Load-Independent Harmonic Mitigation in SCR-Fed Three-Phase Multiple Adjustable Speed Drive Systems with Deliberately Dispatched Firing Angles

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Abstract: Adjustable Speed Drives (ASDs) are widely used in three-phase multi-drive applications in industry for energy savings, where low-cost rectifiers (mainly Diode Rectifiers - DRs) are still employed as the front-ends in practice, also for simplicity in control and reliability in operation. However, significant harmonic distortions appear at the grid, which should be properly tackled according to increasingly stringent standards and/or grid-connection rules. If remain untreated, a poor power quality will cause efficiency drops of the entire system. Currently, communication technologies are still not of much cost-effectiveness, and hence, the use of communication in multiple parallel motor-drive systems for harmonic control is rarely witnessed in industry. In this sense, this paper proposes a harmonic mitigation strategy for multiple parallel ASD systems, where another type of low-cost rectifiers (i.e., Silicon-Controlled Rectifiers - SCRs) with boost converters in the dc-link have adopted to increase the harmonic-current controllability. More specific, the SCR firing angles are deliberately dispatched among the SCR drive units, which results in certain phase shifts of the SCR currents on purpose. In such a manner, the harmonics appearing in the grid current can be mitigated to some extent in multi-drive systems without communication. The effectiveness is independent of the power loading of each drive, when a number of drives are connected. Simulations are carried out to verify the discussion. Furthermore, to make the most use of the SCR-fed structure for harmonic cancellation, a customized modulation scheme has been experimentally demonstrated. Both simulation and experiment results have verified the discussion.

1 Introduction

As an almost standardized solution to motor drive applications, low-cost Diode Rectifiers (DRs) are still popular as the front-end apparatus of three-phase Adjustable Speed Drive (ASD) systems [1]-[3], as it is exemplified in Fig. 1(a). Although DRs have merits including simple structure and control, small volume, low cost, and high reliability during operation, they will introduce large harmonics to the grid [2], [4]-[6]. The power quality issue should be addressed properly according to demands and standards [7]. Otherwise, the overall system efficiency will be degraded, and other equipment connected to the Point of Common Coupling (PCC) may malfunction. The approaches to alleviate the harmonic distortions can be categorized as a) adding passive filters (e.g., dc or ac chokes) [3], b) employing multi-pulse transformer-based front-ends [8], [9], c) using active power filtering techniques [10], [11], and d) hybrid schemes [11]. In respect to the cost-effectiveness and complexity, the use of active Power Factor Correction (PFC) circuits [2] in the dc-link as shown in Fig. 1(a) has enabled much flexibility in the control of the grid current quality.

In the case of single-phase drive systems, the employed PFC systems ensure that the grid current drawn by the rectifiers can be shaped as much close to purely sinusoidal as possible [13]-[15]. This contributes to a significant power quality improvement in single-phase motor drive applications, and it is almost becoming a standardized solution. Similarly, in three-phase ASD systems, the power quality can also be enhanced by incorporating PFC circuits (e.g., boost dc-dc converters) [2], [16]-[18], as it is demonstrated in Fig. 1(a). In that case, the rectified currents (e.g., i_{rd} in Fig. 1(a)) can be controlled [19]. That is to say, by properly regulating the rectified currents i_{rd} through the boost dc-link, the grid currents i_{sabc} can be shaped, and thus the harmonic currents appearing in the grid can be controlled. Notably, the dc-link is to emulate an infinite inductor.

It should be pointed out that, although the PFCs in ASD systems with "uncontrolled" rectifiers (i.e., DRs) can increase the controllability of the power quality to some extent, the performance cannot compete with that in single-phase applications. This is mainly owing to the inherent behaviour of rectifiers in the case of a Continuous Conduction Mode (CCM) [18]. That is, the phase current conducts with a period of 120°. Thus, it is not possible to achieve a purely sinusoidal current with the topology shown in Fig. 1(c) [2]. One possibility is to use interleaved boost converters as the PFC stage [20]. Nevertheless, the configuration in Fig. 1(a) enables the possibility to shape the currents drawn from the grid with a focus on reducing the distortion level, as it has been presented in [21], [22].

On the other hand, in the case of a multi-drive system (consisting of DR units), as demonstrated in Fig. 1(b) that is more commonly seen in practice, the current quality will be almost constant (current THD is around 31%) when boost converters are adopted in the dc-link. However, according to the superposition principle, if the currents drawn by certain ASDs can be phase-shifted, the quality of the vector summation of all currents at the PCC will be improved. To enable this phase control freedom, the DRs can be replaced by another type of rectifiers – the Silicon-Controlled Rectifiers (SCRs). In that case, the power quality will be enhanced by means of a phase-shifted current control [21], [23], [24] and the boost dc-link control/modulation. When certain phase-shifts are introduced to parallel SCR-drive systems, the total currents drawn from the grid will become multi-level, and certain harmonics of interest (e.g., the 5th-order harmonic) will be eliminated theoretically. It thus contributes to an improved quality of the grid current, and also possibilities to optimize the firing angles among the drives. However, the implementation of the optimal firing angles relies on costly communication, which is not desired in practice.

In light of the above issues, this paper proposes a harmonic mitigation strategy for SCR-fed three-phase parallel ASD systems in § 2 without communication, where the basic control structure of such drives is also presented. The proposed harmonic mitigation strategy takes the strength of the phase-shifted current control [21], [23], and then the firing angles are deliberately dispatched (e.g., linear increase) in such a way that the grid current becomes multi-level with no communication, leading to an enhanced power quality. The harmonic mitigation effectiveness is also independent of the loading of each drive when a number of drives are connected. Simulations on multi-drive systems have been performed in order to verify the effectiveness of the proposed solution, and the results are presented in § 3. Furthermore, to fully exploit the controllability of harmonics enabled by the boost-based dc-link, a customized selectively harmonic cancellation modulation scheme is applied to a drive system in § 4, and the performance is also verified experimentally. Finally, concluding remarks are given in § 5.

2 Harmonic Issues and Mitigation

2.1 Current Control and Harmonic Characteristics

As aforementioned, the use of PFC circuits enables a flexible control (modulation) of the dc-link current (i.e., the rectified current i_{rd} in Fig. 1(a)). Figs. 1(c) and 1(d) present the detailed hardware schematic and the control structure of the dc-link current for an SCR-drive system, respectively. Assuming that the rectified current i_{rs} is controlled as a purely dc current (denoted as I_{rs}) through the PFC according to Fig. 1(d), the currents drawn from the grid will thus be a rectangular wave with a conduction angle of 120°. This means that the incorporated dc-dc converter is expected to emulate an ideal inductor at the dc-link. It also indicates that it is not possible to achieve a sinusoidal current with one boost converter in the dc-link. Taking the phase-a grid current as an example, it can be expressed in a compact format as [25]

$$i_{ga}(t) = i_{sa}(t) = \frac{2\sqrt{3}}{\pi} I_{rs} \sum_{h}^{\infty} \left\{ \frac{(-1)^n}{h} \sin\left[h(\omega t - \alpha_f)\right] \right\} \tag{1}$$

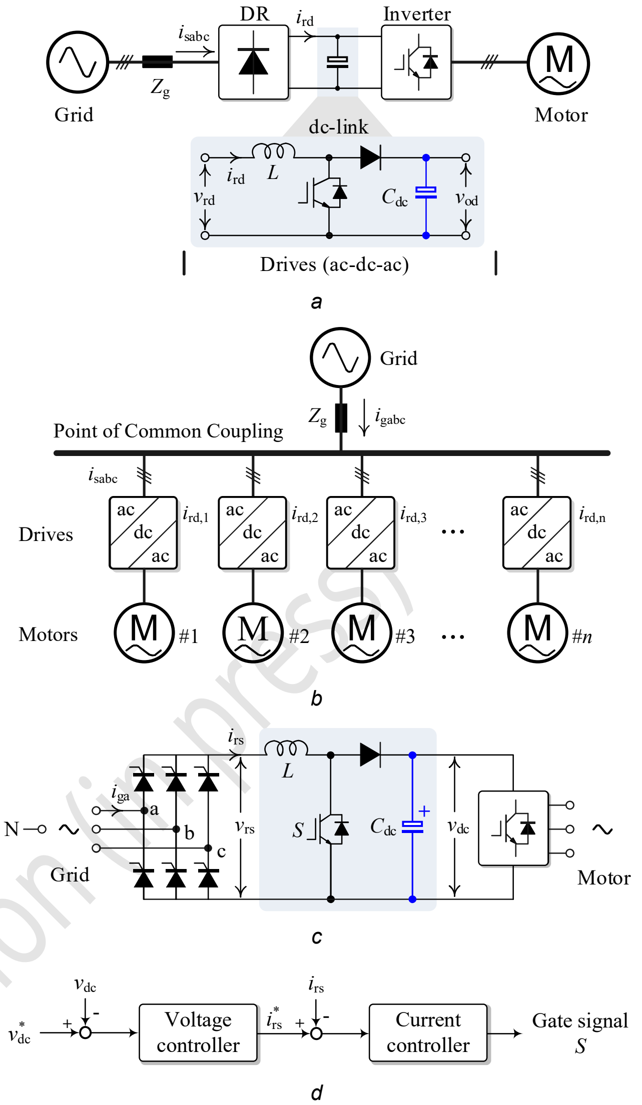

Fig. 1 *Examples of the DR-fed drive systems:* **(a)** *single-drive unit with a boost dc-dc converter in the dc-link,* **(b)** *multi-drive systems (n drive units),* **(c)** *hardware schematic of an SCR-fed three-phase drive system with a boost converter in the dc-link, and* **(d)** *control structure of the boost dc-link stage.*

where $h = 6n\pm1$ with $h > 0$ being the harmonic order, $n = 0, 1, 2, \ldots$, and α_f is the firing angle of the SCR unit. For the DR system, the harmonics appearing in the grid current can be obtained by setting $\alpha_f = 0$ in (1). According to (1), the amplitude of the h-th harmonic component appearing in the grid current (e.g., i_{sa}) can be given as

$$I_{sa}^{h} = \frac{2\sqrt{3}}{\pi h} I_{rs} \tag{2}$$

with I_{sa}^{h} being the h-th harmonic current amplitude. Equation (2) indicates that the harmonic component amplitude will be inversely proportional to the harmonic order h once the dc-link rectified current is controlled as a purely dc current. Furthermore, the amplitude of the resultant harmonic components in (2) is independent of the firing angle α_f.

Accordingly, the Total Harmonic Distortion (THD) level of the grid current can be obtained as well as the harmonic distribution, which is shown in Fig. 2. It can be observed in Fig. 2 that the rectangular current with a conduction period of 120° by controlling the rectified current to be dc brings high harmonics (e.g., the 5th harmonic is 20% of the fundamental) to the grid, leading to a poor THD of approx. 31%. This current THD is irrelevant to the firing angle α_f in

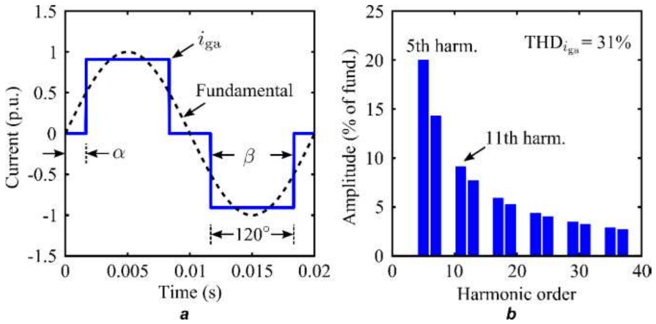

Fig. 2 *Harmonic characteristics of the phase-a current drawn by a SCR drive system:* ***(a)*** *ideal current waveform ($\alpha = \alpha_f + 30°$ and $\alpha_f = 0$, $\beta = 120°$) and* ***(b)*** *harmonic distribution.*

a single-SCR-fed drive system. Connecting such apparatus to the grid comes with a penalty on the owners, since the grid operator has to pay for the power quality compensation. Furthermore, it is implied in Equation (1) that the firing angle α_f can control the average rectified output voltage v_{rs} (and thus the dc-link voltage v_{dc} through the control of the PFC), as well as the phase of the grid current i_{ga} (i.e., i_{sa}). This further explains that the grid currents can be controlled by adjusting the firing angle in terms of shapes and phases. Notably, it is not possible to achieve a sinusoidal shape only by controlling the single boost converter due to the commutation characteristics in three-phase rectifiers (i.e., the conduction periods of 120°).

2.2 Proposed Harmonic Mitigation Strategy

In order to avoid the penalty, the current quality should be improved, when such harmonic sources (i.e., the SCR- or DR-fed drives) are connected to the grid. Mixing non-linear loads [24] offers much convenience to reduce the harmonics while being size- and cost-effective in contrast to prior-art solutions (e.g., 12-pulse and 18-pulse transformer rectifiers). Fig. 1(b) gives a layout of multi-drive systems. In that case, the THD level of the total grid currents can be lowered and the targeted harmonics (e.g., the 5th harmonic) can be minimized, as long as the firing angle of each SCR-fed drive system is properly designed [21], [23], being the phase-shifted current control. Hereafter, a two-SCR-drive system (#1 and #2 in Fig. 1(b)) is considered to illustrate the grid current quality improvement (i.e., lowering THD level) by the phase-shifted current control. First, the h-th order harmonic current phasors of the drive units (#1 and #2) can be given as

$$\begin{cases} \mathbf{I}_{sa,1}^{h} = I_{sa,1}^{h} e^{j\varphi_{sa,1}^{h}} \\ \mathbf{I}_{sa,2}^{h} = I_{sa,2}^{h} e^{j\varphi_{sa,2}^{h}} \end{cases} \tag{3}$$

in which $I_{sa,1}^h$, $I_{sa,2}^h$ are the magnitudes, and $\varphi_{sa,1}^h$, $\varphi_{sa,2}^h$ are the phases of the h-th harmonic component for the corresponding SCR-fed drive unit. They can be calculated according to the Fourier analysis [25]. Alternatively, the magnitudes and phases can be obtained through Equations (1) and (2).

Nevertheless, based on the superposition principle, the phasor of the h-th order harmonic component of the total grid current (phase-a) can be given as

$$\mathbf{I}_{ga}^{h} = \mathbf{I}_{sa,1}^{h} + \mathbf{I}_{sa,2}^{h} = I_{sa,1}^{h} e^{j\varphi_{sa,1}^{h}} + I_{sa,2}^{h} e^{j\varphi_{sa,2}^{h}} \tag{4}$$

Subsequently, the amplitude of the h-th order harmonic of the grid current is obtained as

$$I_{ga}^{h} = \left[\left(I_{sa,1}^{h} \right)^2 + \left(I_{sa,2}^{h} \right)^2 - 2 I_{sa,1}^{h} I_{sa,2}^{h} \cos\delta \right]^{1/2} \tag{5}$$

with I_{ga}^h being the amplitude of the h-th order harmonic of the grid current and $\delta = \pi - |\varphi_{sa,1}^h - \varphi_{sa,2}^h|$. It is thus indicated in Equations (4) and (5) that, if the h-th harmonic component of the grid current should be cancelled (i.e., $I_{ga}^h = 0$), the two drives have to:

1) Draw the same level of the harmonic currents from the grid (i.e., $I_{sa,1}^h = I_{sa,2}^h$) and
2) Have a phase difference of 180° between the two harmonic currents (i.e., $|\varphi_{sa,1}^h - \varphi_{sa,2}^h| = \pi$).

In practice, it is not easy to always ensure the currents drawn by the two drive units are at the same level, being the main drawback of the phase-shifted current control [21]. An advanced communication technology can be adopted to enhance the control performance, since it provides the loading information [26]. However, the communication can be more complicated in multiple ASD systems (more than two drives), where it may become costly (the total expenses may exceed the initial outlay).

Accordingly, a cost-effective solution for harmonic mitigation in multiple ASD systems is proposed in the following, where its implementation is independent of the loading condition. Specially, in the proposed harmonic mitigation strategy, the firing angles of the SCR-fed drive units are linearly designed within a specified range ($\alpha_{f,0}$ to $\alpha_{f,max}$) in the consideration of the resultant power factor. That is to say, the firing angle for each SCR-fed drive is deliberately dispatched as

$$\alpha_f^k = \alpha_{f,0} + (k-1)\frac{\alpha_{f,max} - \alpha_{f,0}}{N-1} \tag{6}$$

in which α_f^k represents the firing angle of the SCR-fed drive unit #k, k is the drive number, and N is the total number of drives forming the multi-drive system. It is implied in Equation (6) that the harmonic mitigation strategy does not require any communication among the SCR-fed drives, but it can achieve a satisfactory performance in terms of a low THD of the grid current and a relatively high power factor.

Although the implementation of the proposed scheme does not rely on expensive communication, the number of the drives N that have been connected to the PCC should be available according to Equation (6). Moreover, a central control unit that governs all the parallel drive systems is also essential to implement the proposed harmonic mitigation strategy. Those make the proposed scheme especially suitable for the applications in industrial production lines. In addition, the more the SCR drives are connected to the PCC, the better the performance will be. In that case, the grid current will have more levels, and its shape will be close to a sinusoidal waveform, leading to a better quality (a lower THD). It is noted that the firing angle range (i.e., $\alpha_{f,0}$ to $\alpha_{f,max}$) should not be very wide to maintain a satisfactory power factor (e.g., higher than 0.95); otherwise power factor compensation equipment (e.g., power factor correction capacitor banks) has to be installed.

3 Verification of the Proposed Approach

In order to evaluate the proposed harmonic mitigation strategy for multi-drive systems, numerical simulations in MATLAB have been performed firstly, where the currents drawn by the SCR-fed multiple drive systems have been programmed according to Equation (1) so that the harmonic characteristics can be studied. Fig. 3(a) shows the numerical

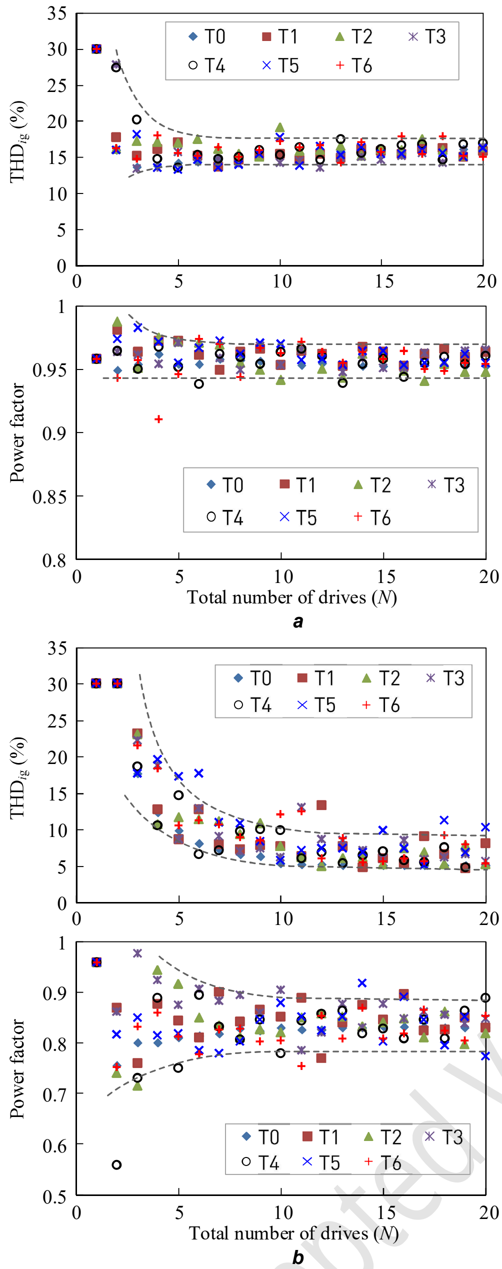

Fig. 2 *Performance of a multi-drive system considering various number of drives under different loading conditions with linearly dispatched firing angles (Top: THD level of the total current at PCC, i.e., the grid current; Bottom: resultant power factor):* **(a)** *$0° \leq \alpha_f \leq 30°$ and* **(b)** *$0° \leq \alpha_f \leq 60°$. If there is no phase-shifting (all DR-fed drives), a THD of 31% and a power factor of 0.96 will be obtained.*

simulation results of a multi-drive system under a random loading condition with the proposed method, where the firing angles are deliberately dispatched ($\alpha_{f,0}$ = 0 and $\alpha_{f,max}$ = 30°). Notably, for Test-0 (T0), the currents drawn by the SCR-fed drive units are at the same level for comparison, while for the rest tests (T1 to T6), the loading is random. More specifically, in the simulations, the loading of each drive is generated randomly using the function "rand()" in MATLAB. Then, the level of the rectified current of each drive can be calculated accordingly. Finally, the currents drawn by each drive are summed up, becoming the grid current of multi-level. It is clear that in some cases the loading of certain drives can be far below the rated. It can be observed in Fig. 3(a) that the resultant THD level of the total current (i.e., the grid current) is around 14-18% and a power factor of around 0.94-0.97 has been achieved. This indicates that the current quality as well as the power factor is independent of the loading conditions

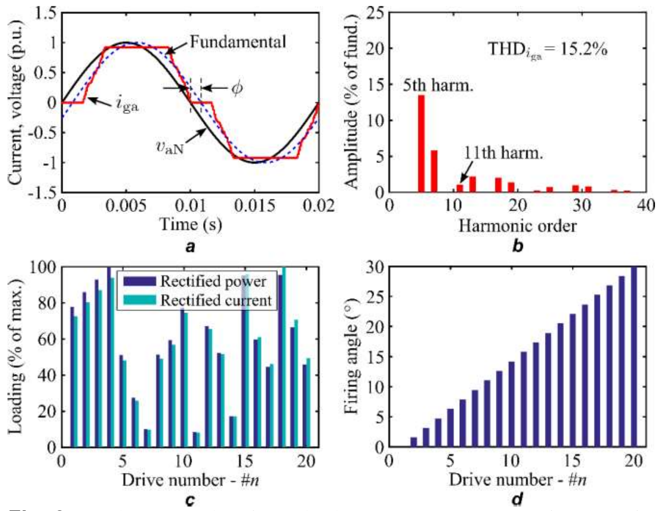

Fig. 3 *Simulation results of a multi-drive system consisting of 20 SCR-fed drive units (N = 20) under a random loading condition with linearly dispatched firing angles ($0° \leq \alpha_f \leq 30°$):* **(a)** *typical waveforms of the phase-a voltage v_{aN} and currents i_{ga},* **(b)** *harmonic distribution of the grid current,* **(c)** *loading of the multi-drive system (rectified power - $\overline{v_{rs} \cdot i_{rs}}$, rectified current - $\overline{i_{rs}}$), and* **(d)** *dispatched firing angles.*

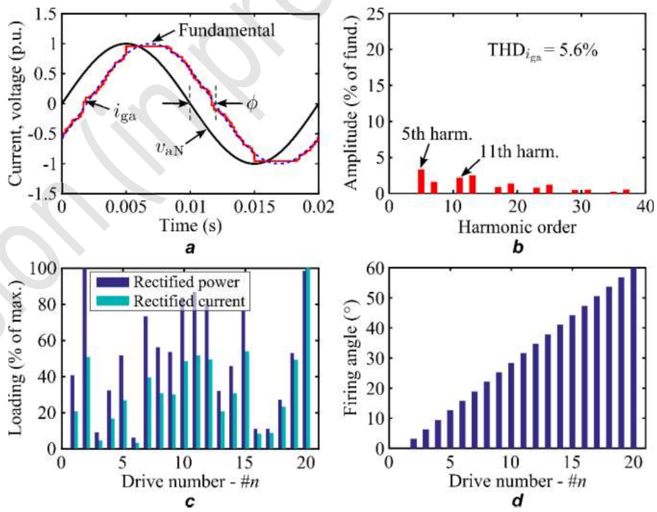

Fig. 4 *Simulation results of a multi-drive system consisting of 20 SCR-fed drive units (N = 20) under a random loading condition with linearly dispatched firing angles ($0° \leq \alpha_f \leq 60°$):* **(a)** *typical waveforms of the phase-a voltage v_{aN} and currents i_{ga},* **(b)** *harmonic distribution of the grid current,* **(c)** *loading of the multi-drive system (rectified power - $\overline{v_{rs} \cdot i_{rs}}$, rectified current - $\overline{i_{rs}}$), and* **(d)** *dispatched firing angles.*

as discussed in § 2, when the proposed method is adopted. It is further implied in Fig. 3(a) that with more parallel drive units, the THD level of the grid current and the power factor tend to be bounded (i.e., becoming more independent of the loading condition). In the worst cases, all drives are operating at the rated power (or only one drive is operating), the THD level of the total grid current will become 31%.

Following, the firing angle range has been extended to 60° (i.e., $\alpha_{f,0}$ = 0 and $\alpha_{f,max}$ = 30°), where for Test T0, the currents drawn by the SCR-drives are at the same level. The results are presented in Fig. 3(b). It can be observed in Fig. 3(b) that the THD level of the grid can be brought to around 8% when the firing angle range for dispatching is extended. Similar trends can also be seen from Fig. 3(b) – the THD level and the power factor variations are bounded, when the number of drives increases. However, as it has been mentioned, the THD improvement is achieved at the cost of power factor (see Fig. 3(b)). Hence, a trade-off between the power quality and the power factor has to be made when the

Table 1 Parameters of a multi-drive system (referring to Fig. 1(b)) consisting of four SCR-fed units

Parameter	Symbol	Value
Boost converter inductor	L	2 mH
dc-link capacitor	C_{dc}	470 μF
Grid frequency	f_g	50 Hz
Grid phase voltage (rms)	v_{abcN}	220 V
Grid impedance	Z_g (L_g, R_g)	0.18 mH, 0.1 Ω
Proportional gain of $G_{PI}(s)$	k_p	0.25
Integral gain of $G_{PI}(s)$	k_i	15
Hysteresis band	-	0.25 A

Table 2 Optimized firing angles for the four-drive system (P = [0.5, 6, 4, 2] kW).

Optimization range (°)		$\alpha_f \in$ [0 15]	$\alpha_f \in$ [0 30]	$\alpha_f \in$ [0 45]
Optimal firing angles $\alpha_{f,n}$ (°)	$\alpha_{f,1}$	6.4	12.3	38.4
	$\alpha_{f,2}$	15	18.3	45
	$\alpha_{f,3}$	15	30	26.1
	$\alpha_{f,4}$	0	0	2.1
Grid current THD (%)		20.6	13.3	11.2
Power factor		0.97	0.96	0.94

Notes: Subscripts (i.e., 1, 2, 3, and 4) represent the drive number.

proposed strategy is employed in multi-drive systems. Otherwise, it may incur more investments into compensating the resultant power factor.

In addition, Figs. 4 and 5 show the results of one case of Fig. 3 in details respectively in order to demonstrate the effectiveness of the proposed strategy. It can be seen in Figs. 4(b) and 5(b) that the THD of the grid current i_{ga} is significantly reduced in contrast to that of a single-drive system shown in Fig. 2. Furthermore, if the firing angles are designed within a wide range (e.g., $0° \leq \alpha_f \leq 60°$), the current THD level becomes even smaller, where the shape of the grid current is very close to sinusoidal, as it is shown in Fig. 5(a). However, it also introduces a large power factor angle ϕ that should be compensated in practice. In a word, the simulations have verified the effectiveness of the proposed strategy for multi-drive systems.

Apart from the above numerical studies, more simulations have been carried out in MATLAB/Simulink referring to Fig. 1, where four SCR-fed drive systems (P = [0.5, 6, 4, 2] kW) are considered. A Proportional Integral (PI) controller $G_{PI}(s)$ has been adopted to control the dc-link voltage (i.e., v_{dc}), where the reference dc-link voltage has been set as v_{dc}^{*} = 650 V. A hysteresis controller has been employed as the current controller to regulate the rectified dc-link current (i.e., i_{rs}). The system and controller parameters are listed in Table 1. Simulation results are shown in Fig. 6.

Fig. 6 demonstrates the simulation results of the multi-drive system, where the firing angles are linearly dispatched within a small range (i.e., α_f = [0, 10°, 20°, 30°]) in consideration of the resultant power factor. It can be seen that the grid currents i_{gabc} are not purely rectangular when comparing to those shown in Fig. 2(a) but more close to a sinusoidal shape (more levels due to the phase-shifts to the SCR drives). Thus, the current quality is improved in terms of a lower THD, as it is given in the harmonic distribution plot of Fig. 6(c). Furthermore, the power factor in this case has been calculated as 0.91, where compensating devices can be adopted.

Additionally, the dynamic performance of the multi-drive system is studied, where the system power levels have experienced step changes from P = [0.5, 6, 4, 2] kW to P = [1.5, 2, 4, 6] kW; while, the firing angles remained the same as the designed (i.e., α_f = [0, 10°, 20°, 30°]). Fig. 7 shows the

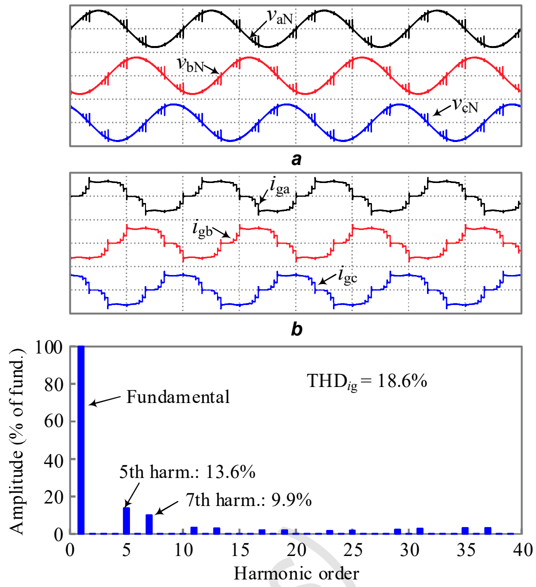

Fig. 5 *Simulation results of the multiple parallel ASD system consisting of four SCR-fed drive units with linearly designed firing angles ($0° \leq \alpha_f \leq 30°$):* **(a)** *grid phase voltages $v_{abc,N}$ [400 V/div],* **(b)** *total grid currents [40 A/div], time [10 ms/div], and* **(c)** *the Fast Fourier Transform (FFT) of the phase-a grid current i_{ga}.*

simulation results. It demonstrates that the multiple ASD systems employing the proposed harmonic mitigation strategy can operate smoothly during load transients. At the same time, the THD and the power factor variations are within certain bands (i.e., THD: 18.6% → 16.8%, power factor: 0.94 → 0.92), which is in agreement with the previous discussions (see Fig. 3). However, large overshoots in the dc-link voltages and slow dynamics have been observed, which requires further parameter-tuning.

Nevertheless, the above have validated the effectiveness of the proposal in terms of harmonic mitigation in multi-drive systems, where communication is not mandatory. However, it should be noted that, once the communication is available, the grid current quality could be significantly enhanced. In that case, the firing angles can be optimally dispatched according to loading conditions [27]. Table 2 gives an example of the optimized firing angles for the four-drive system with known power levels, where the particle swarm optimization algorithm is adopted. Clearly, compared to the case of linearly dispatched firing angles (see Fig. 6), the THD level can be further reduced once the optimization firing angle range is above [0 30º], as shown in Table 2. However, the power factor will be poor if the optimization range is too wide. In addition, there is a possibility to improve the grid current quality by operating certain drives in partial-loading conditions with optimal firing angles and optimal power levels. This is out of the cope of this paper, and implementing of the optimized results is another challenging issue, which also relies on communication.

Moreover, in order to validate the performance of multiple drive systems with deliberately assigned firing angles, experimental tests have been performed. Notably, the experimental tests were carried out under low voltage conditions (i.e., input phase-a voltage: 85 V in root-mean-square; output voltage: 250 V) and the rectified current levels are assumed at the same level. Due to the line impedance and the small number of drives (i.e., N = 3 and 4), the firing angles are not exactly linearly assigned in the experiments. Control systems have been implemented according to Fig. 1(d). The

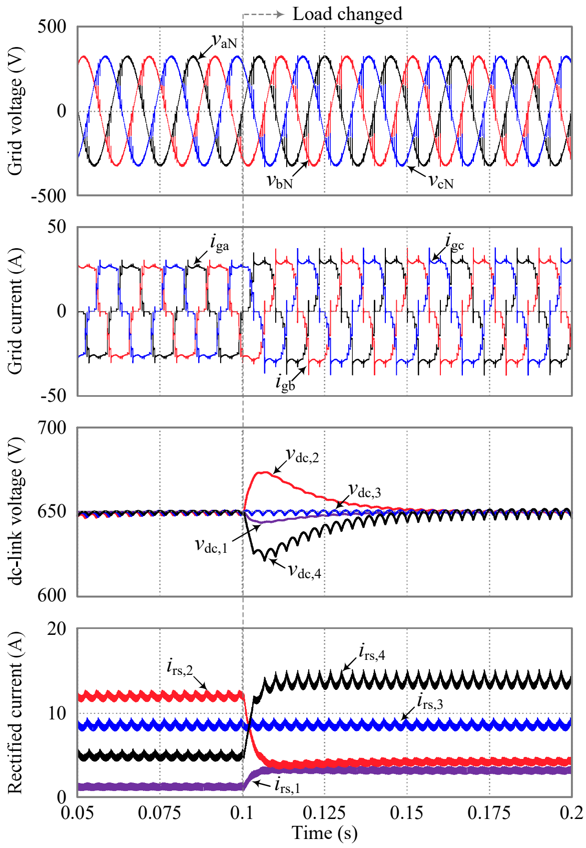

Fig. 7 *Transient performance of the multi-drive system consisting of four SCR-fed drive units with the deliberately dispatched firing angles, i.e., α_f = [0, 10°, 20°, 30°], where the subscripts (i.e., 1, 2, 3, and 4) represent the drive number.*

proportional and integral gains of the PI controller for the dc-link voltage are 0.01 and 0.1, respectively; the hysteresis band for the hysteresis current controller is 2 A. The control and modulation algorithms are implemented in digital signal processors. Experimental results are shown in Fig. 6. As it can be seen in Fig. 6, when more drives are connected and the firing angles are almost linearly dispatched, the THD level of the total grid current can be significantly reduced. In that case, the grid current will become multilevel. Compared to the single-drive unit, the THD level has been reduced to 10.9% and 8.3% for the three-drive and four-drive system, respectively. It should be pointed out that, in practice, the rectified current levels are not the same (i.e., the loading is not the same among the parallel drives). This will inevitably affect the harmonic mitigation performance of the system. However, once the number of drives (e.g., N = 10 or 20) is large, the THD of the total current will become independent of the loading when the firing angles are linearly assigned. In general, the experimental tests demonstrate the effectiveness of the harmonic mitigation scheme for multiple drive systems by deliberately dispatching the firing angles.

4 DC-link Current Modulation for Selective Harmonic Mitigation

Although the use of SCRs and boost converters in the dc-link has improved the power quality (e.g., from 31% to around 15% if α_f is linearly assigned within 0° ≤ α_f ≤ 60°), the potential of the boost dc-link to further lower the power quality is not exploited. Hence, in this section, a customized dc-link current modulation is demonstrated on a two-drive system (a DR- and a SCR-fed drive) to further mitigate the

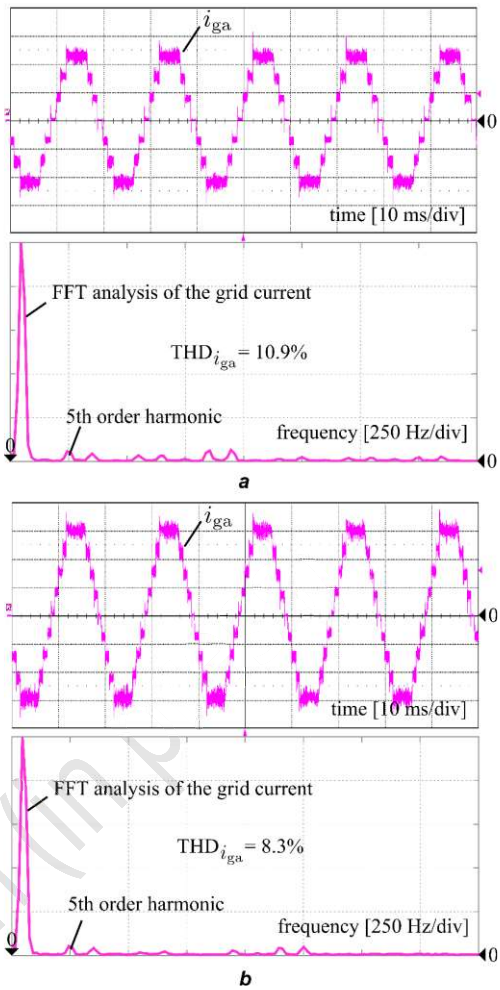

Fig. 6 *Performance (experimental results) of a multi-drive ASD system with the phase-shifted current control (grid current i_{ga} [5 A/div]; Bottom: Fast Fourier Transform – FFT analysis of the grid current i_{ga} [% of fund., 20%/div])*: **(a)** *three drives (α_{f1} = 0° -- DR unit, α_{f2} = 20°, α_{f3} = 42.7°, power factor: 0.91) and* **(b)** *four drives ((α_{f1} = 0° -- DR unit, α_{f2} = 16.7°, α_{f3} = 33°, α_{f4} = 50°, power factor: 0.92).*

harmonics at the PCC. The performance is also compared with the conventional solution (i.e., only with the phase-shifted current control and the rectified current is controlled as a flat current).

Fig. 9(a) shows the shape of the demonstrative modulation signal and its harmonic distribution, where it is observed that the modulation signal selectively mitigates the 7th and the 13th order harmonics, when applied to a single motor drive with a boost converter in the dc-link (see Fig. 1(a)). However, the total harmonic distortion is higher compared to that of the grid current without modulation (see Fig. 2(b)). It is also seen in Fig. 9(a) that the 5th order harmonic and the harmonics of fivefold the fundamental frequency are the major harmonic distortions. Hence, a phase-shift of 36º is applied to the SCR unit, which should mitigate the 5th order harmonics and all the harmonics of fivefold the fundament frequency in the grid currents. The resultant current shape is shown in Fig. 9(b), where it can be seen that all the harmonics of fivefold the fundament frequency have been mitigated, and thus a THD of 12% is achieved. It means that the SCR with a boost converter in the dc-link can improve the power quality in multiple motor drive systems.

In order to further verify the effectiveness of the harmonic mitigation by the SCR-fed drive system with the customized dc-link modulation scheme, experimental tests have been

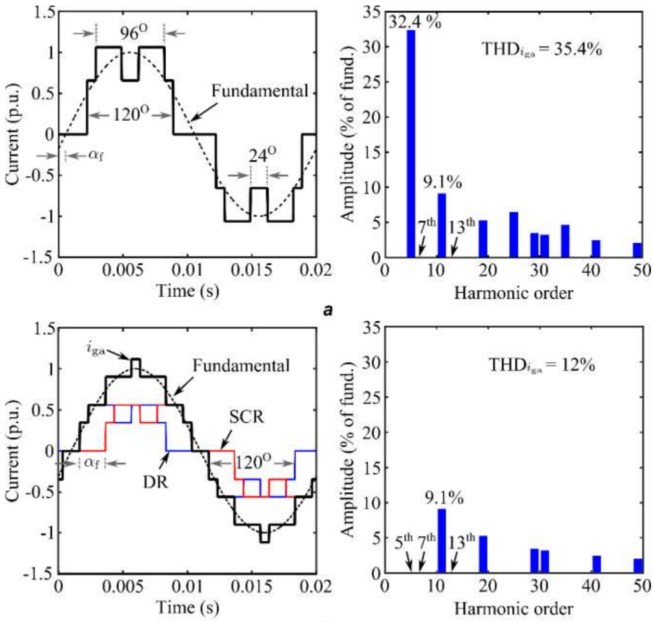

Fig. 8 *Performance of a two-drive ASD system with boost converters in the dc-link:* ***(a)*** *harmonic characteristics of the customized dc-link modulation scheme for selective harmonic cancellation (i.e., the 7th and the 13th harmonics) and* ***(b)*** *harmonic characteristics of ideal current shapes of the two-drive system (i.e., a DR-fed and a SCR-fed drive) when the dc-link modulation scheme (see Fig. 9(a)) is applied to the two drives (a phase-shift of 36° has been applied to the SCR-fed drive).*

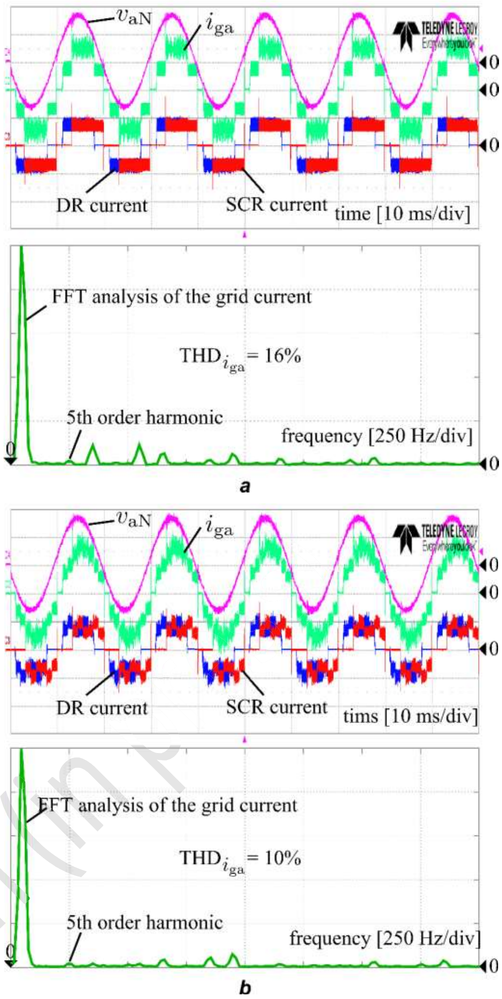

Fig. 9 *Performance (experimental results) of the ASD system with boost converters in the dc-link (Top: grid voltage v_{aN} [200 V/div], grid current i_{ga} [10 A/div], DR input current [10 A/div], SCR input current [10 A/div]; Bottom: Fast Fourier Transform – FFT analysis of the grid current i_{ga} [% of fund., 20%/div]):* ***(a)*** *only with the phase-shifted current control (α_f = 36°, the total power is 6.63 kW and the PF is 0.93) and* ***(b)*** *with the phase-shifted current control (α_f = 38°) and the customized modulation scheme (designed to mitigate the 7th and 11th harmonics), where the total power is 6.86 kW and the PF is 0.94.*

carried out on a two-drive system (a DR- and a SCR-fed drive). The system parameters are shown in Table 1. Controller parameters are the same as those for the tests in Fig. 8. The experimental results are shown in Fig. 10, where one motor is connected to the DR unit according to Fig. 1 and a resistive load is connected to the SCR unit. It can be seen in Fig. 10(a) that with the SCR-fed drive included in the multi-drive system, the harmonics of the total grid currents at the PCC can be mitigated to some extent by phase-shifting the current drawn by the SCR unit. Here, in the experiments, a phase-shift of 36º has been applied to the SCR unit, which should in theory mitigate the 5th order and all the other harmonics of fivefold the fundamental frequency. However, due to the line impedance and quantization errors, the 5th order harmonic is not completely cancelled out but lowered significantly by the phase-shift control of the SCR-fed unit, as shown in Fig. 10(a). As a consequence, the total harmonic distortion level has been significantly reduced to 16% in comparison to the DR-fed drives (either a single-drive or a multi-DR drive system, whose harmonic distribution is shown in Fig. 2(b)).

Additionally, in order to improve the current quality, a customized modulation scheme that aims to mitigate the 7th and 11th order harmonics has been applied to the two drive units, and the experimental results are shown in Fig. 10(b). Notably, considering the line impedance, the firing angle is slightly increased to 38° to cancel out the 5th order harmonic and all harmonics of fivefold the fundamental frequency. Observations from Fig. 10(b) indicate that the SCR-fed unit together with a customized modulation scheme for the boost dc-link can improve the power quality, like the case shown in Fig. 9(b). The effectiveness lies in two points:

- The SCR-fed system enables the phase-shift control that can cancel out certain harmonics in the total grid currents (e.g., the 5th order and all harmonics of fivefold the fundamental frequency), and
- The boost dc-link results in the possibility to modulate the rectified currents (and thus to shape the grid currents) in order to mitigate specific harmonics (e.g., the 7th and 11th order harmonics).

As a consequence, a THD of 10% has been achieved, as shown in Fig. 10(b). In both cases, a power factor above 0.9 (i.e., 0.93 and 0.94, respectively) has been obtained, and as aforementioned, power factor correction devices can be installed per demands. In addition, it should be mentioned that, if more drives with boost converters in the dc-link are considered and customized modulation schemes are employed, the THD level of the grid currents can further be lowered. If properly designed, the resultant power quality can be competitive to that achieved by multi-pulse transformer based rectifiers.

5 Conclusion

In this paper, the harmonic issues in multiple parallel motor drive systems have been briefly investigated, and accordingly, a cost-effective harmonic mitigation strategy has been proposed for the SCR-fed ASD systems, where the firing angles for the SCR units are designed within a certain range and then deliberately dispatched among the parallel drives. With the proposed harmonic mitigation method, the THD level of the total grid current has been reduced, while the power factor can be maintained at a satisfactory level. Simulations and experimental tests have validated the effectiveness of the proposal, being of load-independent, which can practically be implemented on a production line without communication. More important, since boost converters have been employed in the dc-link in order to increase the controllability of the grid current harmonics, customized dc-link current modulation schemes can then be used to selectively cancel out the harmonics. In that case, the current quality can be improved. The effectiveness of this harmonic mitigation scheme has also been demonstrated by simulations and experiments. If the customized modulation schemes are applied to multiple drive systems, a low THD level of the grid current can be achieved.

6 References

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