A DC-Link Modulation Scheme with Phase-Shifted Current Control for Harmonic Cancellations in Multi-Drive Applications

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Abstract—This letter proposes a harmonic mitigation strategy to cancel out current harmonics induced by the front-end rectifiers in multi-drive systems, which consist of diode rectifiers, Silicon-Controlled Rectifiers (SCR), and boost converters in the DC-link. The proposed strategy is a combination of a new DC-link modulation scheme with a phase-shifted current control enabled by the SCR. The DC-link current modulation scheme is implemented by adding and subtracting specific modulation levels, which makes the total currents drawn from the grid “multi-level”, resulting in an improved current quality. Simulations and experiments have validated the effectiveness of the proposed harmonic mitigation solution for multi-drive systems.

Index Terms—Harmonics, DC-link modulation, phase-shifted currents, diode rectifier, Silicon-Controlled Rectifier (SCR), three-phase multiple drive systems, adjustable speed drives.

I. INTRODUCTION

LOW-COST diode rectifiers and SCR’s are still very popular as the front-ends in modern adjustable speed drive systems [1], [2], as exemplified in Fig. 1. Harmonic emission and energy conversion efficiency are two major concerns for those drive systems [1]–[5]. Diode rectifiers and SCR’s can achieve lower power losses, but increase the harmonics due to their high non-linearity. Therefore, a vast array of harmonic mitigation solutions have been developed for such applications using either: a) passive solutions (e.g., AC or DC chokes) that are suitable in low power applications, b) multi-pulse transformer-based rectifiers as the front-ends [6], [7], c) active power filtering techniques [8]–[10], and d) hybrid solutions [11], [12]. Those harmonic mitigation strategies either increase the system overall volume or complicate the entire control system (or require auxiliary circuits), and thus leading to increased cost, which is undesired in the drive systems.

In order to tackle these issues, a new DC-link current modulation scheme for multi-drive systems is proposed in this letter. The new modulation scheme is derived by adding and subtracting specific modulation levels in such a way that the total currents drawn by the rectifiers become “multi-level” [13], [14], leading to a mitigation of the current harmonics. Moreover, by phase-shifting the SCR currents, the grid current quality can be enhanced in terms of a lower Total Harmonic Distortion (THD) and a mitigation of the harmonics of interest. If the modulation patterns are pre-programmed appropriately, the harmonic cancellation is enabled by a mix of the new modulation scheme and the phase-shifted current control, and it can be competitive to multi-pulse systems (e.g., 12-pulse diode rectifiers) [14]. In addition, an improvement of the harmonic cancellation strategy can be attained by optimizing the modulation patterns. Notably, one of the advantages of the proposal is to achieve low current THD even at partial power loading conditions in a cost- and size-effective way.

The rest of this letter is organized as follows. In § II, the principle of the phase-shifted current control to mitigate the harmonics is introduced, followed by the new modulation scheme for the DC-link current. Simulations and experiments are carried out in order to verify the analysis. The results will demonstrate the effectiveness of the proposed DC-link modulation scheme with the phase-shifted current control in terms of harmonic cancellations in multi-drive applications. In § III, a basic comparison between the proposed solution with prior-art strategies is performed. Finally, conclusions are drawn in § IV.

II. PROPOSED DC-LINK MODULATION SCHEME

A. Phase-Shifted Current Control

According to Fig. 1, assuming that the DC-link current of the SCR unit \( i_{ls} \) (i.e., the rectified current) is controlled as a purely DC current (denoted as \( I_{ls} \)), the currents \( i_{ls} \) drawn by the SCR will be rectangular [15]. Taking the phase-A current as an example, it can be expressed by its Fourier series as,

\[
i_{ls}(t) = \frac{2\sqrt{2}}{\pi} I_{ls} \sum_{n=1}^{\infty} \left\{ \frac{(-1)^n}{n} \sin[n(\omega t - \alpha_f)] \right\}
\]

Fig. 1. Schematic and control structure of a multi-drive system with boost converters as the DC-link, where hysteresis current controllers are employed: (PLL - Phase Locked Loop; PI - Proportional Integrator).

where \( \alpha_f \) is the firing angle, \( \omega \) the angular frequency, and \( I_{ls} \) the DC-link current.
It can further be explained by Fig. 2, which exemplifies that the $h$th harmonic can completely be eliminated by introducing a phase-shift of $180^\circ/h$ to the SCR (i.e., $\alpha_f = 180^\circ/h$). This is valid only when the two rectifier systems are drawing the same amount of currents from the grid, being the main drawback of the phase-shifted current control.

### B. DC-Link Modulation Scheme

As mentioned above, when the rectifier output currents are controlled as DC currents, the currents drawn from the grid will be rectangular [15]. This will bring distortions to the grid, and even with the phase-shifted current control, only certain harmonics can be fully cancelled out in theory. In order to further reduce the harmonics, a DC-link modulation scheme is proposed, which will ensure that the currents drawn from the grid are “multi-level”. As shown in Fig. 3, the proposed scheme is synthesized using pre-programmed modulation patterns (i.e., the desired phase-A current shape) and it is applicable to any single-drive system with a boost converter in the DC-link. Once the new modulation scheme (e.g., $u_s$ or $u_d$) is employed in the DC-link (as the “Modulation” blocks in Fig. 1), the currents drawn by the rectifiers should follow the pre-programmed modulation patterns. Thus, harmonic mitigations can be accomplished by properly designing the modulation patterns shown in Fig. 3. In this letter, a new modulation pattern has been designed by adding and subtracting specific modulation levels, as it is illustrated in Fig. 4, where the modulation patterns are centered and synchronized in respect to the phase-A grid voltage (i.e., $v_{an}$). The following demonstrates how harmonic mitigations are achieved in the SCR system by the designed modulation pattern shown in Fig. 4.

It is indicated in Fig. 4 that the pre-programmed modulation pattern $u_{ms}$ consists of rectangular signals $u_0, u_1,$ and $u_2$ with a conduction angle of $\beta_0$ (120°), $\beta_1,$ and $\beta_2$ and a phase-shift of $\alpha_0,$ $\alpha_1,$ and $\alpha_2,$ correspondingly. Therefore, the $h$th harmonic component of these rectangular signals (i.e., $u_0, u_1,$ and $u_2$) can be expressed as

$$u_h^i(t) = a_h^i \cos(h \omega t) + b_h^i \sin(h \omega t)$$

in which, $i = 0, 1, 2,$ and $h = 1, 3, 5, \cdots$ is the harmonic order, $a_h^i$ and $b_h^i$ are the Fourier coefficients [15] that are given by

$$a_h^i = \frac{2m_i}{n_\pi} [\sin(h \alpha i) - \sin(h \alpha i + h \beta_1)]$$

$$b_h^i = \frac{2m_i}{n_\pi} [\cos(h \alpha i) - \cos(h \alpha i + h \beta_1)]$$

Subsequently, according to the superposition principle and Fig. 4, the harmonic component ($u_{ms}^h$) of the new modulation pattern (i.e., $u_{ms}$) can be obtained as

$$u_{ms}^h(t) = (a_h^0 + a_h^1 - a_h^2) \cos(h \omega t) + (b_h^0 + b_h^1 - b_h^2) \sin(h \omega t)$$

with its Root-Mean-Square (RMS) magnitude being,

$$U_{ms}^h = \frac{\sqrt{2}}{2} \left[ (a_h^0 + a_h^1 - a_h^2)^2 + (b_h^0 + b_h^1 - b_h^2)^2 \right]^{1/2}$$

By solving $U_{ms}^h = 0$ (h $\neq 1$) and $U_{ms}^h = M$ with $M$ being the modulation index, harmonic cancellations can be achieved. When implemented according to Fig. 3, the currents drawn by the SCR will exactly follow the waveforms of the modulation pattern (e.g., $u_{ms}$). However, it should be noted that up to two low-order harmonics (e.g., $h = 5$ and $h = 13$) in a single-drive system with a boost converter based DC-link.
an assumption that the rectifiers as discussed the DC-link current (i.e., \( i_0 \)), beyond the two low-order harmonics modulation level (i.e., \( i_2 \)). In that case, the resultant total scheme, which results in a better current quality. Notably, \( u_{\text{md}}^h \) (9). Fig. 5 demonstrates the harmonic characteristics of the diode rectifier system, and \( u_{\text{md}}^h \) (i.e., \( \alpha_0 \), \( \alpha_1 \), \( \alpha_2 \)). The effectiveness of the phase-shifted current control is further confirmed by experimental results shown in Table I.

### III. Simulation and Experimental Results

In order to verify the effectiveness of the proposed modulation with the phase-shifted current control, simulations and experiments have been done, referring to Figs. 1 and 3, where resistors are used as the loads. Hysteresis and PI controllers are selected to control the DC-link current \( (i_b \) and \( i_d \) and the output voltage \( (v_{\text{om}} \) and \( v_{\text{od}} \) with \( v_{\text{om}} = v_{\text{od}} = 700 \) V), respectively. The system parameters are listed in Table I.

Firstly, the phase-shifted current control is examined with only one modulation level (i.e., \( u_0 \) in Fig. 4). The results are presented in Fig. 6, showing that the THD\(_{i_g}\) can be reduced to some extent, when the phase-shifted current control is enabled (i.e., \( \alpha_f \neq 0 \)). Moreover, the THD\(_{i_g}\) has been minimized to 15.85% at \( \alpha_f = 30^\circ \). In addition, in order to cancel out an individual harmonic, the firing angle of the SCR unit has to be specified according to Table II (e.g., 36\( ^\circ \) for cancelling out the 5th harmonic). The effectiveness of the phase-shifted current control is further confirmed by experimental results shown in Fig. 7(a). However, due to the presence of the grid impedance, the 5th harmonic is not fully eliminated (cf., Fig. 7(a)) by the phase-shifted control even when \( \alpha_f = 36^\circ \). Nevertheless, the phase-shifted current control can reduce the harmonics, leading to a lower THD\(_{i_g}\).

![Diagram](image)

**Fig. 5.** Typical waveforms of the phase-A currents in a multi-drive system (Fig. 1) with the proposed modulation scheme and the phase-shifted control, where the current shapes follow the modulation pattern in Fig. 4.

![Diagram](image)

**Fig. 6.** THD\(_{i_g}\) and low-order harmonics of the grid current in the multi-drive system with the phase-shifted current control.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power rating</td>
<td>( P_g )</td>
<td>6 kW (total)</td>
</tr>
<tr>
<td>DC-link inductor</td>
<td>( L_s, L_d )</td>
<td>2 mH</td>
</tr>
<tr>
<td>DC-link capacitor</td>
<td>( C_{\text{dc}} )</td>
<td>470 ( \mu )F</td>
</tr>
<tr>
<td>Grid frequency</td>
<td>( f_g )</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Grid phase voltage (RMS)</td>
<td>( v_{\text{abc}, g} )</td>
<td>220 V</td>
</tr>
<tr>
<td>Grid impedance</td>
<td>( Z_g (L_g, R_g) )</td>
<td>0.18 mH, 0.1 ( \Omega )</td>
</tr>
<tr>
<td>PI controller</td>
<td>( k_{p}, k_i )</td>
<td>0.01, 0.1</td>
</tr>
</tbody>
</table>

![Diagram](image)

**Table I.** Parameters of the multi-drive system (Fig. 1).
A novel harmonic mitigation strategy with prior-art solutions [16], [17]

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Typical THD</th>
<th>Complexity</th>
<th>Cost</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proposed solution</td>
<td>10% - 12%</td>
<td>++</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>12-pulse rectifier</td>
<td>10% - 15%</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>18-pulse rectifier</td>
<td>4% - 7%</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
</tr>
<tr>
<td>Active filtering</td>
<td>3% - 8%</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
</tr>
</tbody>
</table>

Note: 1. The more “+”, the more complicated, the higher in cost, or the larger in volume (and also the heavier in weight); 2. Include the implementation and control complexity; 3. Not include the drive cost.

In addition, the proposed harmonic mitigation strategy is compared with the prior-art solutions [16], [17], as shown in Table II in terms of effectiveness in harmonic mitigations (typical resultant grid current THD), implementation and control complexity, cost, and volume. The basic benchmarking further highlights the merits of the proposed solution for harmonic cancellation in multi-drive systems with boost converters in the DC-link. When the unbalance loading issue is well addressed in practice, the proposed solution can be a cost-effective strategy for harmonic mitigations. It can compete with the 12-pulse rectifier in the harmonic performance.

IV. CONCLUSIONS

In this letter, a new DC-link modulation scheme aiming at harmonic mitigations has been proposed for three-phase multi-drive systems with boost converters in the DC-link. This new modulation scheme has been implemented by adding and subtracting specific modulation levels, so that the currents drawn by the rectifiers are “multi-level”. Furthermore, an improved quality of the grid current has been achieved by combining the proposed modulation scheme with a phase-shifted current control in multi-drive systems. The effectiveness of the proposed harmonic mitigation solution has been verified.

REFERENCES