# Reliable Control of Direct PWM AC-AC Buck Converter With Short Circuit Protection

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***Abstract*—In this paper, a reliable control strategy is proposed for the direct pulse-width-modulation (PWM) ac-ac buck converter, to address the commutation problems and also to offer a handling capability against short circuit faults. A number of states are defined for the switching of the ac-ac converter depending on the sensed input voltage, whereby safe and continuous current paths are maintained at all times including voltage zero-crossing points. Moreover, fault handing switching states are able to protect the converter against short circuit currents. Safe transitions between different states are achieved as well. The realization of the control method is introduced and analyzed in detail. Measured results from experiments confirm that the proposed strategy manages to provide a safe and smooth operation for the ac-ac buck converter even under short circuit faults.**

***Keywords—AC-AC converters; fault handing; PWM control; soft commutation; short circuit protection.***

## I. INTRODUCTION

AC-AC power conversion has been used in various residential and industrial applications such as heating, power line conditioning, and motor drive control [1-3]. Some prevailing ac-ac converters have obvious disadvantages: ac choppers using thyristors have the drawback of poor power quality, matrix converters are complex in structure and control, and indirect ac-dc-ac converters are costly and bulky due to the two stages of power conversion [4, 5]. Various advanced ac-ac converter topologies have been reported such as Z-source converters [6], resonant converters [7], and switched capacitor converters [8]. However they are relatively complicated in circuit structure and/or control. By contrast, direct pulse-width-modulation (PWM) ac-ac converters have the merits of simple structure, easy control, small size, high efficiency, low cost, and high power quality. The advantages enable them to be utilized in applications where only voltage regulation is required [9]. In addition, they can also perform isolating, conditioning, and input power filtering [10, 11].

Direct PWM ac-ac converters can be derived from corresponding dc-dc converter topologies by substituting the unidirectional switches with bidirectional ones, for example the buck, boost, buck-boost, and Cuk types [11, 12]. In particular, as a typical type to reduce the voltage level, the ac-ac buck converter is widely researched and applied [13]. Numerous topologies based on the buck type converter have been discussed in literatures, for example, multilevel ac-ac converters for high power and voltage applications [14], and topologies to obtain arbitrary voltage frequency, phase, and amplitude [3, 15].

However, the traditional PWM ac-ac converters have commutation problems caused by overlap and dead times, which would give rise to current and voltage spikes that are harmful to semiconductor devices. Several strategies have been reported with the aim to solve the commutation problems. A convenient method to allow finite dead times is adding resistor-capacitor snubbers, which however are bulky and also degrade the efficiency and power quality [16, 17]. Soft commutation methods based on the polarity of voltage/current have been proposed in [13, 18, 19] and [20] to provide alternate current paths during dead times, but they would be unreliable around voltage zero-crossing points. Recent efforts have been made to reconfigure the switching legs which greatly relieve the commutation issues [17, 21, 22]. Nonetheless, a few additional inductors and capacitors are necessary which increase the volume, decrease efficiency, and even bring stability problems [22]. Furthermore, the input and output do not share the same neutral line, but a common neutral connection is a vital consideration in non-isolated single-phase line conditioners [23].

Another a critical issue of power converters is the protection under abnormal conditions, especially when they experience short circuit faults [24, 25]. The poor overcurrent capability of semiconductors, with a typical tolerance of two to three times the nominal current for a few tens of microseconds, renders the converters to be susceptible to high fault currents and thus would lead to catastrophic destruction [26, 27]. However, to the knowledge of the authors, none of the previous work has investigated the fault protection of PWM ac-ac converters. As a result, the converters would be damaged when short circuits inadvertently occur, since traditional ac circuit breakers and fuses with high fault current tolerance and tens or even hundreds of milliseconds of responding time is far from the requirement to protect the semiconductors [27].

In order to tackle the commutation issues and also to handle fault currents in the PWM ac-ac buck converter, in the present work a comprehensive control strategy based on a range of switching states is proposed. The aforementioned deficiency of the soft commutation methods around zero-crossing points can be resolved with a special state, whereby the reliability is improved and power quality can be enhanced. Fault currents can be bypassed and eventually die away through dedicated switching states once being detected to be above a threshold value. In this way the converter is able to survive from short circuit faults. Furthermore, safe transitions between different switching states are realized to keep safe current paths. Experimental results validate the effectiveness of the proposed control method. The strategy can be extended for other types of PWM ac-ac converters to improve their performances.

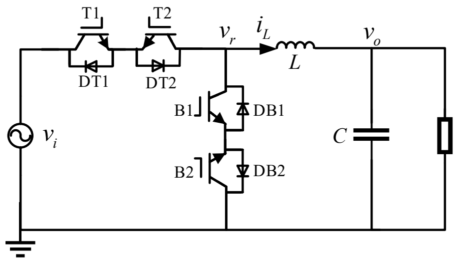



Fig. 1. Single-phase PWM ac-ac buck converter.

## II. PWM Control of AC-AC Buck Converter

The traditional single-phase PWM ac-ac buck converter is shown in Fig. 1. Switches T1 and T2 form the top switching leg, and B1 and B2 are in the bottom leg. Ideally, the top and bottom legs are switched complementarily and the switching is instantaneous. However in practical, there are unavoidable dead and/or overlap times due to non-instantaneous behavior of the power semiconductor switches and also delay in gate driver circuits. During dead times, the inductor current would be interrupted which generates high voltage spikes in the circuit, while in overlap times the power source is shorted giving rise to high current spikes, i.e., commutation problems [10, 17]. The high voltage and current spikes will severely damage the semiconductor switches [20].

The proposed PWM switching method is illustrated in Fig. 2. A large switching period $T_s$ is used for demonstration purpose. There are three switching stages depending on the value of the input voltage $v_i$. It should be noted that the sensing of the input and output voltages is generally essential for the voltage regulation, hence it will not bring in extra cost for voltage sensors. When $v_i$ is positive and above a value of $V_z$, T2 and B2 are fully turned on, and T1 and B1 are complementarily modulated with regulated duty ratios, this switching state is termed as POS PWM. Oppositely, when $v_i$ is negative and below a value of $-V_z$, T1 and B1 are fully turned on, and T2 and B2 are modulated with regulated duty ratios, the state is NEG PWM. When $v_i$ is in the zero-crossing range $[-V_z, V_z]$, T1 and T2 are fully turned on while B1 and B2 are turned off, the state is called THRU. With a proper value of $V_z$, the THRU state is able to solve the zero-crossing problem of the soft commutation strategies in [18-20] when the polarity detection of the input voltage is inaccurate or it is distorted with harmonics. Furthermore, the harmonic distortion of the output voltage can be reduced because the voltage over the zero-crossing range is not chopped, and the switching loss can be minimized because there are always two switchers that are fully turned on [18].

To avoid the shoot-through problem, dead times are required in both the POS and NEG PWM states for the PWM switches. Continuous current paths still exist during the dead times through the anti-parallel diodes and the fully on switches [19]. In Fig. 2, the duty ratio is updated at the beginning of each switching period. It can be seen that smooth transitions are achieved between different switching states. For example, before entering the THRU state from NEG PWM, T1 and T2 have already been turned on and thus only B1 needs to be switched off, ensuring a safe current path through the top leg.

Therefore, the commutation problems are resolved by the proposed method.

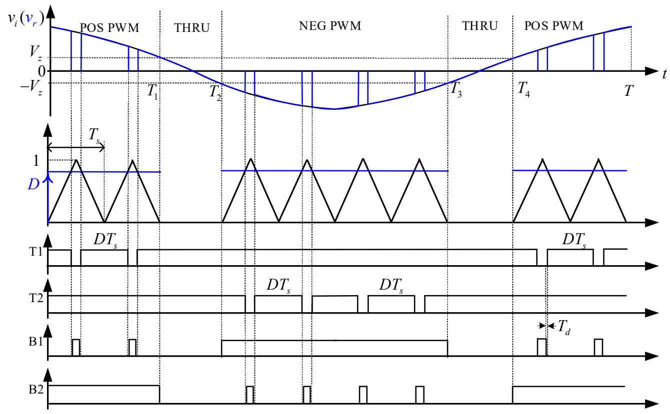



Fig. 2. PWM control of ac-ac buck converter.

## III. Short Circuit Protection Switching Control

Because of the limited thermal-electrical capacity and thus poor overcurrent capability of semiconductor devices, power converters should be equipped with protection design against over-currents, especially under short circuit faults [27, 28]. Different from some other converters such as dc-dc and dc-ac in which the switchers can be turned off when a fault current is presented [24, 28], the ac-ac converters cannot be simply shut down because in this case there is no diode path and thus would interrupt the inductor currents and cause voltage spikes.

The faults studied in this paper are assumed to be at the load side, for example short circuit which is a critical problem in residential occasions. Several switching states are proposed in addition to the normal PWM ones to accomplish the short circuit protection capability. The protection states are activated when the load current $i_{ou}$ exceeds a threshold value $I_s$.

If the fault occurs in the POS PWM state, T1 and B1 will be fully remained on and the other two be off, this state is called POS RECT. If the fault is in NEG PWM, T2 and B2 will be kept on and the other two in off. In this way, safe transitions between the states are realized and the inductor current will flow through the reverse biased diodes. For example, for the NEG PWM, only T2 or B2 needs to be turned off to get to NEG RECT, and safe current paths still exist: when $i_L > 0$ it will be taken by T1 and DT2, when $i_L < 0$ it will conduct through B1 and DB2. In any case, the fault current will decay.

It is more troublesome when the input voltage is in the zero-crossing range, because of the possible inaccuracy in the voltage sensing and a resultant unreliable sensed polarity. Therefore in this range, the bottom leg should be switched on while the top leg be off, termed as OD state. There are two scenarios regarding the transition to the OD state.

First, if the fault current appears in the POS or NEG PWM states and it has already been dealt with by the POS or NEG RECT states but has not died away yet. To transfer to the OD state, B1 or B2 that is off in the RECT states should be immediately turned on, and after a short time the switch T1 or T2 that is on should be turned off. In this way, the fault current is diverted to the bottom leg.

Second, if the fault is triggered in the zero-crossing range, i.e., the PWM switching is in THRU state. Ideally if the input voltage is positive, B2 should be switched on (POS THRU), then switching off T1, afterwards B1 is on and finally turning off T2. Similarly, if the polarity is negative the OD state can be reached through a series sequences (firstly to NEG THRU in which B1 is immediately turned on) to sustain the current continuity. However, these procedures take relatively long time, and as aforementioned the polarity sensing would be inaccurate and thus the sequences would be invalid. Nonetheless, if $V_z$ is sufficiently small, when the legs are shot through the leg current would be limited by the internal impedance of the lines and devices. Therefore, a more efficient transition is to turn all switches on shortly (STR) and afterwards switch the top leg off.

If the fault current is not decayed to zero in the OD state while the input voltage changes to be above $V_z$ or below $-V_z$, the state needs be transferred to POS or NEG RECT. For the positive range, T2 should be turned on (POS OD) before B1 is turned off, or T1 be turned on (NEG OD) and then B2 be off. In any cases, all switches can be turned off (OFF state) once the current has safely died away.

Based on the switching states, smooth PWM voltage regulation is achieved, as well as a safe protection attribute. A summary of the defined switching states is given in Table I.

TABLE I. SWITCHING STATES

| State | ON | OFF |
|---|---|---|
| POS PWM | T2, B2, T1/B1 | B1/T1 |
| NEG PWM | T1, B1, T2/B2 | B1/T2 |
| THRU | T1, T2 | B1, B2 |
| POS THRU | T1, T2, B2 | B1 |
| NEG THRU | T1, T2, B1 | B2 |
| POS RECT | T2, B2 | T1, B1 |
| NEG RECT | T1, B1 | T2, B2 |
| OD | B1, B2 | T1, T2 |
| POS OD | T2, B1, B2 | T1 |
| NEG OD | T1, B1, B2 | T2 |
| STR | T1, T2, B1, B2 | - |
| OFF | - | T1, T2, B1, B2 |

## IV. RESULTS

The ac-ac buck converter has been developed to regulate the mains voltage which in the UK is often, for historic reasons, higher than the nominal value (230 V) to an optimized voltage (220V), aiming to protect sensitive devices and to manage electricity consumption. The circuit diagram is shown in Fig. 3, in which EMC filters are used in both the input and output sides and an LC filter is applied also in the input side. The EMC filters will only influence the system characteristics in high frequencies. Circuit and control parameters are given in Table II. Experiments have been carried out to validate the proposed control strategy.

TABLE II. CIRCUIT AND CONTROL PARAMETERS

| Symbol | Quantity | Value |
|---|---|---|
| $V_i$ | Input voltage amplitude | 325-350 V |
| $\omega$ | AC angular frequency | $2\pi\cdot 50$ rad/s |
| $V_o$ | Nominal output voltage amplitude | 311 V |
| $V_z$ | Zero-crossing range | 28 V |
| $f_s$ | Switching frequency | 20 kHz |
| $P$ | Power rating | 4 kVA |
| $L$ | Filter inductance | 214 µH |
| $C$ | Filter capacitance | 20 µF |
| $I_s$ | Fault threshold current | 70 A |

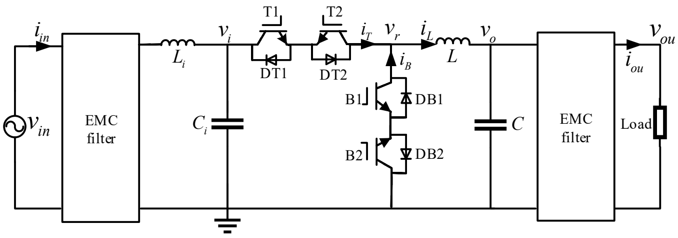



Fig. 3. Circuit diagram of the system based on the PWM ac-ac buck converter.

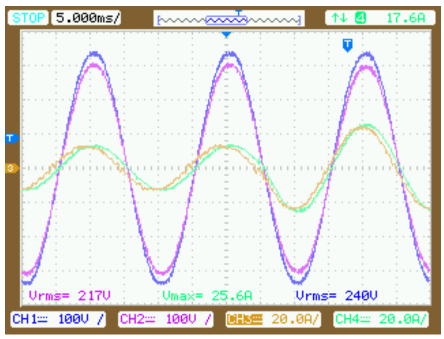



Fig. 4. Voltage regulation in experiment with a step change in load (CH1: $v_{in}$, CH2: $v_{ou}$, CH3: $i_{in}$, CH4: $i_{ou}$).

IGBTs FGH40N60SMD are used as the switches in the top leg, and STGW80H65DFB are used in the bottom leg. The later, with a higher pulsed-collector-current than the former (240 vs 120 A), is beneficial for taking over high fault currents. Although it has a higher rated power dissipation, considering that the majority of current is flowing through the top leg, the bottom IGBTs will not give rise to much loss. For the short circuit test, the load side is shorted using a cable with a resistance of 0.08 Ω, and the impedance of the supply line is measured at about 0.12 Ω. Therefore, the theoretical peak short circuit current is approximately 1.6 kA. Such a high current will definitely damage the IGBTs. However, it should be noted that there are inductors in the circuit which limit the rising rate of the fault current. More importantly, the converter is designed with short circuit protection switching control with fast response, enabling it to cope with the fault current. Selected experimental results are provided to prove the effectiveness of the proposed control strategy.

First of all, the voltage regulation is checked. Fig. 4 shows the waveforms when there is a step change in load from 23.5 Ω (≈ 2060 W) to 13.7 Ω (≈ 3533W). As can be observed, smooth results are gained without voltage or current spikes. The waveform of $v_r$ around the zero-crossing range in which the voltage is not chopped is shown in Fig. 5. More detailed results are presented in Fig. 6 in which the load is 23.5 Ω. The current spikes are caused by noises because sufficiently long cables are connected to the legs of IGBTs for measuring the currents using current clamps.

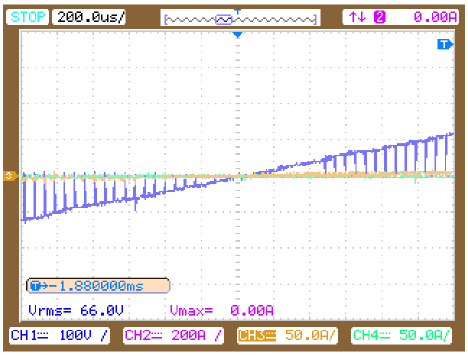



Fig. 5. $v_r$ around votlage zero-crossing range.

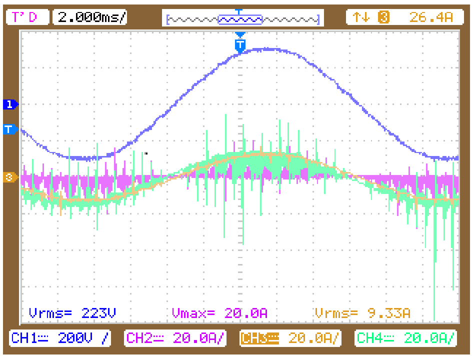
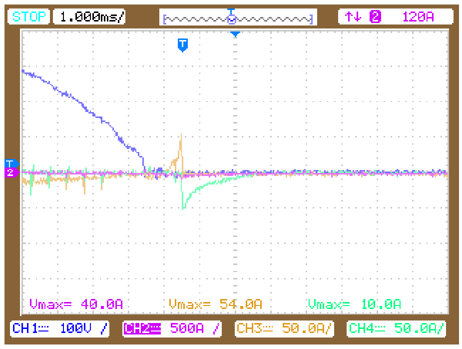


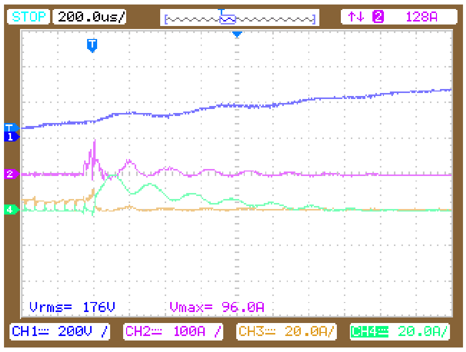

Fig. 6. Voltage regulation in experiment (CH1: $v_{ou}$, CH2: $i_B$, CH3: $i_{ou}$, CH4: $i_T$).

Short circuit tests have then been carried out. When the fault is triggered in the zero-crossing range, the result shown in Fig. 7(a) indicates that the current from the shoot-through STR state is safely within the maximum overcurrent capability of the IGBTs. The current decays because the switching state goes to OD eventually. When the fault occurs at a low input voltage point, the result is shown in Fig. 7(b). As can be observed, there is a delay time of about 20 μs for the fault handing to response to the fault current, mainly rooting from sampling and analog-to-digital conversion [29]. Nevertheless, the current rise in the top leg over this delay is limited by the inductors. Once the protection is working, the current is taken over by the bottom leg and finally dies away. When the fault current appears at a high voltage point, the currents through the top and bottom legs would be higher, see Fig. 7(c) and (d). As clearly revealed in these two figures, the fault current through the output filter inductor is diverted to the bottom leg, and in this case the voltage across the top and bottom legs changes to approximately the value of input voltage and zero, respectively. The peak fault current through the bottom leg could be larger than 200 A, but still in the safety range of STGW80H65DFB. The fault currents are finally reduced to 0 within hundreds of microseconds and all the switches are then turned off.

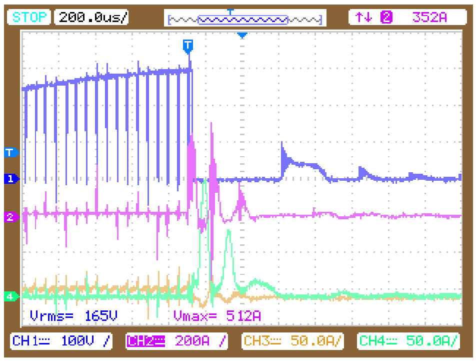
All the experiment results confirm that the proposed control strategy manages to address the traditional commutation issues and to provide the PWM ac-ac buck converter with fault protection to prevent damage from short circuit faults. The proposed strategy can be used in other PWM ac-ac converter topologies.



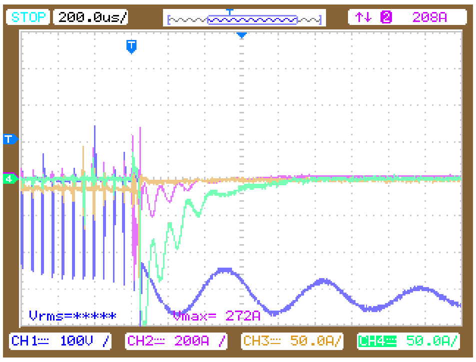

(a)




(b)




(c)




(d)

Fig. 7. Experimental short circuit tests. (a) Fault in zero-crossing range (CH1: $v_{ou}$, CH2: $i_{ou}$, CH3: $i_T$, CH4: $i_B$). (b) Fault at a low voltage (CH1: $v_{in}$, CH2: $i_{ou}$, CH3: $i_T$, CH4: $i_B$). (c) Fault at a high positive voltage (CH1: $v_r$, CH2: $i_{ou}$, CH3: $i_T$, CH4: $i_B$). (d) Fault at a high negative voltage (CH1: $v_i - v_r$ voltage across the top leg, CH2: $i_{ou}$, CH3: $i_T$, CH4: $i_B$).

## V. Conclusion

The most crucial issue in the control of direct PWM ac-ac converters is to maintain continuous and safe current paths. A comprehensive control method has been proposed for the ac-ac buck converter, which is able to increase reliability, reduce power loss, and enhance power quality. Numerous switching states have been defined to resolve the common commutation problems and to provide fault current protection. The short circuit protection, for the first time to be taken into account, has been achieved by several states and safe transitions between them are realized. Experimental results have validated the capability of the control strategy in offering the ac-ac buck converter with reliable voltage regulation and safe fault protection. The proposed strategy can be applied to other PWM ac-ac converters to improve their performances especially in terms of short circuit protection.

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