Integrated AC to AC Converters for Single-phase Input to Two-phase Output Motor Drives

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***Abstract*—The single-phase to two-phase converters have become attractive for low-power motor drives due to the full electromagnetic isolation between phases of two-phase motors. One of the commonly used topologies is the ac/dc/ac pulse width modulation (PWM) converter which contains twelve active power semiconductor switches and a common dc link. To minimize the system cost and size for low power applications, an integrated ac/ac converter with a single-phase input and a two-phase output which reduces the switch count to six is proposed in this paper. Additionally, modulation scheme and filters for the proposed converter are developed and modeled in details. In this paper a systematic comparison among the conventional ac/dc/ac converters, matrix converters, and the proposed integrated ac to ac converters for single-phase input to two-phase output motor drives applications is performed in terms of the output voltage/current capability, total harmonics distortion (THD), and system cost. Furthermore, closed-loop speed controllers are developed for the three topologies, and the maximum operation range and output phase currents are investigated. Simulation and experimental results validated the effectiveness of the developed converters and control strategies.**

***Index Terms*—AC/AC converter, two-phase motor, axial flux permanent magnet machine, motor drive.**

I. INTRODUCTION

The single-phase grid has been widely used in power distribution systems for residences and small commercial buildings, where single-phase to two-phase and single-phase to three-phase power conversions are required to drive low-power motors [1] [2]. In particular, two-phase machines have shown attractiveness due to the magnetic and electrical isolation between two phases, and low cost on developing the drive systems [3] [4].

To achieve the single-phase to two-phase power conversion, one of the most commonly utilized topologies is the ac/dc/ac pulse width modulation (PWM) converter which requires ten or twelve active power semiconductor switches and a common dc link [5]. However, especially for low power applications, a component minimized topology offering the same functionality can reduce switch counts and therefore the system cost. [6]

On the other hand, researchers have been working on reducing dc capacitance for a minimized system cost. The matrix converter, which does not require either any dc-link circuit or large energy storage elements has been studied and developed [7]. The key element in a matrix converter is the fully controlled four-quadrant bidirectional switch module, which allows high frequency operation but contains two power semiconductor devices for each module [8]. Additionally, filters must be used at the input of matrix converters.

A systematic study on the comparison among the conventional back-to-back converters, matrix converters, and component-minimized ac/ac converters is in great need considering some aspects of the subject matter has been discussed but scattered in the existing literature. In this paper, three topologies, the modulation scheme, and filter designs for the two commonly utilized topologies and the proposed integrated ac/ac converter are presented. Closed-loop speed controllers and an experiment prototype are developed. As a result, a systematic comparison on system cost and output performance is studied and validated.

II. CONVENTIONAL SINGLE-PHASE INPUT TO TWO-PHASE OUTPUT CONVERTERS: AC/DC/AC CONVERTER AND MATRIX CONVERTER

As one of the commonly utilized topologies, the ac/dc/ac PWM converter usually contains a full-wave rectifier, a dc link, and two H-bridges to drive the two phases of the load (Fig. 1). The input filter and dc capacitors smooth the input current and dc voltage, respectively. The rectifier can be operated in active or passive mode, and the PWM modulation for the inverter can be expressed as follows:

$$\begin{cases} V_{PhA} &= V_{A^+} - V_{A^-} = m\left(\frac{V_{dc}}{2}\right)\cos\left(\omega t - \varphi\right), \\ V_{PhB} &= V_{B^+} - V_{B^-} = m\left(\frac{V_{dc}}{2}\right)\sin\left(\omega t - \varphi\right), \end{cases} \quad (1)$$

where V_{PhA} and V_{PhB} are the terminal voltages of Phase A and Phase B of the load, respectively. V_{A^+}, V_{A^-}, V_{B^+}, and V_{B^-} represent the voltage at the points A^+, A^-, B^+, and B^-, respectively. m and V_{dc} are the modulation index and dc voltage amplitude, respectively. The angular frequency of the two-phase machine ω is obtained from $\omega = 2\pi f$, and φ is the initial phase of the reference wave.

The single-phase to two-phase matrix converter (Fig. 2) includes 8 active bidirectional switching modules, input filter,

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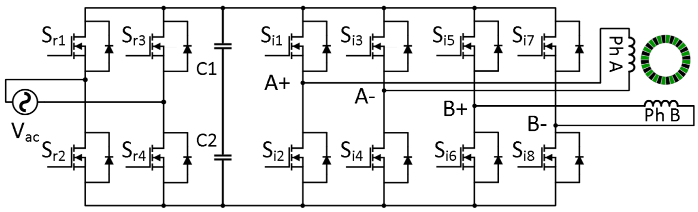


Fig. 1: A conventional back-to-back converter for single-phase full-wave input and two-phase output.

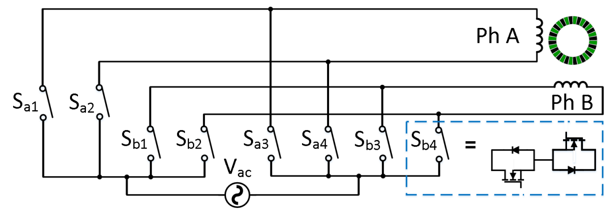


Fig. 2: Matrix converter for single-phase input two-phase output.

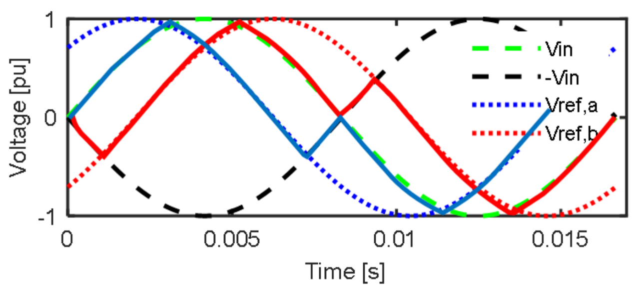


Fig. 3: Modulation scheme developed for single-phase to two-phase matrix converter.

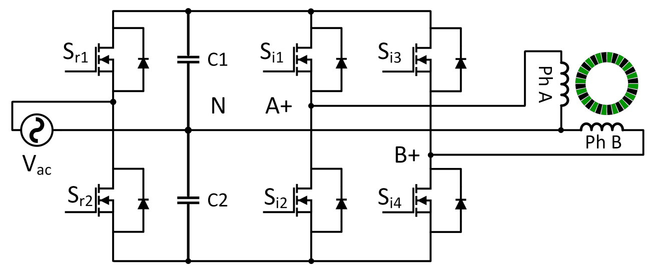


Fig. 4: The proposed integrated ac/ac converter for single-phase input to two-phase output.

TABLE I: The operating scheme for single-phase to two-phase matrix converter.

Mode	I	II	III	IV
$V_{refA} \times V_{ac}$	+	+	-	-
$\|V_{refA}\|$ - $\|V_{ac}\|$	+	-	-	+
$\|S_{a1}\|$	On	PWM	Off	Off
$\|S_{a2}\|$	Off	Off	PWM	On
S_{a3}	Inverse of S_{a1}			
S_{a4}	Inverse of S_{a2}			

and load side filter. To be specific, each switching module usually has 2 active semiconductor switching devices. The key benefit of matrix converter is the elimination of dc link capacitor; however, the input filter and load side filter are required in matrix converters. Besides, since there is no natural freewheeling path, commutation has to be actively controlled at all times. The control scheme (Fig. 3) and operating scheme (Table I) for matrix converters thus are more complicated than ac/dc/ac converters, which is presented as follows:

$$\begin{cases} V_{ac} &= V_g \cos(\omega t) = V_{refA} + V_{refB}, \\ V_{refA} &= \left(\frac{V_g}{\sqrt{2}}\right) \cos\left(\omega t + \frac{\pi}{4}\right), \\ V_{refB} &= \left(\frac{V_g}{\sqrt{2}}\right) \sin\left(\omega t + \frac{\pi}{4}\right), \end{cases} \tag{2}$$

where V_{ac} is the input voltage and V_g is the amplitude of input voltage. V_{refA} and V_{refB} represent the reference voltage for Phase A and Phase B, respectively.

III. Load Impedance Compensation and Modulation Scheme for the Proposed Integrated AC to AC Converters

In this topology, the neutral point of dc link is accessed by both rectifier and inverter, and the dc capacitor provides conduction path for both rectifier and inverter (Fig. 4). As a result, inverter switching is interfering with the rectifier control, and the load side impedance has an influence on voltage/current amplitude balance. To develop control scheme for the proposed converter, a load impedance compensation angle is necessary and appropriate filter designs are required.

Consider input voltage and current can be formulated as:

$$\begin{cases} v_g(t) &= V_g \cos\left(\omega_g t - \theta_g\right), \\ i_g(t) &= I_g \cos\left(\omega t\right), \end{cases} \tag{3}$$

where $v_g(t)$ and $i_g(t)$ indicate input voltage and current, respectively. V_g and I_g are the amplitudes and θ_g represents the phase angle between grid voltage and current.

For the load side, the load voltage and current can be expressed as:

$$\begin{cases} v_l(t) &= V_l \cos\left(\omega_l t - \sigma\right), \\ i_l(t) &= I_l \cos\left(\omega t - \sigma + \theta_l\right), \end{cases} \tag{4}$$

where $v_l(t)$ and $i_l(t)$ indicate load side voltage with amplitude V_l and load side current with amplitude of I_l. θ_l represents the phase difference between load voltage and load current, and σ is the compensation angle used for control development. Then the power $p_c(t)$ flows into dc capacitor can be written as:

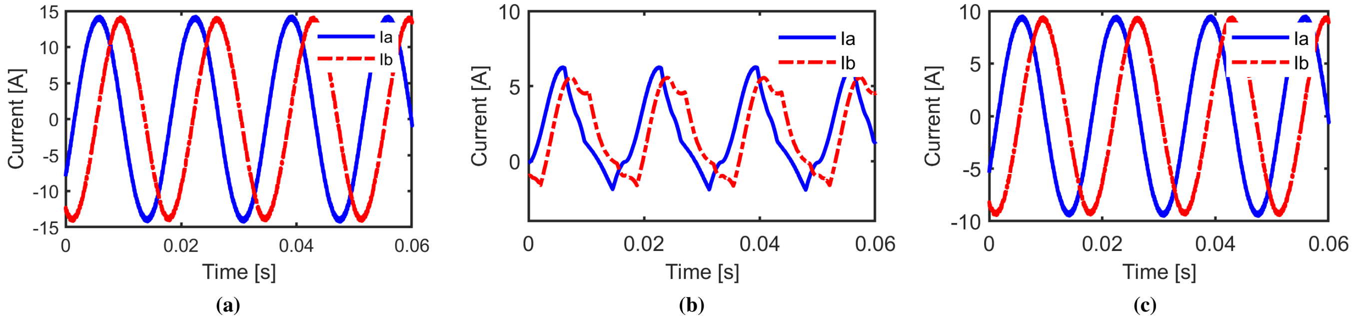


Fig. 5: The output phase currents of, (a) a conventional single-phase to two-phase back-to-back converter, (b) a single-phase to two-phase matrix converter, and (c) the proposed integrated ac/ac converter.

TABLE II: The comparison among the three topologies with the same input ac source (V_{ac} = 120Vrms) and the same loading (R_{ph} = 1Ω, L_{ph} = 5mH).

Converter	Input filter	dc cap	Switch count	$V_{ph,rms}(\%)$	$I_{ph,rms}(A)$	$P_{out}(W)$	THD (%)
Conventional	Small	Small	12	100	10	271	1.7
Matrix	Small	No	8 bidirectional	61.2	3.1	21	22.1
Integrated ac/ac	Large	Large	6	66.7	6.7	167	3.7

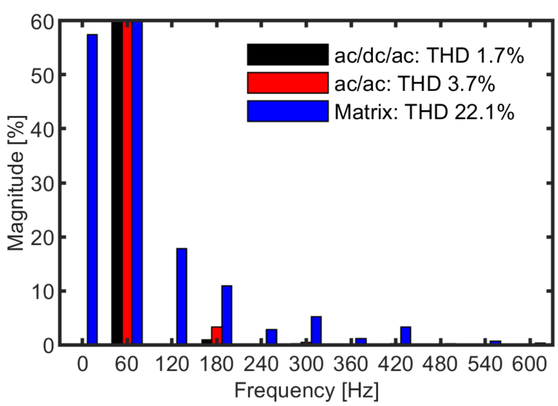


Fig. 6: The current harmonic spectra in % of the magnitude at 60Hz fundamental frequency for the three types of converters.

$$p_c(t) = \frac{V_g I_g}{2}\cos\theta_g - \frac{V_l I_l}{2}\cos\theta_l - \frac{V_l I_l}{2}\cos\left(\theta_l - \frac{\pi}{2}\right) + \frac{V_g I_g}{2}\cos\left(2\omega_g t - \theta_g\right) - \frac{V_l I_l}{2}\cos\left(2\omega_l t - 2\sigma + \theta_l\right) - \frac{V_l I_l}{2}\cos\left(2\omega_l t - \frac{\pi}{2} - 2\sigma + \theta_l\right) \quad (5)$$

To have a balanced dc capacitor power flow which is supposed to be controlled to zero, the modulation scheme with load impedance compensation angle σ can be obtained as:

$$\begin{cases} V_A &= V_s\cos(\omega t + \sigma) = V_s\cos(\omega t + \frac{\theta_g+\theta_l}{2}), \\ V_B &= V_s\sin(\omega t + \sigma) = V_s\sin(\omega t + \frac{\theta_g+\theta_l}{2}). \end{cases} \quad (6)$$

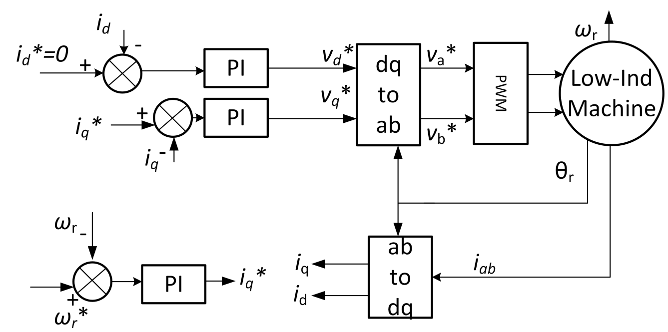


Fig. 7: Closed-loop speed control strategy for a two-phase axial flux PM machine drive system.

IV. Filter Designs for the Proposed Integrated AC to AC Converters

The real power flowing from single-phase ac source into dc link can be expressed as:

$$P_i = \frac{V_{ac}V_{dc}}{X_i}\sin\theta \quad (7)$$

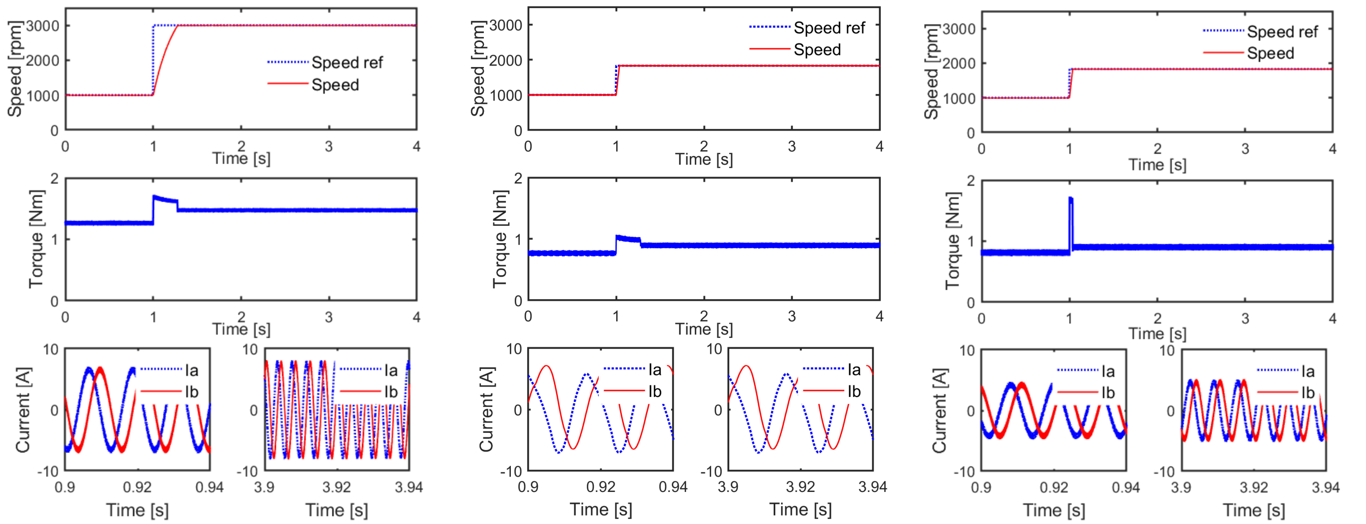
where X_i and θ represent the reactance of input L filter and angle difference between input V_{ac} and dc link V_{dc}, respectively. The input power factor pf can be expressed as:

$$pf = \cos\phi = \frac{V_{dc}\sin\theta}{\sqrt{V_{ac}^2 + V_{dc}^2 - 2V_{ac}V_{dc}\cos\theta}} \quad (8)$$

A constant k can be defined as:

$$k = \frac{V_{dc}/2}{\sqrt{2}V_{ac}} \quad (9)$$

and the value of reactance X_i maintains the input power factor as:



(a) (b) (c)

Fig. 8: Simulation results, including the motor speed, estimated electromagnetic torque, and phase currents of closed-loop speed control for a two-phase axial flux PM motor drives in response to the reference speed step change from 1000rpm to maximum operating speed, (a) a conventional single-phase to two-phase back-to-back converter, (b) a single-phase to two-phase matrix converter, and (c) the proposed integrated ac/ac converter.

TABLE III: PARAMETERS OF THE DEVELOPED MOTOR AND DRIVE PROTOTYPE.

Number of poles p	10
Inertia of rotor J	0.04 kg.m^2
Phase inductance L_s	1.9 mH
Phase resistance r_s	0.5 Ω
Fundamental frequency f	250 Hz
Rated torque T	1.2 Nm
Rated speed ω_n	3,000 r/min
Rated current I_n	4.4 A
Rated power P_{rated}	0.5 hp
Switching frequency f_w	5 kHz

$$X_i = \frac{V_{ac}^2\sqrt{k^2-1}}{P_i} \tag{10}$$

In this study, the system is operated at unity power factor in which $V_{dc} = \sqrt{2}V_{ac}/2$. As a result, the input L filter and dc capacitance C can be designed, respectively, as follows:

$$L = \frac{X_i}{\omega}, \qquad \Delta V_{C,ripple} = \frac{I_{C,ripple}}{\omega C} \tag{11}$$

V. Simulation and Experimentation

Simulation and experimentation were carried out to validate the feasibility and effectiveness of the proposed integrated ac/ac converter, ac/dc/ac converters, and matrix converters. With the residential electricity (single-phase ac 120Vrms, 60Hz), the conventional ac/dc/ac PWM converter can provide 10A output current (Fig. 5a), while the matrix converter with direct modulation method is able to provide 3.1A under the same condition (Fig. 5b). For the proposed integrated ac/ac converter, the output current under the same condition is up to 6.7A (Fig. 5c).

By using Fast Fourier transform (FFT) tools to analyze the current results, the THD for the conventional ac/dc/ac converter, matrix converter, and the proposed integrated ac/ac converter shows 1.7%, 22.1%, and 3.7%, respectively (as shown in Fig. 6). A systematic comparison among these three topologies is listed in Table II.

In addition, a speed closed-loop controller (Fig. 7) is developed to drive a two-phase axial flux PM machine using residential electricity as input ac source. Responses of motor speed and currents to a step change in the reference speed are presented in Fig. 8. The parameters of the designed machine is listed in Table III. With a conventional back-to-back converter, the rated speed 3000rpm can be reached (Fig. 8a). In contrast, the proposed ac/ac converter and a matrix converter with direct modulation can be operated up to 2000rpm and 1830rpm (Fig. 8c and 8b), respectively. The results of estimated electromagnetic torque and output phase currents are also presented and compared.

Furthermore, a prototype of the proposed ac/ac converter is built (Fig. 9) for the designed two-phase axial flux PM motor drives using residential electricity (single-phase ac 120Vrms, 60Hz). The dSPACE control board generates gating signals to drive the converter. Based on the proposed modulation schemes, gating signals for the two phases are generated 90 electrical degrees apart from each other, matching the machine drive requirements. CREE SiC MOSFET power semiconductors C2M0280120D (rated at 1200V/10A and operated at switching frequency 5kHz and 50kHz) are employed for the prototype drive system. An experiment prototype (Fig. 10) shows the dc link voltage (Fig. 10a, ripple percentage within

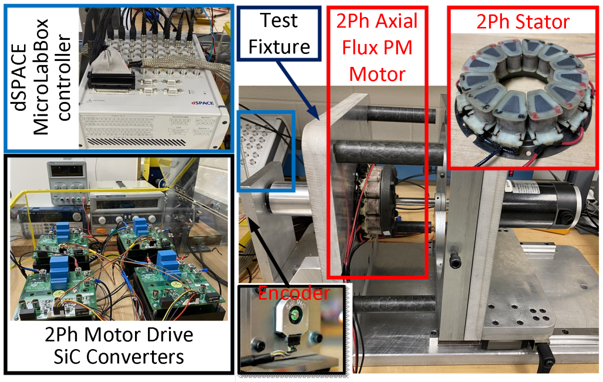


Fig. 9: Experimental setup for two phase axial flux permanent magnet machine and wide band gap device power electronics drive.

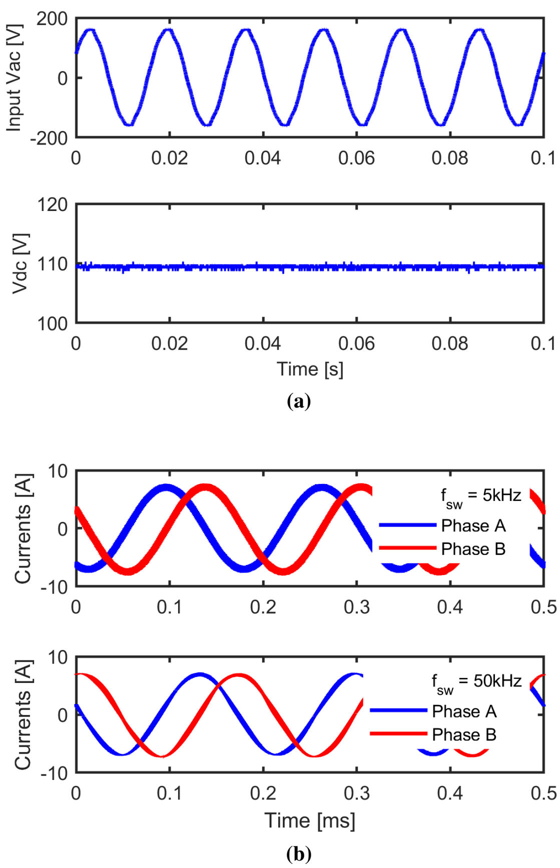


Fig. 10: Experimental results of the proposed ac/ac converter, (a) input ac voltage and dc link voltage with developed voltage filter, and (b) output phase currents.

5% using developed dc link voltage filter) and output two-phase currents (Fig. 10b) with RL load (R_s = 0.5Ω, L_s = 1.9mH) at different switching frequencies.

VI. Conclusion

This paper proposed an integrated ac/ac converter for single-phase input and two-phase output motor drives which reduced the switching device count to 6 and maintain the same functionality and output performance. Furthermore, a systematic comparative study of three converter topologies for single-phase to two-phase low-power motor drives, including topologies and associated modulation schemes, system cost, filter size, output voltage capability, speed operation range, and output distortion, is presented. The conventional ac/dc/ac topology can output the full output voltage capability with a low distortion (THD 1.7%); however, it requires 12 active semiconductor switching devices and dc capacitors which therefore increases the system cost. The matrix converter does not have any dc link; however, it still requires a large number of switching devices (8 bidirectional modules) and offers a reduced output voltage range (61.2%) with a very high THD of 22.1% under the same condition. In the proposed topology, the switch count is largely reduced to 6 and the output distortion also remains low (THD 3.7%). The modulation scheme and filter design are also included. In addition, a prototype for a two-phase axial flux permanent magnet motor drive has been built and the experimental results validated the effectiveness of the proposed ac/ac converter and converter control schemes.

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