Abstract

A new pulse multiplication technique based on six-pulse thyristor converters is proposed in this paper. With the proposed technique, 12-pulse, 18-pulse, and 24-pulse operations have been obtained both on the input current and on the output voltage. A control strategy over the whole range of phase angle is provided along with sophisticated input current and output voltage analysis. Experimental results from a laboratory prototype verify the proposed theory.

Index Terms: Harmonic, multipulse, pulse multiplication, thyristor.

I. INTRODUCTION

THE six-pulse thyristor converter rated up to several thousand of horsepower has been widely used as a front-end ac-to-dc power converter for dc drives or uninterruptible power systems (UPSs). The high contents of six-pulse related input current harmonics could couple into nearby telephone circuits and cause misoperation of protective relaying and circuit breakers. To avoid such undesirable harmonic effects, tuned passive filters have been employed on the ac side of the converter. However, passive filters generate their own harmonic problems, including delayed system response following disturbances and suffer from the resonance problem with unknown system impedances. Active power filters could be a solution to these problems, but the initial cost of the equipment makes it difficult to put them into practical use, especially in high-power applications.

Multiple connection of thyristor bridges increases the pulse number of the converter and, therefore, reduces low-order harmonic contents without increasing high-order harmonics. With parallel or series connection of two bridges, the 12-pulse converter eliminates the fifth and seventh harmonics in the input current. In order to further increase the pulse number, multiple connection of bridges and the corresponding phase-shifting transformers are necessary, but this increases the cost and size of the equipment [1].

Several multipulse techniques based on parallel or series connection have been proposed [2]–[5]. A harmonic reduction technique has been proposed to utilize auxiliary thyristors connected to taps on the interphase transformer (IPT) of parallel-connected thyristor converters [2]. A dc current reinjection technique, which multiplies the pulse number and eliminates harmonics based on 12-pulse series-connected thyristor converters has been proposed for high-voltage applications such as HVdc conversion [3], [4]. The multipulse techniques based on the 12-pulse converter employ phase-shifting transformers to supply two sets of three-phase voltage displaced in phase by 30° [2]–[5] and an IPT in case of parallel connection to absorb the instantaneous voltage differences between the bridges [2]. Due to the unsymmetrical nature of the delta-wye winding of the phase-shifting transformer and phase unbalance of the two bridges, the average output voltages of the two bridges may be unequal, resulting in current unbalance between bridges and a severe saturation problem in the IPT circuit. This causes each bridge to operate in a discontinuous conduction mode in which each rectifier conducts only for 60° and carries the full-load current [6]. Unsymmetry of the delta-wye winding could be alleviated by a three-phase autotransformer or an extended-delta transformer configuration [5]. However, the firing angle imbalance of the two bridges to remedy the current unbalance could cause some undesirable effects, such as harmonic problems [6]. In this paper, a new pulse multiplication technique based on six-pulse thyristor converters is proposed. With the proposed technique, 12-pulse, 18-pulse, and 24-pulse operations are obtained, both on the input current and on the output voltage. The proposed scheme exhibits the following advantages.

- There is no current unbalance unlike the 12-pulse-based multipulse converter.
- Phase-shifting transformers are not necessary. Instead, relatively low kilovoltampere transformers (around 50% of the input power) are employed.
- Output voltage ripples as well as input current harmonics are reduced with the proposed technique.
- Variation of source frequency and load does not affect the operation of the proposed scheme.
- The proposed approach can be considered as an add-on option.

Fig. 1. Proposed 12-pulse converter.
A control strategy over the whole range of phase angle is provided along with sophisticated input current and output voltage analysis. Experimental results from a 220-V 3-kVA laboratory prototype are provided.

II. PROPOSED 12-PULSE SCHEME

Fig. 1 shows the circuit topology of the proposed 12-pulse converter. The proposed scheme is based upon the six-pulse thyristor converter with additional circuitry to permit pulse multiplication. The additional circuitry consists of three parts: a voltage-dividing circuit, a current injection circuit, and a zigzag transformer. The voltage-dividing circuit includes two dc blocking capacitors $C_1$ and $C_2$ and a low-kilovoltamperes transformer $T_F$, operating at the ripple frequency which is $\delta \times f$ the fundamental frequency. The zigzag transformer creates a neutral point " n" and equally distributes injected current $i_n$ into three input phases. An injection transformer $T_m$ is connected between the neutral point " n" of the zigzag transformer and the dc-link midpoint " m," and two auxiliary thyristors $T$ and $T'$ inject a square-wave current on the primary side of the transformer $T_F$.

Assuming negligible ripple voltages across the capacitors $C$ and $L$ due to large capacitances, voltage $v_{mn}$ on the primary side of transformer $T_F$ is given by

$$v_{mn} = v_{pn} - \frac{1}{2} v_d.$$  

The waveform of voltage $v_{mn}$ at phase angle $30^\circ$, is shown in Fig. 2, and its frequency is triple the fundamental frequency. Fig. 3 illustrates the operation of two auxiliary thyristors according to the commutation voltage $v_{mn}$. To assure natural commutation, thyristor $T_1$ is fired at an angle $\beta_1$, which is measured from the rising edge of voltage $v_{mn}$. Since thyristor $T_2$ is forward biased at this moment, it is turned on and carries output current $i_o$. This causes current $i_n = \frac{N_1}{N} I_o$ and $i_n = \frac{N_2}{N} I_o$ to be induced on the primary winding of transformer $T_F$. By the repeated firing of the two thyristors, the injected current $i_n$ becomes square wave in shape as shown in Fig. 2. The current $i_n$ is equally divided into two currents $i_p$ and $i_o$ on the dc side and three currents $i_1$, $i_2$, and $i_3$ on the ac side. That is,

$$i_p = i_t = \frac{i_n}{2}.$$  

$$i_1 = i_2 = i_3 = \frac{i_n}{3}.$$  

Now, switching functions $S_{t+}$ and $S_{t-}$ for phase " a" are defined to relate bridge output currents to bridge input currents, as shown in Fig. 4. The switching functions for phases " b" and " c" can also be defined by

$$S_{a+} = S_{b+} + 120^\circ$$  
$$S_{a+} = S_{b+} - 120^\circ$$  
$$S_{a+} = S_{b+} + 120^\circ$$  
$$S_{a+} = S_{b+} - 120^\circ.$$  

Then, bridge input currents can be expressed in terms of bridge output currents and switching functions as

$$\begin{bmatrix} i_{a+} \\ i_{a-} \end{bmatrix} = \begin{bmatrix} S_{a+} \\ S_{a-} \end{bmatrix} \begin{bmatrix} I_o \\ \beta \end{bmatrix} + \begin{bmatrix} S_{a+} \\ S_{a-} \end{bmatrix} i_{o+}.$$  

Due to equal distribution of current on the ac side, the input current becomes

$$i_a = i_{a+} - i_{a-} = I_o - \frac{i_n}{3}$$  
$$i_b = i_{a+} - i_{a-} = I_o - \frac{i_n}{3}$$  
$$i_c = i_{a+} - i_{a-} = I_o - \frac{i_n}{3}.$$
Finally, from (2)–(7), the input current can be obtained by
\[
\begin{align*}
    i_a &= \frac{1}{6} i_s (3S_{s+} - 3S_{s-} - 2) + I_s (S_{s+} + S_{s-}) \\
    i_b &= \frac{1}{6} i_s (3S_{b+} - 3S_{b-} - 2) + I_s (S_{b+} + S_{b-}) \\
    i_c &= \frac{1}{6} i_s (3S_{c+} - 3S_{c-} - 2) + I_s (S_{c+} + S_{c-}).
\end{align*}
\]
(3)

It can easily be noticed from (8) that the input current waveform depends on the injected current \( i_s \), that is, on turns ratio \( k = N_s / N \) and on firing angles \( \beta \) and \( \beta' \). The optimum turns ratio has been found to be \( k = 0.929 \). The optimum firing angles \( \beta (=\beta) \) and \( \beta (=\beta+60^\circ) \) for the lowest input current total harmonic distortion (THD) have been obtained with respect to phase angle \( \alpha \) and are shown in Fig. 5. With the optimum firing angle, the minimum THD of 14.19\% has been obtained over the whole range of phase angle \( \alpha \) between 0\(^\circ\) and 180\(^\circ\), as shown in Fig. 6. Various current waveforms at phase angle \( \alpha = 30^\circ \) are shown in Fig. 2. Input current \( i_s \) is shown to have 12-pulse characteristics.

III. HIGHER PULSE OPERATION

The proposed 12-pulse approach is extended for higher pulse operations such as 18-pulse, 24-pulse, etc. For \( P \)-pulse operation, \( (P \neq 6) \) auxiliary thyristors are connected to taps on the secondary winding of transformer \( T_F \) as shown in Fig. 7. With appropriate firing of the auxiliary thyristors, the waveforms of injected current \( i_s \) have three-level for 18-pulse operation and four-level for 24-pulse operation, respectively. This results in improvement in input currents and output voltages as shown in Fig. 8. To assure natural commutation, the firing order of auxiliary thyristors must be from right to left when voltage \( v_{\text{m in}} \) is positive, whereas it must be from right to left when \( v_{\text{m in}} \) is negative. Equations (1)–(9) derived in Section II are also valid for the higher pulse operation.

![Fig. 6. Input current THD versus phase angle.](image)

![Fig. 7. Auxiliary circuit operation (\( = 30^\circ \)). (a) 18-pulse. (b) 24-pulse.](image)

In the meanwhile, bridge output voltage \( v_o \) is identical to the output voltage of the conventional six-pulse converter as shown in Fig. 2. On the other hand, the output voltage of the proposed scheme is given by
\[
v_o = v_{d} + v_{r}.
\]
(9)

Voltage \( v_r \) becomes \( v_r = (N_r/N_d) v_{\text{m in}} \) with \( T_r \) turned on while it becomes \( v_r = -(N_r/N_d) v_{\text{m in}} \) while \( T_r \) is turned on. Thus, voltage \( v_r \) is added to bridge output voltage \( v_d \) resulting in output voltage improvement as shown in Fig. 2.

![Fig. 8. Input current and output voltage waveforms (\( = 30^\circ \)). (a) 18-pulse. (b) 24-pulse.](image)

**TABLE I**
CONTROL METHOD AND PERFORMANCE.

<table>
<thead>
<tr>
<th>Turn ratio of ( T_F )</th>
<th>12-Pulse converter</th>
<th>18-Pulse converter</th>
<th>24-Pulse converter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turn ratio of ( T_F )</td>
<td>( N_r/N_d = 0.929 )</td>
<td>( N_r/N_d = 1.233 )</td>
<td>( N_r/N_d = 1.380 )</td>
</tr>
<tr>
<td>Optimum firing angle ( \beta ) (See Fig. 5)</td>
<td>1. ( \beta = \beta )</td>
<td>1. ( \beta = \beta )</td>
<td>1. ( \beta = \beta )</td>
</tr>
<tr>
<td>2. ( \beta = \beta + 60^\circ )</td>
<td>2. ( \beta = \beta + 60^\circ )</td>
<td>2. ( \beta = \beta + 60^\circ )</td>
<td>2. ( \beta = \beta + 30^\circ )</td>
</tr>
</tbody>
</table>

| Firing order | \( T_1 \rightarrow T_2 \rightarrow T_3 \) | \( T_1 \rightarrow T_2 \rightarrow T_3 \rightarrow T_4 \) | \( T_1 \rightarrow T_2 \rightarrow T_3 \rightarrow T_4 \) |
| Firing order | \( T_1 \rightarrow T_2 \rightarrow T_3 \rightarrow T_4 \) | \( T_1 \rightarrow T_2 \rightarrow T_3 \rightarrow T_4 \) | \( T_1 \rightarrow T_2 \rightarrow T_3 \rightarrow T_4 \) |
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| Firing order | \( T_1 \rightarrow T_2 \rightarrow T_3 \rightarrow T_4 \) | \( T_1 \rightarrow T_2 \rightarrow T_3 \rightarrow T_4 \) | \( T_1 \rightarrow T_2 \rightarrow T_3 \rightarrow T_4 \) |
| Input current THD | 14.19\% | 9.26\% | 7.42\% |
| Output voltage \( RF (\alpha = 30^\circ) \) | 8.83\% | 6.43\% | 5.45\% |

Table I summarizes the optimum tap positions, the optimum firing angles, and the firing order of the auxiliary thyristors for the proposed pulse multiplication. It is noted that the degree of freedom of the optimum firing angles for each of the auxiliary thyristors is just one. Fig. 5 shows the optimum firing angles with...
respect to phase angle to achieve the minimum input current THD for 18-pulse and 24-pulse operation. Input current THDs with the proposed firing strategy are shown in Fig. 6. In the case of 18-pulse (24-pulse) operation, the input current THD for phase angle higher than 170° (167°) and lower than 10° (13°) rises since the auxiliary thyristors cannot be forward biased in this range.

### TABLE II: TRANSFORMER VOLTMEMPERE AND COMPONENT RATING (\( = 90° \)).

<table>
<thead>
<tr>
<th>Transformer Voltage</th>
<th>Conventional</th>
<th>Proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>V_{1n}</td>
<td>0.7975</td>
<td>0.8165</td>
</tr>
<tr>
<td>V_{2n}</td>
<td>0.5775</td>
<td>0.6092</td>
</tr>
<tr>
<td>V_{mn}</td>
<td>1.0000</td>
<td>1.2357</td>
</tr>
<tr>
<td>I_{1}</td>
<td>100.00</td>
<td></td>
</tr>
</tbody>
</table>

### TABLE III: VOLTAGE AND CURRENT RATING OF THE 1 Y TRANSFORMER.

<table>
<thead>
<tr>
<th>Voltage/rating</th>
<th>Conventional</th>
<th>Proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>V_{mn}/V_{LL}</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>I_{mn}/I_{1}</td>
<td>0.8165 a</td>
<td>0.8450 a</td>
</tr>
<tr>
<td>V_{mn}/V_{LL}</td>
<td>a</td>
<td>a</td>
</tr>
<tr>
<td>I_{mn}/I_{1}</td>
<td>0.8165</td>
<td>0.900</td>
</tr>
</tbody>
</table>

Fig. 9. Alternative scheme for isolation and/or voltage matching.

However, it should be noted that transformer TF_{1s} and transformer TF_{mn} are physically smaller than might be expected because they operate at 360 and 180 Hz, respectively.

In the applications where the operating range of the phase angle is limited below or above 90°, the voltmampere ratings of the transformers could be smaller than the listed value. Component ratings of the proposed schemes are also compared with those of the conventional 12-pulse converter. Note that the auxiliary thyristor has a small voltage rating compared to the main thyristor.

A large ripple in voltage \( v_{sa} \) due to small capacitance \( C_s \) distorts the commutation voltage \( v_{mn} \), which may cause a commutation failure of the auxiliary thyristors. Therefore, capacitance \( C_s \) should be determined taking into account the permissible level of the ripple voltage. The capacitance can be determined by

\[
C_s = \frac{K_s}{K_i \omega V_{LL}}
\]

where \( K_s \) is the ripple factor and \( K_i \) is the capacitor constant according to the pulse number.

### IV. ALTERNATIVE SCHEME

In some applications such as UPSs or static var compensators (SVCs) where voltage matching and/or isolation is needed, the zigzag transformer for equal distribution of the injected current can be omitted. Instead, the current is injected directly to the neutral of the delta-wye transformer as shown in Fig. 9. The operating principle of the alternative scheme shown in Fig. 9 is the same as the proposed scheme shown in Fig. 1. Bridge input current \( I_1 \) and \( I_2 \) are identical for both schemes. Therefore, all the equations except (3), (7), and (8) in the previous section are also valid for the alternative scheme. Assuming that the turns ratio of the delta-wye transformer is \( \alpha \), the current in the primary delta winding is expressed as

\[
i_{sh} = a \cdot i_n + \frac{1}{3} i_n
\]

\[
i_{t} = a \cdot i_n + \frac{1}{3} i_n
\]

\[
i_{c} = a \cdot i_n + \frac{1}{3} i_n
\]
VI. CONCLUSION

In this paper, a new pulse multiplication technique based upon the six-pulse thyristor converter has been introduced. The proposed scheme characterized in Fig. 1 does not necessitate phase-shifting transformers. Instead, transformers rated around 50% of the input power are employed. The proposed schemes also do not have the current unbalance problem unlike the multipulse technique based on parallel connection of bridges.

Optimum firing angles for minimum input current THD have been provided over the whole range of phase angle between 0 and 180. Design parameters such as optimum tap positions of auxiliary thyristor and component ratings have been obtained. Further pulse multiplication such as 30-pulse, 36-pulse, etc., is possible with the proposed technique. The experimental results validated the proposed pulse multiplication technique.

REFERENCES