topologies. Section 4 discusses the simulations and experimental results of the ATRUs discussed and Section 5 concludes the manuscript.

2. 18-Pulse ATRU Topologies

The 18-pulse operation requires three sets of three-phase AC supply with one set in phase with the primary voltage while others being shifted by calculated angles to meet the required results. Traditionally, this was achieved by using an isolated transformer which phase shifts two of the secondary voltages by specified angles and keep one of the secondary in phase with the primary. This, however, was not an appropriate solution since it was costlier, heavier and bulky. Instead, an autotransformer system was introduced which offers a small-size, low-weight and low-cost solution. In this paper, only those auto transformer configurations are compared which do not require the use of extra elements such as IPT or ZSBT, hence much smaller sizes and weights along with the benefits of reduced equivalent power capacity. Below mentioned are the different topologies of 18-pulse auto transformers.

2.1. Scheme A: Symmetric 18-Pulse Differential Delta

In symmetric differential delta configuration, autotransformer splits the balanced three-phase AC supply into nine phases such that each supply phase is shifted by ±40°. These nine phases can also be regarded as three sets of three phases which are capable of supplying three parallel connected 6-pulse rectifier bridges to feed the DC load. In this configuration, each diode conducts current for 40° individually while each pair of diodes conducts current for 20°. The diagram in Figure 2b shows the current conduction sequence of diode bridge rectifiers where line to line voltage appears across each diode. Supply voltage $U_{ABC0}$ and the secondary voltages sets $U_{ABC1}$ and $U_{ABC2}$ forms total nine phases where diode connected with phase $A_0$ will conduct for 20° along with diode connected to phase $C_1$ and then for 20° with diode connected to phase $B_1$. If carefully designed with proper windings, there is no current imbalance problem among diode bridges therefore it does not require the use of IPT or ZSBT. Each bridge will contribute to equal power flow, i.e., one third of the total power which is shown in per unit form in Figure 2a.
2.2. Scheme B: Symmetrical 18-Pulse Differential T-Delta

Very similar in function to the symmetric differential delta configuration, differential T-Delta configured autotransformer offers the same services. To obtain nine phases from available three-phase supply, the configuration shown in Figure 3a is used. Each diode conducts load current for 40° individually by mutually conducting current for 20° each with other two diodes. The current conduction sequence as shown in Figure 3b is the same as that of scheme A.

2.3. Scheme C: Asymmetric 18-Pulse Differential Delta

In scheme A and B discussed above, the power flow through each bridge is one third of the total power, however this technique can be modified in a way such that two thirds of the total power flows through the primary voltages $U_{ABCD}$ while remaining one third of the power flows through the autotransformer, resulting in reduced winding losses and kVA capacity of the transformer [20]. In this case, the amplitude and phase of secondary voltages are adjusted so that the secondary voltages $U_{ABC1}$ and $U_{ABC2}$ interact continuously with the primary bridge on a line-to-line basis. The connection diagram and phasor diagram of this scheme are depicted in Figure 4a,b where secondary voltages are stepped down to 0.767 relative per unit amplitudes with phase-shifts of ±37°. Considering the resultant line voltages applied to the DC terminals of the rectifiers, the primary bridge will always be involved in conduction with the secondary bridges.

![Figure 2](image1.png)

**(a)** Differential delta configured symmetric 18 pulse autotransformer; **(b)** Phasor diagram.

![Figure 3](image2.png)

**(a)** Differential T-Delta configured autotransformer; **(b)** Conduction sequence.

![Figure 4](image3.png)

**Figure 3.** (a) Differential T-Delta configured autotransformer; (b) Conduction sequence.
3. Voltages and Currents Analysis

This section discusses the derivation of voltage and current equations along with the transformer power capacities. Due to difference in autotransformer topologies, every rectification system has its own equivalent power capacities and DC voltage/current levels. The required DC voltage level in aircraft is 270 V therefore it is recommended to implement such a topology that offers the output voltage somewhere near this value. Below are the voltages and currents analysis of the topologies discussed here.
3.1. Scheme A

Circuit diagram of scheme A is shown below in Figure 6a where all the three bridges (B₀, B₁ and B₂) are responsible for equal power flow i-e 1/3rd of the total power flow while the voltage phasor diagram is shown in Figure 6b. Assuming the input line voltages to be unity, the voltage ratios \( K₁, K₂ \) and \( K₃ \) are derived using sine rule for general triangles as:

\[
\begin{align*}
\frac{K₁}{\sin(40°)} & = \frac{K₂}{\sin(20°)} = \frac{K₃}{\sin(120°)} = \sqrt{3} \times \sin(120°) \times \sin(70°) \\
\text{and } K₃ &= 1 - 2K₂
\end{align*}
\]

(1)

![Circuit diagram of scheme A](image)

**Figure 6.** (a) Circuit diagram of scheme an autotransformer rectifier unit (ATRU); (b) Voltage phasor diagram.

Solving for the unknowns, we get \( K₁ = 0.293, K₂ = 0.156 \) and \( K₃ = 0.688 \).

Since the output voltage changes after every 40° hence \( U_{dc} \) is calculated by integrating the output voltage of auto transformer for 40°. Let \( U_{LL} \) and \( U_{∅} \) be the rms magnitudes of the line to line and phase voltages respectively feeding auto transformer and \( U_{L,Out} \) be the output voltage of auto transformer, then, load voltage is calculated as:

\[
U_{dc} = \frac{9}{\pi} \times \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \hat{U}_{L,Out} \cos(\omega t) d(\omega t) = \frac{18}{\pi} \times \hat{U}_{L,Out} \times \sin\left(\frac{\pi}{3}\right) = 1.9596 \times \hat{U}_{L,Out}
\]

(2)

where \( \hat{U}_{L,Out} \) is the peak value of \( U_{L,Out} \) and is equal to \( U_{∅} \), hence

\[
U_{dc} = 1.9596 \times \sqrt{2} \times U_{∅} = 2.77 \times U_{∅} = 1.6 \times U_{LL}
\]

(3)

\( U_{dc} \) is 18% higher than that of conventional 6-pulse converter.

For currents, Figure 2a can be used to find out all branch currents of phases A₀, B₀ and C₀ using Kirchhoff’s current law and ampere turns equations discussed but for the sake of simplicity, only \( I_{A₁}, I_{A₁K₂} \) and \( I_{A₀K₃} \) are given in Equations (4)–(6).

\[
I_{A₀K₃} = \frac{\sqrt{2}}{3} \frac{I_{dc}}{3} \sqrt{(K₁ + K₂)^2 + K₁^2 + K₂^2}
\]

(4)

\[
I_{A₁K₂} = \frac{I_{dc}}{3} \sqrt{(1 + K₁ - K₂)^2 + 2K₁^2 + (K₁ - K₂)^2 + K₂^2 + (1 - K₂)^2}
\]

(5)
Rest of the branch currents can be found using the same procedure. Transformer total capacity ($C_T$) is given by the summation of voltage-current products in all windings:

$$C_T = 6 K_1 U_{LL} I_{A_1} + 6 K_1 U_{LL} I_{K2A_1} + 3 K_3 U_{LL} I_{K3A_0}$$  \(7\)

And the equivalent capacity ($C_{T,eq}$) is given by

$$C_{T,eq} = \frac{1}{2} \frac{C_T}{U_{DC} I_{dc}}$$  \(8\)

### 3.2. Scheme B

Circuit diagram for scheme B ATRU is shown in Figure 7a where the power flow through bridges is the same as that of scheme A. From the phasor diagram in Figure 7b, using geometrical solution, taking the phase voltage as unity p.u., winding voltages for $K_1$ and $K_2$ can be derived i.e., $K_1 = 0.293$ and $K_2 = 0.156$.

$$U_{LL}$$ is defined as the magnitude of the supply line voltage to the autotransformer, $U_{LLout}$ as the magnitude of the output line voltage feeding the rectifiers, and $U_\phi$ as the magnitude of both the output and input phase voltages of the autotransformer. From the phasor diagram of Figure 7b, the instantaneous output voltage can be obtained as the projection of the highest value of the line voltage vectors $U_{LLout}$ over a fixed reference axis, e.g., the positive real axis. Thus, the voltage ripples in the output DC has a frequency of eighteen times the supply frequency. The output line voltage of the autotransformer, $U_{LLout}$ can be derived from basic trigonometric relationships as:

$$U_{LLout} = \frac{\sin(160^\circ)}{\sin(10^\circ)} U_\phi = 1.97 U_\phi$$  \(9\)
Consequently, the mean value of the output voltage is:

\[
U_{dc} = \frac{9}{\pi} \times \int_{-\pi/18}^{\pi/18} \hat{U}_{LL,out} \cos(\omega t) d(\omega t) = 0.995 \times \hat{U}_{LL,out}
\]  

(10)

where \(\hat{U}_{LL,out}\) is the peak value of \(U_{LL,out}\), hence

\[
U_{dc} = 0.995 \times 1.97 \times \sqrt{2} \times U_{\varphi} = 2.77 \times U_{\varphi} = 1.6 \times U_{LL}
\]  

(11)

In an ideal case, there is no coupling between windings on different limbs so that load current is smooth, and magnetizing current is considered to be zero. To calculate the main current paths, the individual input currents are first obtained from the conduction sequence of the diodes as shown in Figure 3a,b. They are then appropriately combined by means of Kirchhoff’s current law and the natural amp-turns balance in the autotransformer. The rms value of the autotransformer currents, or rectifier inputs, is defined by:

\[
I_{A1} = \sqrt{\frac{2\pi}{\pi} \int_{0}^{2\pi} \hat{I}_{dc}^2 d\omega t = \frac{\sqrt{2}}{3} I_{dc}}
\]  

(12)

Primary winding current is given as:

\[
I_{C_{a0}} = \sqrt{\frac{(1/k_1)^2 + 2(1/k_2)^2}{1/k_2 \times 1/k_1} \times \frac{\sqrt{2}}{3} I_{dc} = 0.1729 I_{dc}}
\]  

(13)

where \(I_{dc}\) is the load current.

The angle between phases can be validated by

\[
\varphi = \tan^{-1} \left( \frac{K_2 + K_1 \cos 60^\circ}{K_2 - K_1 \sin 60^\circ} \right) = \tan^{-1} \left\{ \sqrt{3} \left( \frac{2 K_2 + K_1}{2 - 3 K_1} \right) \right\}
\]  

(14)

Similarly, the autotransformer power capacity can be calculated as the summation of the volt-amp rating of all windings divided by two i.e.,

\[
C_T = \frac{1}{2} \sum_{j=1}^{T} U_{rmsj} \times I_{rmsj}
\]  

(15)

where \(T\) is the total number of windings. Substituting Equations (13) and (14) into Equation (16) to get:

\[
C_{T,eq} = \frac{\sqrt{2} P_0 K_1 K_2}{1.6} \left\{ \frac{2 K_1 + 2 K_2 + \sqrt{K_1^2 + 2 K_2^2}}{2 K_1 K_2} \right\}
\]  

(16)

3.3. Scheme C

The nine-phase rectifier with asymmetrical autotransformer configuration is similar to that of scheme A with few modifications for reducing the autotransformer equivalent power capacity. It consists of the two auxiliary three-phase diode bridges (\(B_{r1}\) and \(B_{r2}\)) which are connected to the secondary voltages \(U_{ABC_1}\) and \(U_{ABC_2}\), while the main three-phase diode bridge (\(B_{r0}\)) is connected directly to the AC mains. As shown in Figure 8b, the resultant phasor diagram for this case, the input voltages to auxiliary bridges are phase-shifted by \(\pm 37^\circ\) having relative per unit amplitude
of 0.767. As shown in Figure 8c, in every cycle of the line voltages, the main bridge conducts for 80° interval while auxiliary bridges conducts for 20° each, resulting in 18-pulse characteristics at the DC link voltage.

**Figure 8.** (a) Circuit diagram; (b) Voltage phasor diagram; (c) Rectifier input voltages and currents waveforms.
Circuit diagram of scheme C is shown in Figure 8a while voltage phasor diagram and voltage waveforms are shown in Figure 8b,c. The input line voltages are taken as unity per unit (p.u.). The voltage ratios $K_1$, $K_2$ and $K_3$ are derived using sine rule for general triangles.

\[
\begin{align*}
K_1 & = \frac{K_2}{\sin(20^\circ)} = \frac{K_4}{\sin(120^\circ)} = \frac{\sin(20^\circ)}{\sin(120^\circ) \times \sin(80^\circ)} \\
K_3 & = 1 - 2K_2
\end{align*}
\]

(Solution)

Solving for the unknowns, $K_1 = 0.137$, $K_2 = 0.258$ and $K_3 = 0.484$.

Let $U_{LL}$ and $U_\emptyset$ be the respective rms magnitudes of the line to line and phase voltages feeding auto transformer and $U_{LLout}$ be the output voltage of auto transformer, from Figure 8c showing voltage waveforms of scheme C, load voltage is calculated as:

\[
U_{dc} = \frac{9}{\pi} \int_{\pi}^{\pi/2} (U_{C2} - U_{B0})d\omega = \frac{9}{\pi} \left[ \frac{U_1}{U_0} \sin(20^\circ) + 2 \frac{U_1}{U_0} \sin(140^\circ - \phi) \sin 10^\circ \right]
\]

(Solution)

Since $U_1 = 0.7672U_0$ and $\phi = 36.92^\circ \approx 37^\circ$ therefore

\[
U_{dc} = 1.7233 \hat{U}_{LLout} = 2.4371 U_\emptyset = 1.407 U_{LL}
\]

The root mean square (RMS) current values in windings are given by Equations (20)–(22) and these values are matching those given by the simulation results.

\[
I_{K_2A_1} = \frac{I_{dc}}{3} \sqrt{2K_1^2 + K_2^2 + (1 - K_2)^2}
\]

\[
I_{K_3A} = \frac{\sqrt{2}I_{dc}}{3} \sqrt{K_1^2 + K_2^2}
\]

\[
I_{A_1} = \frac{I_{dc}}{3}
\]

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

\[
C_T = 6K_1 U_{LL} I_{A_1} + 6K_2 U_{LL} I_{K_2A_1} + 3K_3 U_{LL} I_{K_3A}
\]

And the total transformer equivalent power capacity ($C_{T,eq}$) is defined as:

\[
C_{T,eq} = \frac{1}{2} \frac{C_T}{U_{DC} I_{dc}}
\]

3.4. Scheme D

Let $U_{LL}$ be defined as the magnitude of the autotransformer supply line voltage, $U_{LLout}$ be the magnitude of the output line voltage that feeds the rectifiers, and $U_\emptyset$ be the magnitude of both the output and input phase voltages of the autotransformer.

From Figure 9a, voltages in each winding can be calculated. Three phase power source of $U_{inf(L-N)}$ voltage, taken as unity p.u., is applied to terminals A, B and C. Winding ratio of $K_1$ is calculated as:

\[
K_1 \sin 40^\circ = \frac{U_{inf(L-N)}}{\sin 80^\circ} \quad \text{yields} \quad K_1 = 0.6527 \ U_{inf(L-N)}
\]
In a similar manner using geometry, other windings ratios may be calculated and hence windings voltages which are:
\[
\begin{align*}
U_{K_1} &= 0.6527U_{in(L-N)} \\
U_{K_2} &= 0.1206U_{in(L-N)} \\
U_{out(L-N)} &= U_{K_3} = U_{\phi} = 0.8794U_{in(L-N)} \\
U_{\text{delta}} &= U_{K_1}
\end{align*}
\]

(26)

For winding voltages, from Figure 9b, load voltage can be calculated as:
\[
U_{dc} = \frac{9}{2\pi} \times \int_{-\frac{\alpha}{\phi}}^{\frac{\beta}{\phi}} \hat{U}_{L\text{out}} \cos(\omega t) d(\omega t) = \frac{9}{\pi} \times \hat{U}_{L\text{out}} \times \sin\left(\frac{\pi}{\beta}\right) = 0.9798\hat{U}_{L\text{out}}
\]

(27)

The total DC output voltage comprises of two nine pulse midpoint converters in series so:
\[
U_{dc} = 2 \times 0.9798 \times \sqrt{2} \times U_{out(L-N)} = 2.77 \times 0.8794 \times U_{in(L-N)} = 1.407U_{in(L-N)}
\]

(28)

For current relationship, assume $K_1$ delta winding ratio to be unity p.u. while delta winding is considered to be the same as that of $K_1$. By applying Kirchhoff’s current law to the points $A$, $B$ and $C$ along with the concept of summation of ampere turns at these nodes equals zero, input current $I_{in}$, phase winding current $I_A$ and delta winding current $I_D$ can be expressed as:
\[
I_A = \frac{2K_3I_{A_0} + I_{A_2} - 2I_{B_1} - K_3I_{B_0} + I_{B_1} + I_{C_1} - K_3I_{C_0} - 2I_{C_2} + I_{A_1}}{3(K_2 + K_3)}
\]

(29)

Since $K_1$ is taken as unity p.u., $K_2$ and $K_3$ are calculated to be 1.347 and 0.185 respectively. Hence
\[
I_A = \frac{0.37I_{A_0} + I_{A_2} - 2I_{B_1} - 0.185I_{B_0} + I_{B_1} + I_{C_1} - 0.185I_{C_0} - 2I_{C_2} + I_{A_1}}{4.596}
\]

(30)

Similarly the current in delta winding and input current can be calculated by:
\[
I_D = \frac{K_3I_{A_0} - I_{A_2} - I_{B_1} + K_3I_{B_0} - I_{B_1} - I_{C_1} + K_3I_{C_0} - I_{C_2} - I_{A_1}}{3}
\]

(31)

\[
I_{in} = I_{K_3} + I_{A_2} + I_{A_1} = I_{A_0} - I_{K_2} + I_{A_2} + I_{A_1}
\]

(32)

Using simulation results of currents, branch currents were calculated as:
\[
I_{K1} = 0.471 I_{dc}, \ I_A = 0.231 I_{dc}, \ I_{K3} = 0.58 I_{dc}, \ I_D = 0.322 I_{dc}
\]

(33)
Autotransformer equivalent kVA rating is calculated as:

\[
\text{Total KVA in } K_1 = 6 \times 0.6527 \times 0.41 U_{dc} \times 0.471 I_{dc} = 0.76 U_{dc} I_{dc}
\]
\[
\text{Total KVA in } K_2 = 3 \times 0.8794 \times 0.41 U_{dc} \times 0.231 I_{dc} = 0.249 U_{dc} I_{dc}
\]
\[
\text{Total KVA in } K_3 = 3 \times 0.1206 \times 0.41 U_{dc} \times 0.58 I_{dc} = 0.086 U_{dc} I_{dc}
\]
\[
\text{Total KVA in delta} = 3 \times 0.653 \times 0.41 U_{dc} \times 0.322 I_{dc} = 0.258 U_{dc} I_{dc}
\]

\[
\text{Autotransformer equivalent KVA rating} = \frac{0.76 + 0.249 + 0.086 + 0.258}{2} = 0.6765 U_{dc} I_{dc}
\]

4. Simulation and Hardware Results

This section deals with the discussion about simulation and experimental results of all the four schemes discussed. All the four schemes were modeled in MATLAB-2015a (Simulink) (The MathWorks, Inc, Natick, MA, USA) environment keeping the same solver, ode23tb (stiff/TR-BDF2), with the circuit parameters given in Table 2. For the design of experimental prototypes, core materials of standard dimensions, SD 32 × 32 × 100 (0.1 m/m) (I) were selected having dimensions as shown in Figure 10. These core materials are developed for 400 Hz operating frequency and has the optimum flux density \(B_0\) of 0.971 Tesla. Adjusting the optimum current density \(J_0\) to 270 A/cm\(^2\), number of windings in each branch were calculated by multiplying winding ratios \((K)\) terms with 115 \(U_{rms}\) hence keeping \(V/turn\) to be equal to one. Results were measured using Agilent digital oscilloscope and were exported to MATLAB in the csv format for reconstruction. Simulation and experimental results for scheme A, B, C and D are shown by Figures 11–14 respectively. Input voltages with currents to autotransformer and load voltage with load current for these figures are depicted in the right of Figures. Total harmonic current distortion (THD) of each topology was measured from the input line current of simulation as well as experimental setup which is given in Table 3 along with their characteristics and non-characteristics odd harmonics. To make the comparison easier, limits of harmonics set by IEEE 519 are also mentioned against each harmonic number.

Table 2. Circuit parameters of schemes A, B, C and D.

| Scheme | \(U_{in}\) (RMS) | \(C_{eq}\) (uF) | \(L_{dc}\) (mH) | \(R_{dc}\) (Ω) | \(K_1\) | \(K_2\) | \(K_3\) | Phase Shift Angle | \(U_{dc}\) |
|--------|----------------|----------------|----------------|----------------|---------|---------|---------|------------------|---------|
| A      | 115            | 0.51           | 400            | 1              | 30      | 0.293   | 0.156   | 0.688           | 40°     | 1.6 \(U_{LL}\) |
| B      | 115            | 0.58           | 300            | 1              | 30      | 0.293   | 0.156   | N.A.            | 40°     | 1.6 \(U_{LL}\) |
| C      | 115            | 0.31           | 1000           | 1              | 30      | 0.137   | 0.258   | 0.484           | 36.9°   | 1.407 \(U_{LL}\) |
| D      | 115            | 0.68           | 10             | 1              | 30      | 0.653   | 0.879   | 0.1206          | 40°     | 1.407 \(U_{LL}\) |

Figure 10. Core material dimensions used for all schemes prototypes.
Figure 11. Simulation (a,c,e) and experimental (b,d,f) results of rectifier input voltages and currents; autotransformer line current; load voltage and current.

Figure 12. Cont.
Figure 12. Simulation and experimental results of rectifier input voltages and currents (a,b), autotransformer line current (c,d), load voltage and current (e,f).

Figure 13. Cont.
Figure 13. Simulation and experimental results of rectifier input voltages and currents (a,b), autotransformer line current (c,d), load voltage and current (e,f).

Figure 14. Simulation and experimental results of rectifier input voltages and currents (a,b), autotransformer line current (c,d), load voltage and current (e,f).
Table 3. Line current harmonics.

| Harmonic No. | Scheme A | Scheme B | Scheme C | Scheme D | Limits |
|--------------|----------|----------|----------|----------|--------|
|              | Sim Meas | Sim Meas | Sim Meas | Sim Meas |        |
| 1            | 100      | 100      | 100      | 100      | 100    |
| 3            | 0.29     | 0.35     | 0.18     | 0.14     | 0.18   |
| 5            | 0.26     | 0.30     | 0.14     | 0.12     | 0.12   |
| 7            | 0.20     | 0.21     | 0.18     | 0.18     | 0.18   |
| 9            | 0.03     | 0.01     | 0.06     | 0.01     | 0.01   |
| 11           | 0.21     | 0.15     | 0.05     | 0.05     | 0.05   |
| 13           | 0.07     | 0.12     | 0.14     | 0.14     | 0.14   |
| 15           | 0.15     | 0.19     | 0.16     | 0.16     | 0.16   |
| 17           | 2.95     | 3.10     | 2.85     | 2.85     | 2.85   |
| 19           | 2.13     | 2.18     | 2.09     | 2.09     | 2.09   |

THD           | 3.82     | 3.95     | 3.61     | 3.91     | 3.91   |

4.1. Scheme A

From the results showing input voltages and currents to the rectifier Figure 11a,b, separation of the auxiliary voltages from primary voltages is ±40°, having the same magnitude as that of primary, therefore each diode conducts for a period of 40° as shown in Figure 11a (simulation) and 11b (experimental). Commutation period among diodes currents is very small therefore it does not cause voltage spikes in load voltage \(U_{dc}\). The input line current (c, d) clearly depicts 18 steps in one cycle proving 18-pulse rectification. Simulation result (c) shows relatively smoother input line current since experimental (d) results accounts for the noise as well. Same goes for the load voltage and current (e, f) where experimental result (f) is more deteriorated by noise than simulation (e) however results are within close resemblance. The total harmonic distortion (THD) level of this configuration (simulation = 3.82%, experimental = 3.95%) is within limits as per IEEE standards but the higher load voltage \(U_{dc}\) level (18% high) and relatively high transformer equivalent capacity \(C_{T,eq} = 0.51\) makes it less suitable for the aircraft systems.

4.2. Scheme B

The results of this topology is not much different than scheme A since both have almost the same parameters. The separation of the auxiliary voltages from primary voltages is ±40°, having the same magnitude as that of primary, therefore each diode conducts for a period of 40° as shown in Figure 12a (simulation) and Figure 12b (experimental). Commutation period among diodes currents is very small in simulation but is a bit longer in experimental which is due to leakage inductance of the autotransformer windings. This is the reason that voltage spikes are noted in the experimental (f) values of load voltage \(U_{dc}\). The input line current (c, d) clearly depicts 18 steps in one cycle proving 18-pulse rectification however spikes are detected in experimental values (d) which is due to elongated commutation period. The load voltage and current shows deterioration due to noise as well as elongated commutation period. The total harmonic distortion (THD) level for this configuration (simulation = 3.61%, experimental = 3.91%) is also within limits as per IEEE standards but again the higher load voltage \(U_{dc}\) level (18% high) and relatively high transformer equivalent capacity \(C_{T,eq} = 0.58\) makes it less suitable for the aircraft systems.

4.3. Scheme C

The results of this topology are different since this implementation is a modification in scheme A. The separation of the auxiliary voltages from primary voltages is ±37°, having 0.767 p.u. magnitude as compared to primary (unity p.u.). Each diode in the primary bridge \(B_{p0}\) conducts for a period of 80° while that of auxiliary bridges conducts for 20° each as shown in Figure 13a (simulation) and
Figure 13b (experimental). The input line current (c, d) clearly depicts 18 steps in one cycle proving 18-pulse rectification however noise is small in experimental values (d) as compared to scheme A. The load voltage and current shows less ripples and the load voltage is only 4.2% higher than required 270 V which is acceptable and will account for voltage drops in lines. The total harmonic distortion (THD) level for this configuration (simulation = 2.27%, experimental = 3.55%) is lower than previous schemes and is within limits as per IEEE standards. The transformer equivalent capacity ($C_{T,eq}$ = 0.31), lower THD values and acceptable load voltage level makes it more suitable for the aircraft systems.

4.4. Scheme D

This topology is much different than the previous three since this topology step down the input voltage and split it into nine phases. The separation of the auxiliary voltages from primary voltages is ±40°, having 0.8794 p.u. magnitude as compared to input supply voltages (unity p.u.). Each diode in the primary bridge (B$_{p0}$) conducts for a period of 40° while that of auxiliary bridges also conducts for 40° each as shown in Figure 14a (simulation) and Figure 14b (experimental). The input line current (c, d) clearly depicts smoother 18 steps in one cycle proving 18-pulse rectification. The load voltage and current shows less ripples and the load voltage is only 4.2% higher than required 270 V which is acceptable and will account for voltage drops in lines. The total harmonic distortion (THD) level for this configuration (simulation = 3.90%, experimental = 3.98%) is within the limits as per IEEE standards. The transformer equivalent capacity ($C_{T,eq}$ = 0.68), relatively higher THD values makes it less suitable for the aircraft systems despite acceptable load voltage level.

5. Conclusions

All the schemes presented here do not require the services of extra elements such as IPT or ZSBT which would add to the size and weight of the overall system. All the schemes have the intrinsic capability of eliminating the non-characteristics low-order current harmonics through harmonic cancellation rather than flux cancellation method. Although all the schemes offer current harmonic levels within limits specified by IEEE 519 (1992), equivalent autotransformer capacity ($C_{T,eq}$) as well as load voltage level of scheme C makes it more suitable for aircraft since it has the smallest size, weight and THD values.

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