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High-Frequency AC-AC Converter with Minimal Capacitance and Compact Transformer for Improved Power Density and Reliability

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Abstract—This paper presents a single-stage three-phase AC-AC converter utilizing a high-frequency alternating link voltage. The converter achieves efficient energy transfer with a minimal film capacitor, eliminating the need for large electrolytic capacitors common in traditional DC-link AC-AC converters. Additionally, a compact high-frequency transformer at the link is proposed, replacing bulky low-frequency transformers for isolation when necessary. These design features collectively enhance power density and reliability compared to conventional converters. The converter requires only 12 switches, minimizing switching and conduction losses in comparison to matrix converters. Despite its single-stage design, the converter is capable of both stepping up and stepping down voltage, along with frequency transformation, eliminating the need for cascaded power converters. The paper introduces variable and fixed switching frequency control methods, and the performance is verified through comprehensive simulation and experimental studies.

Index Terms—ac-ac converter, high frequency link, solid state transformer.

1. INTRODUCTION

In the realm of power electronics, the quest for more efficient and compact converters continues to drive innovation. This paper introduces a pioneering approach to AC-AC conversion through a single-stage three-phase converter leveraging a high-frequency alternating link voltage. The traditional use of large electrolytic capacitors in DC-link AC-AC converters is circumvented by harnessing the energy transfer capabilities of a very small film capacitor, enabled by the high-frequency characteristics of the link voltage.

Furthermore, to address the challenges associated with bulky low-frequency transformers, a

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compact high-frequency transformer is proposed for applications requiring isolation. This transformative design not only contributes to a significant reduction in component size but also enhances the reliability and power density of the converter when compared to conventional counterparts.

The converter, requiring a mere 12 switches, stands as an economical alternative to matrix converters, exhibiting lower switching and conduction losses. Remarkably, this single-stage configuration proves to be versatile, capable of both stepping up and stepping down voltage, in addition to facilitating frequency transformation. The need for cascaded power converters is consequently eliminated, simplifying the overall system architecture.

To elucidate the operational principles and control mechanisms of the proposed AC-AC converter, this paper introduces variable switching frequency and fixed switching frequency control methods. Validation of the converter's performance is undertaken through a comprehensive set of simulations and experimental studies. The subsequent sections delve into the intricacies of the converter's design, its inherent advantages, and the experimental findings that underscore its viability for contemporary power electronic applications.

2. LITERATURE SURVEY

In [10], a bidirectional PWM buck-boost ac-ac converter is proposed with only six switches, however, it needs three inductors as energy transferring elements. In [11], a unidirectional threephase ac-ac converter is proposed that combines three singlephase three-leg ac-ac converters. Although this converter has the advantages of multilevel input and output voltages as well as low THD of the currents, it still requires three large dc-link electrolytic capacitors. In [12], a T-type family of ac-ac converters is proposed, which is able to directly perform the acac conversion in a single-stage, and realize a modular converter for reducing the voltage stress of the switches. However, in the three-phase structure, the control algorithm is complex and the converter needs 36 switches, leading to higher losses.

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Resonant ac-ac converters have been proposed in [13-16] as an alternative to the conventional dc-link converters. These converters utilize a high frequency link to introduce zero voltage or zero current switching transitions. Since the link inductor and capacitor in these types of converters need to continuously resonate, high reactive rating for the link components is required, which leads to higher power losses in the ac-link. Another type of ac-link converter is proposed in [17], which utilizes 24 reverse blocking IGBTs (RB-IGBT) and benefits from zero voltage switching for the output-side switches. However, this converter cannot operate properly without a transformer. Also, the input and output currents of this converter do not have pure sinusoidal waveforms. In [18], a three-phase PWM Ćuk ac-ac converter, which requires six switches and three capacitors as energy transferring elements, is modeled and analyzed; the voltage gain is reported to be limited to 2.5. The Ćuk-based converter proposed in [18], is modified in [19] such that the three switches at each side of the converter are replaced by a diode bridge and a switch, which reduces the switch count of the converter. Although the number of switches in the Ćuk-based ac-ac converters proposed in [18] and [19] are small, they require three capacitors for transferring energy. Also, these converters are not capable of frequency transformation, which is a major drawback, and limits their applications. Universal power converters are another class of single-stage power converters that eliminate the need for large electrolytic capacitors. These converters are typically categorized as indirect single-stage converters in which a small energy storage component transfers the power from input to output. Additionally, in most universal converters, galvanic isolation can be provided through a single-phase high frequency transformer added to the link. These converters, which can have any number of sources and loads with any forms, any number of phases, any frequency or voltage amplitude, extend the principles of the operation of indirect dc-dc converters to multiphase systems. The converter proposed in [20], extends the operation of the dc-dc flyback converters to function as a threephase ac-ac conversion system. Although this converter needs only six active devices to perform the three-phase ac-ac power conversion, the ratings of the switches are high and three individual single-phase transformers are required. In

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[21], the principles of the operation of a dc-dc buck-boost converter was extended to a three-phase ac-ac converter. Similar to the conventional dc-dc buck-boost converter, an inductor transfers the power from input phases to output phases of this converter, and the switches have hard switching. In [22], a capacitor was added to the link of the universal buck-boost converter to allow the switches to benefit from zero voltage turn-on and soft turnoff. There are four modes in each switching cycle of this converter, during the first mode the link inductor is charged from one of the input phase pairs, and in mode 3 it is discharged to one of the output phase pairs. Modes 2 and 4 are resonating modes that facilitate the soft-switching. One drawback of this converter is the long resonating modes. Moreover, in each switching cycle, the currents of only one input phase and one output phase are regulated.

In [23], the buck-boost universal converter was further modified to allow the link inductor to be charged and discharged in both positive and negative directions. This resulted in shorter resonating modes. Moreover, in the three-phase ac-ac configuration proposed in [23], each charging and discharging mode is split into two modes to allow the currents of all three input phases and all three output phases to be regulated in each switching cycle; hence, having low current THDs. The performance of this converter was studied in detail in [6]. Despite its numerous advantages, the converter proposed in [23] requires a large number of switches, i.e. 24 switches for the three phase ac-ac configuration. To overcome this limitation, in [24-26], several modified universal configurations, which require a smaller number of switches compared to the converter proposed in [23], were proposed. Despite reducing the number of switches, the conduction losses were increased in these converters. In [27], the Dyna-C topology, which is another family of single-stage universal converters, is proposed for SST applications. This converter consists of two three-phase switch bridges connected through a high-frequency transformer; the magnetizing inductance of this transformer acts as the energy transferring component. In this paper, the control of the universal buck-boost converter proposed in [22] was modified such that there are two charging modes and two discharging modes in each cycle, while keeping the number of active devices equal to 12. However, the reported efficiencies were poor mainly because of the high conduction losses of the incorporated active devices and losses related to the diode reverse recovery [28, 29]. In [30], an auxiliary circuit is added to the Dyna-C converter to enable the soft switching transition of the switches and improve the efficiency, while keeping the desirable features of Dyna-C converter, such as step up/down of the voltage, realizing multiport structure, and high frequency isolation. The detailed design of this soft switching topology for an SST application is thoroughly discussed in [31]. Two other families of soft-switching inductive-link universal power converters inspired by non-inverting dc-dc buck-boost converters are proposed in [32, 33]. In these converters, which can operate in buck, boost, or buck-boost modes, the link peak current is reduced compared to the buck-boost type universal power converters, potentially leading to lower conduction losses. In [34, 35], another class of universal converters, which extends the principles of the operation of a dc-dc Ćuk converter to multiphase systems, was proposed and studied. This converter is dual of the converter proposed in [23]. The link capacitor is the main energy storage component, and a small inductor can be added in series with the link capacitor to allow the switches to benefit from zero current turn-off and soft turn-on. This converter requires large number of switches; a three-phase acac configuration needs 24 switches. In this paper, another class of capacitive-link universal converters, benefitting from a high frequency alternating link voltage is studied, analyzed, and evaluated.

The proposed converter has the same number of switches as conventional PWM back-to-back dc-link converters, while offering high frequency alternating voltage and current in the link. This feature eliminates the need for a large unreliable electrolytic capacitor. Also, in case the galvanic isolation is desired, a compact high frequency transformer can be placed in the link. In contrast to the conventional dc-link converters, this converter has higher power density and longer life-time. In addition, since the number of switches is smaller than the matrix converters, the proposed converter can promise higher efficiency compared with the matrix converters. Moreover, the voltage gain limitation is not an issue in this converter. It is also capable

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of stepping up or stepping down the voltage amplitude as well as changing the frequency. This topology was first proposed in [36, 37], and its performance was evaluated through simulations. This paper provides a thorough analysis on the behavior of this converter and its control algorithm, and evaluates the performance of the proposed converter through both simulations and experiments. Table I compares the proposed ac-ac converter and a number of existing ac-ac converter topologies. Since the converters may not be optimally designed for the simulated (or experimentally tested) system, the comparison may not be fully conclusive. It can be observed that the proposed converter promises good efficiency compared to the existing topologies while offering the least complex topology with only 12 active switches and one small energy transferring element.

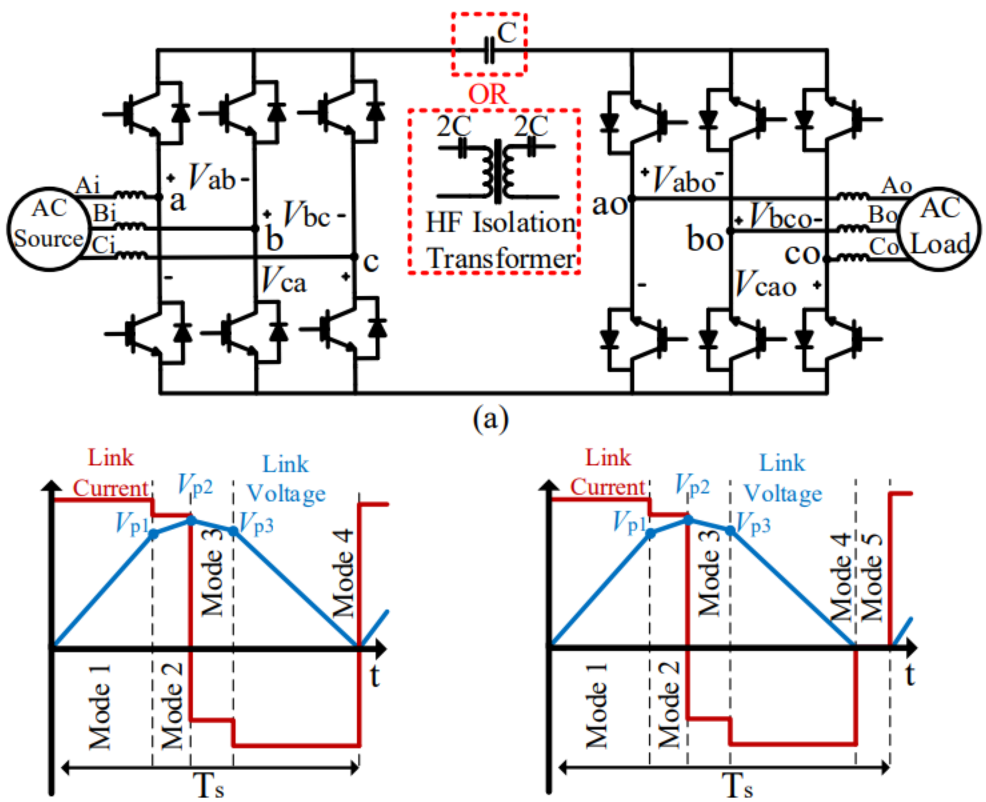

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Fig. 1. (a) The proposed three-phase capacitive-ac-link ac-ac converter, (b) the link voltage and current in variable switching frequency control method, (c) the link voltage and current in fixed switching frequency control method.

The operational status of the converter is determined by two key factors: the operating mode and the specific zone. The control algorithm begins by assessing the current mode, which can be categorized as 1, 2, 3, 4, or 5. Modes 1 and 2 denote charging modes, where the link capacitor receives energy from the input phases, while modes 3 and 4 represent discharging modes, during which the link capacitor releases energy to the output phases. Mode 5, exclusive to the fixed switching frequency method, signifies a state where no power transfer occurs to or from the link capacitor. Once the mode is identified, the switching algorithm proceeds to select the appropriate switches based on the input and output zones. Notably, the zone factor may differ between the input and output sides due to variations in frequency or phase angles of the input and output voltage/current references. These references are represented as Vab*, Vbc*, Vca*, Vabo*, Vbco*, and Vcao* for the line-line voltages across the input and output terminals. The determination of zones will be elaborated in Section III. The subsequent discussion delves into the converter's behavior and the switching algorithm during each mode, detailed in subsections A, B, C, and D. Switch selection is explained with reference to Table II, corresponding to zones 2 and 8 for the input and output, respectively. Notably, abs(a) denotes the absolute value of 'a', and the positive (+) or negative (-) signs alongside voltages and currents indicate their polarities. It is assumed that the flow of current from left to right is considered positive.

TABLE II. THE ASSUMED CONDITION FOR DESCRIPTION OF THE OPERATION PRINCIPLES

Side	Line-Line Voltage References	Actual Currents
Input	$abs(+V_{ab}^{*}) > abs(-V_{ca}^{*}) > abs(-V_{bc}^{*})$	$abs(+i_{Ai}) > abs(-i_{Bi}) > abs(-i_{Ci})$
Output	$abs(-V_{abo}^{*}) > abs(+V_{bco}^{*}) > abs(+V_{cao}^{*})$	$abs(-i_{Ao}) > abs(+i_{Bo}) > abs(+i_{Co})$

A. First charging mode (mode 1)

The first mode of operation is the first charging mode, during which the largest input current (absolute value) charges the link capacitor. Since abs(+Vab*)> abs(-Vca *)> abs(-Vbc*), According to Table II, Vab* has the largest absolute value and is positive, while Vca * and Vbc* are negative. Therefore, by the end of charging period, the input side unfiltered line-line voltages are formed as in Fig. 2 (a) so their averages meet the averages of the line-line voltage references shown in Fig. 2 (b). As can be observed in Fig. 2 (b), the highest, second highest, and lowest absolute line-line voltage references are Vab* ,Vca * , and Vbc* , respectively. Also, since this is a balanced three-phase threewire system, $Vab* = -(Vca* + Vbc*)$. During the first mode, the second highest absolute line-line voltage (phase pair "ca") has to be regulated.

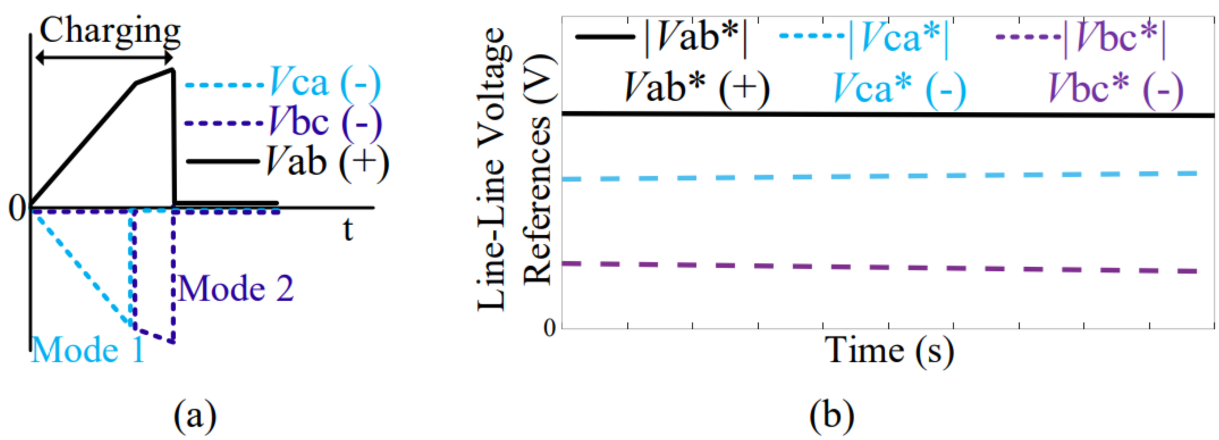

Fig. 2. (a) The unfiltered input line-line voltages during charging interval, (b) absolute input line-line voltage references during this interval.

As shown in Fig. 3 (a), none of the switches of the input side bridge is turned on during the first mode and the anti-parallel diodes conduct the three-phase input currents. Since iAi has the largest value and is positive, the anti-parallel diode of S1 starts conducting and charges the link capacitor and VLink starts increasing. The anti-parallel diodes of the output side bridge will let this current flow back toward the input phases. Since this is a three-phase three-wire system (for input and output sides), the summation of

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the corresponding three-phase currents has to be zero, which implies that $iAi = -(iBi + iCi)$; hence, phases Bi and Ci currents, which are both negative, have to flow through the anti-parallel diodes of switches S5 and S6. It is obvious that the direction of the input currents determines the diodes that conduct the current in mode 1. During mode 1, it can be seen that Vab=+VLink, Vca=-VLink, and Vbc is equal to zero. Once the average of the unfiltered voltage across the input phase pair "ca" (shown in blue color in Fig. 2 (a)) meets the average of input line-line voltage reference Vca * , mode 1 is ended. As depicted in Fig. 2 (a), during mode 1, the second highest input line-line voltage is built up.

The voltage stress of the switches is slightly higher than that of the conventional dc-link converters. However, given recent advances in developing high-voltage semiconductor devices, this issue does not limit the application of the proposed converter. Although the peak voltage stress of the input and output sides are equal, the current stress is different. For the input side bridge, the maximum current passes through the switches during discharging modes, since during these modes the link current also passes through the input side switches. For instance, in mode 4, the current that flows through switch S3 is equal to iAi+iAo. According to Table II, iAi and iAo are the maximum input and output currents, respectively. If these two currents have their peak values, the current passing through switch S3 will be equal to $Ii{,}peak + Io{,}peak$ in which $Ii{,}peak$ is the peak current of the input side and $Io{,}peak$ is the peak current of the output side. The maximum current that passes through the anti-parallel diodes of the input side switches is equal to the peak current of the input side ($Ii,$).

TABLE III. THE SWITCHING PATTERN OF THE PROPOSED THREE-PHASE AC-AC CONVERTER

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Zone		1	2	3	4	5	6	7	8	9	10	11	12
Mode	**Side**												
1	**Input**	-	-	-	-	-	-	-	-	-	-	-	-
	Output	S2o S4o	S2o S4o	S3o S4o	S3o S4o	S3o S5o	S3o S5o	S1o S5o	S1o S5o	S1o S6o	S1o S6o	S2o S6o	S2o S6o
2	**Input**	S6	S3	S2	S5	S4	S1	S3	S6	S5	S2	S1	S4
	Output	S2o S4o	S2o S4o	S3o S4o	S3o S4o	S3o S5o	S3o S5o	S1o S5o	S1o S5o	S1o S6o	S1o S6o	S2o S6o	S2o S6o
3	**Input**	S3 S6	S3 S6	S2 S5	S2 S5	S1 S4	S1 S4	S3 S6	S3 S6	S2 S5	S2 S5	S1 S4	S1 S4
	Output	S2o S4o	S2o S4o	S3o S4o	S3o S4o	S3o S5o	S3o S5o	S1o S5o	S1o S5o	S1o S6o	S1o S6o	S2o S6o	S2o S6o
4	**Input**	S3 S6	S3 S6	S2 S5	S2 S5	S1 S4	S1 S4	S3 S6	S3 S6	S2 S5	S2 S5	S1 S4	S1 S4
	Output	S2o S4o S6o	S2o S3o S4o	S2o S3o S4o	S3o S4o S5o	S3o S4o S5o	S1o S3o S5o	S1o S3o S5o	S1o S5o S6o	S1o S5o S6o	S1o S2o S6o	S1o S2o S6o	S2o S4o S6o
5	**Input**	S3 S6	S3 S6	S2 S5	S2 S5	S1 S4	S1 S4	S3 S6	S3 S6	S2 S5	S2 S5	S1 S4	S1 S4
	Output	S4o S6o	S2o S3o	S2o S3o	S4o S5o	S4o S5o	S1o S3o	S1o S3o	S5o S6o	S5o S6o	S1o S2o	S1o S2o	S4o S6o

3. EXPERIMENTAL RESULTS

A 1-kW prototype, as shown in Fig. 21, has been fabricated, and the three-phase ac-ac converter is experimentally evaluated. The prototype consists of three boards: two switch boards for input-side and output side, and a control board. The specifications of the experimental setup for both control methods are listed in Table IV. The control algorithm is implemented on a TMS320F28335 Delfino microcontroller. the output phase voltages, when the desired output frequency is 120 Hz. The link voltage and current are shown in Fig. 23. As can be seen, during mode 1 that the link current is equal to the highest (absolute value) input phase current and is positive, the link voltage increases. During mode 2 that the link current is equal to the second highest (absolute value) input phase current and still positive, the link voltage increases; however, the rate of increase is lower than that of the first mode. During discharging modes, the energy stored in the capacitive-link discharges into the output. Therefore, the link current is negative, leading to decrement of the link voltage. During mode 3, the second highest (absolute value) output current discharges the link capacitor, while the highest output current discharges the link capacitor in mode 4. It can be seen that once the link voltage is fully discharged, the next cycle starts. Furthermore, Figs. 24 (a) and (b) represent the input and output unfiltered

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line-line voltages, respectively. It can be observed that the longest charging and discharging modes are corresponded to modes 1 and 4, respectively. During charging modes, the output unfiltered line-line voltages are equal to zero and similarly during the discharging modes the input unfiltered line-line voltages are zero. Fig. 25 illustrates the capability of the proposed converter to change the frequency of the output phase voltages during the operation of the converter. It can be observed that the output frequency smoothly changes from 120 Hz to 60 Hz during the full load operation of the converter.

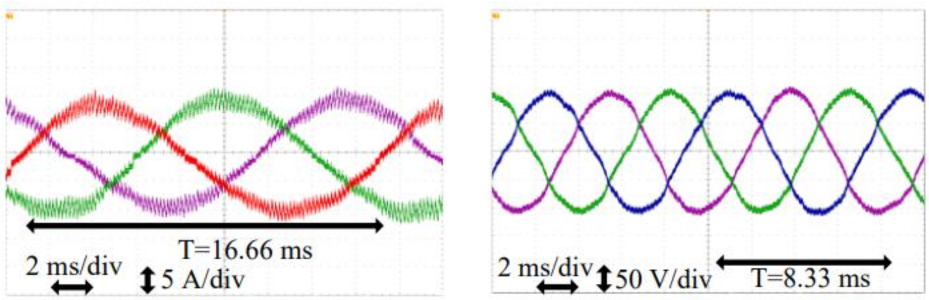

Fig. 3.The experimental results of the three-phase ac-ac converter with variable switching frequency control method, (a) input phase currents and (b) output phase voltages across the resistive load. The output frequency is 120 Hz, while the input frequency is 60 Hz.

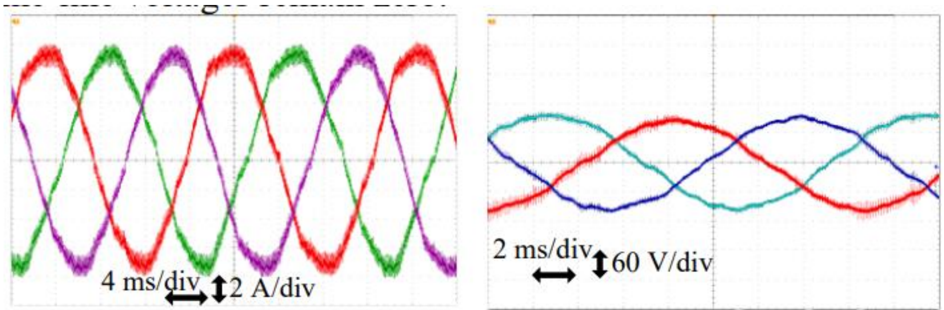

Fig. 4. The experimental results of the three-phase ac-ac converter with fixed switching frequency control method, (a) input phase currents and (b) output phase voltages across the resistive load.

4. CONCLUSION

This paper has introduced a novel single-stage three-phase AC-AC converter featuring a high-frequency alternating link voltage. The utilization of this innovative design brings forth several noteworthy advantages over conventional DC-link converters. The elimination of large electrolytic capacitors is made possible by the high-frequency nature of the link voltage, thereby enhancing efficiency and reducing the overall size of the converter. The reduction in the number of required switches to 12, as compared to matrix converters, leads to lower switching and conduction losses, further enhancing the converter's overall efficiency. The incorporation of variable and fixed switching frequency control methods provides flexibility in the operational aspects of the converter. In summary, the proposed AC-AC converter not only addresses key challenges in traditional converter designs but also presents a compact, efficient, and versatile solution with promising applications in modern power electronic systems. The performance validation through simulation and experimentation solidifies its potential for practical implementation, paving the way for advancements in the field of AC-AC conversion technology.

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