

An Improved Modulation Strategy for Quasi-Z-source Rectifier with Minimum Switching Frequency and High Efficiency

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Abstract— Quasi-Z-Source rectifier can achieve the traditional PWM rectifier's function, as well as implement buck and boost conversion of the input voltage. Due to the unique impedance source network, the shoot through (ST) state increases the reliability of rectifier impressively. As to three-phase Quasi-Z-source rectifier, many modulation strategies are proposed to achieve low output voltage and high efficiency. This paper proposes an improved modulation strategy that can minimize the voltage stress of switches and reduce the equivalent switching frequency of rectifier stage to about $1/3f_s$ (f_s is the frequency corresponding to the switching time period T_s). Minimum voltage conversion ratio is also obtained. During each sextant, only one phase leg operates at a high switching frequency to achieve ST interval control and output voltage regulation, while other two phase legs maintain the fixed switching states. Finally, the proposed modulation strategy is verified by simulation and experiment.

Keywords— Quasi-Z-Source rectifier; Minimum switching frequency; Pulse-width Modulation (PWM) strategy; Minimum voltage conversion ratio

I. INTRODUCTION.

Under the background of environment problems, electric vehicles (EV) are drawing increasing attention as an alternative to conventional gasoline vehicles. Other than the advantages of high efficiency, clean, lower noise, the battery of electric vehicles is also a kind of ideal energy storage equipment for microgrid, which is known as a vehicle to grid (V2G). In the charging period, the rectifier stage is an indispensable and critical part of the efficiency of energy management.

According to China electric vehicle conductive charging system standard GB/T 18487.1-2015, the charging voltage includes three standard scales: 200V~500V, 350V~700V, and 500V~900V. Conventional voltage source rectifier (VSR) is widely used in power supply and DC motor driving and many other areas, for it can realize sinusoidal input current and ensure good power quality. But it can only achieve the boost voltage regulation and has poor anti-interference ability. For three-phase 220V AC power supply, the minimum DC-link voltage is 540V, which does not meet the requirement of battery charging in EV. An additional buck DC-DC converter is necessary for the application mentioned above. To overcome the drawback of low efficiency for two-stage power conversion,

the impedance source rectifier [1] is proposed. Due to its unique impedance source network, the phase-leg shoot through (ST) is permitted so that the reliability is improved. The most typical impedance source rectifier includes Z-Source, Quasi-Z-Source, the later one is shown in Fig.1. It has the continuous output current which is beneficial for battery charge.

The existing PWM strategies for impedance source rectifier include simple constant boost control (SCPWM) [2], maximum boost control (MPWM) [3] and maximum constant boost control (MCPWM) [4], according to the intermediate dc-link voltage utilization. Each of them can be implemented with single-phase leg ST (1P ST) and three-phase leg ST (3P ST) [5]-[8]. 1P ST method inserts ST interval by overlapping the upper and lower switches in each phase leg at every switching commutation. 3P ST method inserts ST interval in three-phase legs simultaneously. The instantaneous ST current is averagely distributed among three-phase legs, which is beneficial to reduce the current stress and conduction loss of power devices. However, it introduces an additional switching commutation.

This paper proposed an improved modulation strategy for Quasi-Z-Source rectifier which fully utilizes the zero state and obtains the maximum modulation index. Therefore, the voltage stress for switches can be minimized, and the equivalent switching frequency of the rectifier bridge can be reduced to $1/3f_s$ [9], which indicates the reduction of switching loss. Therefore, the improved PWM strategy for Quasi-Z-source rectifier has potential to achieve the higher efficiency.

This paper is organized as follows: PWM strategy of the conventional three-phase bridge rectifier is reviewed in Section II. Then the improved PWM strategy with the minimum switching frequency for Quasi-Z-source rectifier is proposed in

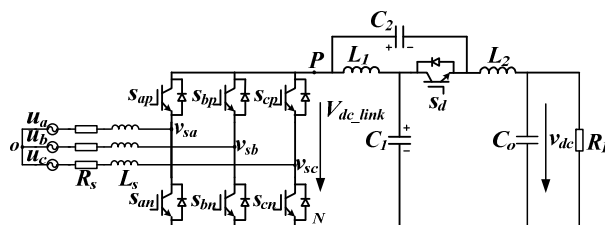


Fig. 1. Quasi-Z-Source rectifier

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Section.III. Section.IV provides the comparison of improved modulation and the existing PWM strategies. In Section.V, simulation and experiment results verify the effectiveness and advantageous of the improved PWM strategy. And final is the conclusion.

II. OPERATION PRINCIPLE OF CONVENTIONAL VSR.

As for the conventional three-phase VSR is shown in Fig.2, the grid voltage v_a , current i_a and switching voltage v_{sa} can be expressed as (1). For other two phases, the expression can be written through the phase shift of $2\pi/3$ and $4\pi/3$.

$$\begin{cases} v_a(\omega t) = \hat{v}_{ac} \cdot \cos(\omega t) \\ i_a(\omega t) = \hat{i}_{ac} \cdot \cos(\omega t - \varphi) \\ v_{sa}(\omega t) = \hat{v}_s \cdot \cos(\omega t - \alpha) \end{cases} \quad (1)$$

Where: \hat{v}_{ac} is the peak value of the grid voltage v_a , \hat{i}_{ac} is the peak value of the input current i_a , \hat{v}_s is the peak value of the ac side voltage of the bridge, α is the lag angle between v_a and v_{sa} , φ is the lag angle between v_a and i_a . $\omega=2\pi f_{line}$, f_{line} is the frequency of three-phase grid voltage.

According to KCL, there is:

$$\begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} = \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} - R_s \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - L_s \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (2)$$

Where: R_s and L_s is the equivalent resistor and filter inductor.

Through Clark and park transformation, the ac-components in abc -frame is transferred to $d-q$ rotating frame. (2) can be rewritten as:

$$\begin{cases} v_{sd} = \hat{v}_{ac} - R_s \hat{i}_{ac} \cos(\varphi) - \omega L_s \hat{i}_{ac} \sin(\varphi) \\ v_{sq} = R_s \hat{i}_{ac} \sin(\varphi) - \omega L_s \hat{i}_{ac} \cos(\varphi) \end{cases} \quad (3)$$

Where: v_{sd} , v_{sq} are the d-axis and q-axis component of switch voltage.

Assuming the circuit works in unity power factor, φ is zero. From the power conservation principle, there is:

$$\frac{3}{2} \hat{v}_{ac} \hat{i}_{ac} = 3 \left(\frac{\hat{i}_{ac}}{\sqrt{2}} \right)^2 R_s + P_o \quad (4)$$

The amplitude of ac-side current can be written as:

$$\hat{i}_{ac} = \frac{3\hat{v}_{ac} - \sqrt{9\hat{v}_{ac}^2 - 24R_s P_o}}{6R_s} \quad (5)$$

By solving (3) and (5) under $\varphi=0$, the modulation index M_i and phase angle α for three-phase rectifier is obtained.

$$M_i = \frac{\sqrt{v_{sd}^2 + v_{sq}^2}}{V_{dc}/2} \quad (6)$$

$$\alpha = -\arctan \frac{v_{sq}}{v_{sd}} \quad (7)$$

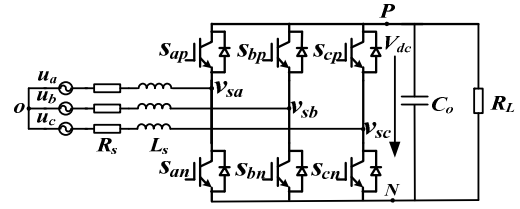


Fig. 2. Conventional three-phase VSR

For conventional three-phase VSR, there is a large aluminum electrolytic capacitor in the dc-side of the three phase bridge, thus the rectified output voltage is almost constant and the available minimum value is $2\hat{v}_s$ and $\sqrt{3}\hat{v}_s$ by using sinusoidal pulse width modulation (SPWM) and space vector modulation (SVM) respectively, which is corresponding to the green solid line and blue dashed line in Fig.3. The modulation waveform expression is as follows.

$$\begin{cases} V_{Sap(San)}^*(\theta) = \frac{1}{2} + \frac{M_i}{2} \cos(\theta) \\ V_{Sbp(Sbn)}^*(\theta) = \frac{1}{2} + \frac{M_i}{2} \cos(\theta - \frac{2}{3}\pi) \\ V_{Scp(Scn)}^*(\theta) = \frac{1}{2} + \frac{M_i}{2} \cos(\theta + \frac{2}{3}\pi) \end{cases} \quad (8)$$

Where: $0 \leq M_i \leq 1$, $0 \leq \theta = \omega t - \alpha \leq 2\pi$.

$$\begin{cases} V_{Sap(San)}^*(\theta) = \frac{1}{2} + \frac{\sqrt{3}M_i}{4} \cos(\theta - \frac{\pi}{6}) \\ V_{Sbp(Sbn)}^*(\theta) = \frac{1}{2} - \frac{3M_i}{4} \cos(\theta + \frac{\pi}{3}) \\ V_{Scp(Scn)}^*(\theta) = \frac{1}{2} - \frac{\sqrt{3}M_i}{4} \cos(\theta - \frac{\pi}{6}) \end{cases} \quad (9)$$

Where: $0 \leq M_i \leq \frac{2}{\sqrt{3}}$, $0 \leq \theta = \omega t - \alpha \leq \frac{\pi}{3}$.

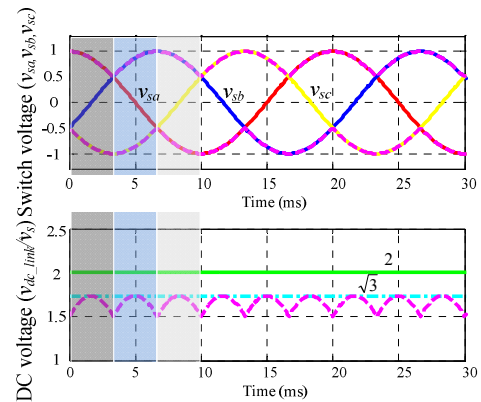


Fig. 3. The available minimum dc-link voltage of three-phase rectifier.

III. IMPROVED PWM STRATEGY OF QUASI-Z-SOURCE RECTIFIER.

A. Improved Modulation Strategy for Quasi-Z-Source

For Quasi Z-source rectifier, no capacitor in DC-bus of the three-phase bridge is installed. Thus, there is another possible selection for DC-bus voltage control which is represented by the magenta dashed line changing with six-time line frequency. It is actually the instantaneous maximum value of three-phase line voltage and it can be expressed as:

$$\langle V_{dc_link} \rangle_{T_s}(\theta) = \sqrt{3} \cdot \hat{v}_s \cdot \cos(\theta - \frac{\pi}{6}) \quad (10)$$

Where: θ is the remainder of $(\omega t - a)$ divided by $\pi/3$, $\theta = (\omega t - a) \% (\pi/3)$.

Because of the unique impedance network of Quasi Z-source rectifier, ST state can be considered as the special zero vector because it does not influence the relationship between AC-side voltage and DC-bus voltage. Thus, ST state interval can be utilized to regulate the voltage ratio of three-phase bridge DC-bus voltage v_{dc_link} and output voltage v_{dc} .

If the DC-bus voltage of Quasi Z-source rectifier is controlled the same as the peak value of three-phase line-to-line input voltage in (10). The power devices in two-phase legs can maintain the fixed switching states. The corresponding switching state is listed in Table. I. The switching states are listed in Table I. The equivalent switching frequency of power devices in the rectifier bridge can be reduced to $1/3f_s$, which is contributed to the reduction of switching loss and is the lowest switching frequency [9].

B. DC Side Voltage Relationship

According to the basic operation principle, Fig.4 shows two equivalent circuits seen from the dc-link of the rectifier bridge. During ST interval, S_d is turned off while two inductors charge two capacitors respectively, $v_{dc_link} = 0$. During Non-ST interval, S_d is turned on, v_{dc_link} charges two inductors and transfer energy to load, $v_{dc_link} = V_{C1} + V_{C2}$. Thus, the average value of dc bus voltage during one switching time period is as follows.

$$\begin{aligned} \langle V_{dc_link} \rangle_{T_s} &= \frac{1}{T_s} \left(\int_0^{d_{ST} T_s} 0 dt + \int_{d_{ST} T_s}^{T_s} (V_{C1} + V_{C2}) dt \right) \\ &= (1 - d_{ST}) \cdot (V_{C1} + V_{C2}) \end{aligned} \quad (11)$$

From (11), $\langle v_{dc_link} \rangle_{T_s}$ can be regulated intermediately by adjusting d_{ST} . For simplify the analysis, supposing the capacitor value C_1 , C_2 and C_o are large enough so that V_{C1} , V_{C2} and V_{dc} is constant.

The equivalent modulation index M_i of Quasi-Z-Source rectifier is defined as

$$M_i = \frac{\hat{v}_s}{(V_{C1} + V_{C2}) / 2} \quad (12)$$

Voltage conversion ratio is defined as output voltage V_{dc} over the peak value of switch voltage.

$$B = \frac{V_{dc}}{\hat{v}_s} \quad (13)$$

In order to realize switching states listed in Table I which is beneficial to reduce switching loss, the average dc-bus voltage should be controlled by ST duty ratio to equal to (10).

$$(1 - d_{ST}) \cdot (V_{C1} + V_{C2}) = \sqrt{3} \cdot \hat{v}_s \cdot \cos(\theta - \frac{\pi}{6}) \quad (14)$$

Average value of ST duty ratio d_{avg} is obtained through integrating equation (14) in one sextant.

$$\begin{aligned} d_{avg} &= \frac{3}{\pi} \cdot \int_0^{\pi/3} \left(1 - \frac{\langle V_{dc_link} \rangle_{T_s}(\theta)}{V_{C1} + V_{C2}} \right) d\theta \\ &= 1 - \frac{3\sqrt{3}}{\pi} \cdot \frac{\hat{v}_s}{V_{C1} + V_{C2}} \end{aligned} \quad (15)$$

In steady state, the voltage of two capacitors is related to the average value of ST duty ratio and output voltage.

$$V_{C1} = \frac{1 - d_{avg}}{1 - 2d_{avg}} V_{dc} \quad V_{C2} = \frac{d_{avg}}{1 - 2d_{avg}} V_{dc} \quad (16)$$

From (13), (15) and (16), the expression of capacitor voltage and ST duty ratio is as following:

$$V_{C1} = \frac{3\sqrt{3}}{\pi B} V_{dc} \quad V_{C2} = \frac{3\sqrt{3} - \pi B}{\pi B} V_{dc} \quad (17)$$

$$d_{ST}(\theta) = 1 - \frac{\sqrt{3}\pi}{6\sqrt{3} - \pi B} \cos(\theta - \frac{\pi}{6}) \quad (18)$$

Rewrite the equivalent modulation index M_i is as following.

$$M_i = \frac{2\pi}{6\sqrt{3} - \pi B} \quad (19)$$

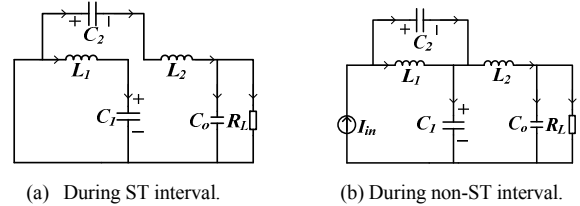


Fig. 4. Equivalent circuit of Quasi-Z source rectifier from DC side.

TABLE I SWITCHING STATE FOR IMPROVED MODULATION STRATEGY.

Phase angle	$0^\circ \leq \theta \leq 60^\circ$	$60^\circ \leq \theta \leq 120^\circ$	$120^\circ \leq \theta \leq 180^\circ$	$180^\circ \leq \theta \leq 240^\circ$	$240^\circ \leq \theta \leq 300^\circ$	$300^\circ \leq \theta \leq 360^\circ$
Mode(A)	$S_{ap}=1; S_{an}=0$	$S_{ap}S_{an}=\text{PWM}$	$S_{ap}=0; S_{an}=1$	$S_{ap}=0; S_{an}=1$	$S_{ap}S_{an}=\text{PWM}$	$S_{ap}=1; S_{an}=0$
Mode(B)	$S_{bp}S_{bn}=\text{PWM}$	$S_{bp}=1; S_{bn}=0$	$S_{bp}=1; S_{bn}=0$	$S_{bp}S_{bn}=\text{PWM}$	$S_{bp}=0; S_{bn}=1$	$S_{bp}=0; S_{bn}=1$
Mode(C)	$S_{cp}=0; S_{cn}=1$	$S_{cp}=0; S_{cn}=1$	$S_{cp}S_{cn}=\text{PWM}$	$S_{cp}=1; S_{cn}=0$	$S_{cp}=1; S_{cn}=0$	$S_{cp}S_{cn}=\text{PWM}$

C. Modulation Waveform Expression

As for improved modulation strategy, the modulation waveforms of six power devices in the three-phase bridge are shown in Fig.5. During each sextant, there are two legs with maximum/minimum switch voltage keeping fixed state to get six fold frequency dc-bus voltage. The third phase leg operates at the high switching frequency to achieve ST interval control and output voltage regulation.

Fig.6 shows the switching state of improved PWM strategy for Quasi-Z-source rectifier in the first sextant. According to volt-second balance principle, the duty ratio of upper switch d_{Sip} and lower switch d_{Sin} , switch voltage of phase-B v_{smid} meet:

$$v_{smid}(\theta) - v_{smin}(\theta) = (d_{Sbp}(\theta) - d_{ST}(\theta)) \cdot (V_{C1} + V_{C2}) \quad (20)$$

$$d_{Sbn}(\theta) = 1 - d_{Sbp}(\theta) + d_{ST}(\theta) \quad (21)$$

$$(1 - d_{ST}(\theta)) \cdot (V_{C1} + V_{C2}) = v_{smax}(\theta) - v_{smin}(\theta) \quad (22)$$

Where: In every sextant, $v_{smin}(\theta)$ is minimum value of rectifier bridge input voltage; $v_{smax}(\theta)$ is maximum value of rectifier bridge input voltage; $v_{smid}(\theta)$ is medium value of rectifier bridge input voltage, $\theta = (\omega t - \alpha) \% (\pi / 3)$.

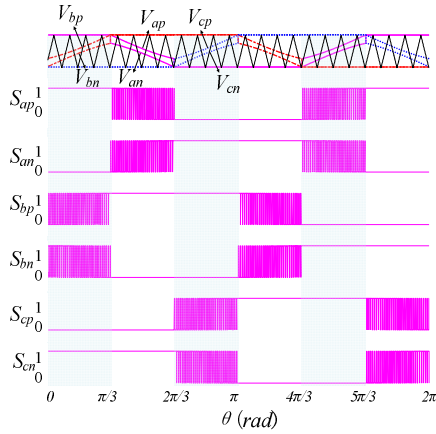


Fig. 5. Modulation and drive waveforms

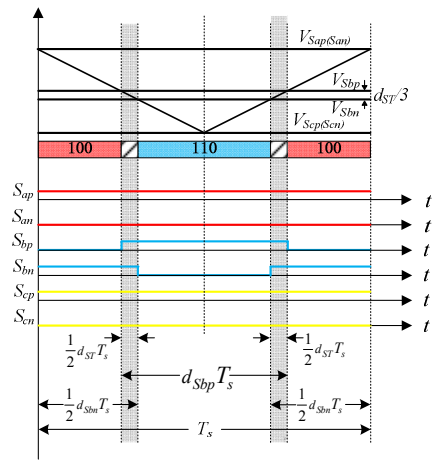


Fig. 6. Switch state in one period

Solving (20) (21) and (22), the corresponding duty ratio expressions of upper and lower switches d_{Sip} and d_{Sin} can be obtained.

$$\begin{cases} d_{Sip}(\theta) = \frac{v_{smid}(\theta) - v_{smin}(\theta)}{v_{smax}(\theta) - v_{smin}(\theta)} \cdot (1 - d_{ST}(\theta)) + d_{ST}(\theta) \\ d_{Sin}(\theta) = 1 - d_{Sip}(\theta) + d_{ST}(\theta) \end{cases} \quad (23)$$

Where: i represents the phase a , phase b or phase c of rectifier bridge.

From the perspective of space vector, substitute the zero vector with ST zero vector, the expression of modulation waveform can also be written as:

$$\begin{cases} V_{max_Sp}(\theta) = V_{max_Sn}(\theta) = 1 \\ V_{mid_Sp}(\theta) = V_{mid}^*(\theta) + \frac{1}{2} d_{ST}(\theta) \\ V_{mid_Sn}(\theta) = V_{mid}^*(\theta) - \frac{1}{2} d_{ST}(\theta) \\ V_{min_Sp}(\theta) = V_{min_Sn}(\theta) = 0 \end{cases} \quad (24)$$

Where: V_{max}^* , V_{mid}^* , V_{min}^* refer to the modulation waveforms of conventional three-phase VSR in (8) and (9). $V_{Sap}(\theta) = V_{max_Sp}(\theta)$, $V_{San}(\theta) = V_{max_Sn}(\theta)$, $V_{Sbp}(\theta) = V_{mid_Sp}(\theta)$, $V_{Sbn}(\theta) = V_{mid_Sn}(\theta)$, $V_{Scp}(\theta) = V_{min_Sp}(\theta)$, $V_{Scn}(\theta) = V_{min_Sn}(\theta)$ refers to modulation waveforms of six switches in the first sextant for improved modulation strategy shown in Fig.5.

IV. CLOSED-LOOP CONTROLLER DESIGN

When Quasi-Z-Source rectifier operates with simple constant modulation strategy [2], $d_{ST} + M_i \leq 1$ is the prerequisite. There are other two control variables: d_{ST} and M_i . The intermediate capacitor V_{C1} and V_{C2} is controlled by d_{ST} . The output voltage is controlled by modulation index M_i . If the constant boost modulation strategy [4] and the maximum boost

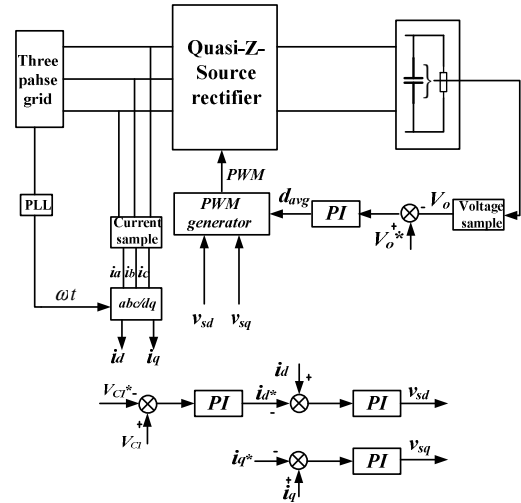


Fig. 7. Control system diagram of Quasi-Z-source rectifier with maximum boost control

control strategy[3] is used, the relationship between d_{ST} and M_i is permanent i.e $d_{ST} = 1 - \sqrt{3}M_i/2$ and $d_{ST} = 1 - \sqrt{3}M_i/2 \cdot \cos(\theta - \pi/6)$. Therefore, there only one control variable d_{ST} being used. The control diagram is shown in Fig.7. Dual loop controller in AC side aim to regulate the input current working in the unity power factor and a single loop in DC side aims to control the output voltage.

The controller is responsible for PWM modulation drive signal. Solving equation (15), (17) and (19), the relationship between M_i and d_{avg} is shown as following.

$$M_i = \frac{2\pi}{3\sqrt{3}}(1 - d_{avg}) \quad (25)$$

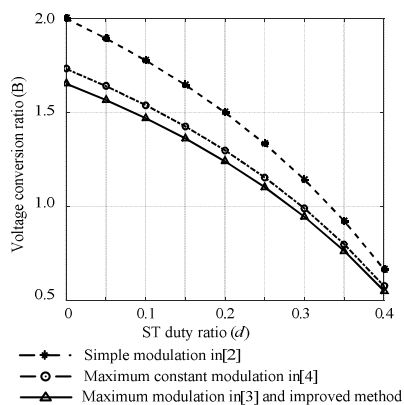
The phase angle of switch voltage is calculated by:

$$\theta = \omega t + \arctan(v_{sq}/v_{sd}) \quad (26)$$

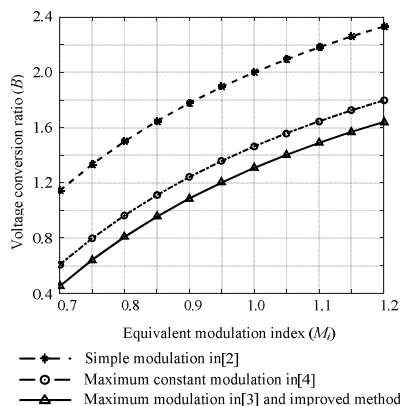
The modulation expression can be obtained from combining equation (8), (9) and (24) easily. The detailed modulator parameter design can be found in paper [6].

V. COMPARISON WITH OTHER STRATEGIES

Fig.8 presents the relationship for Quasi-Z-Source rectifier



(a) Voltage conversion ratio versus ST duty ratio.



(b) Voltage conversion ratio versus equivalent modulation index.

Fig. 8. Voltage conversion ratio comparison of different modulation strategies.

between voltage conversion ratio and ST duty ratio, voltage conversion ratio and equivalent modulation index when the improved modulation method is compared with other existing strategies. It is clear that the improved modulation strategy has the minimum voltage conversion ratio. The voltage stress of semiconductors vary with voltage conversion ratio is drawn when different modulation strategies are used in Fig.9. Under the same voltage conversion ratio, the improve modulation strategy has the minimum voltage stress of semiconductors and minimum equivalent switch frequency which is contributed to reducing power loss and improving efficiency.

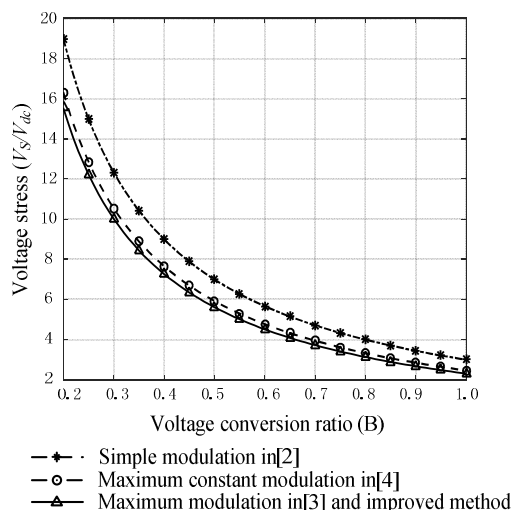


Fig. 9. Semiconductor voltage stress comparison of different modulation strategies

VI. SIMULATION AND EXPERIMENT VERIFICATION.

To verify the effectiveness of improved modulation strategy and theoretical analysis, Matlab/Simulink module is used. The main circuit parameter is as following: $V_{ac}=311V$, $V_o=400V$, $f_{line}=50Hz$, $L_1=L_2=10mH$, $L_s=2mH$, $R_s=0.01\Omega$, $C_1=C_2=1mF$, $C=1mF$, $R=100\Omega$. Fig.10 provides the drive waveforms. And Fig.11 presents the main circuit operation waveforms when the peak value of input phase voltage is 311.

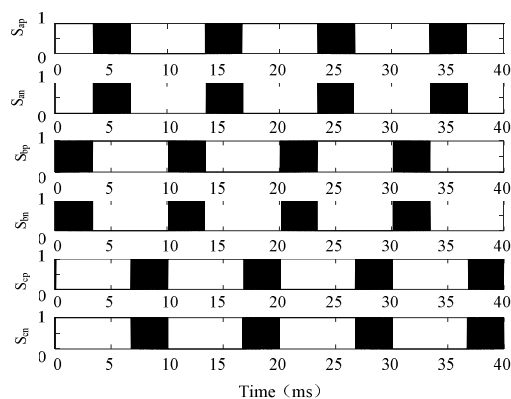


Fig. 10. Drive signal waveforms of improved modulation strategy.

According to calculation, the intermediate capacitor voltage V_{Ci} is 514V and input current peak value is 3.43A. The simulation results suit the theoretical computation well, which prove the validity of improved modulation strategy.

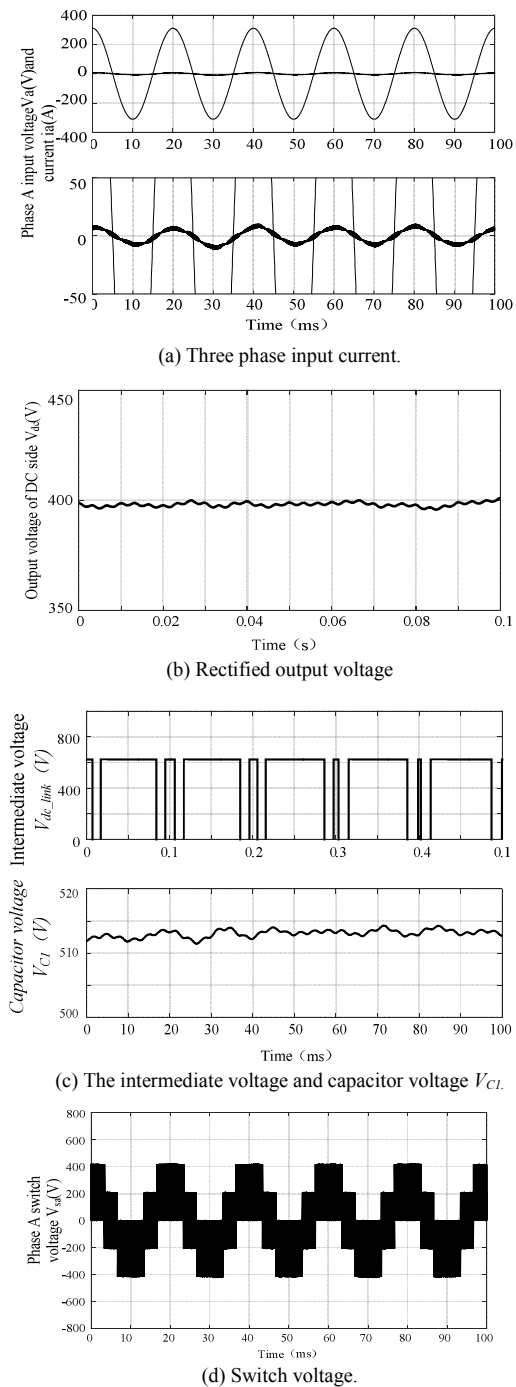
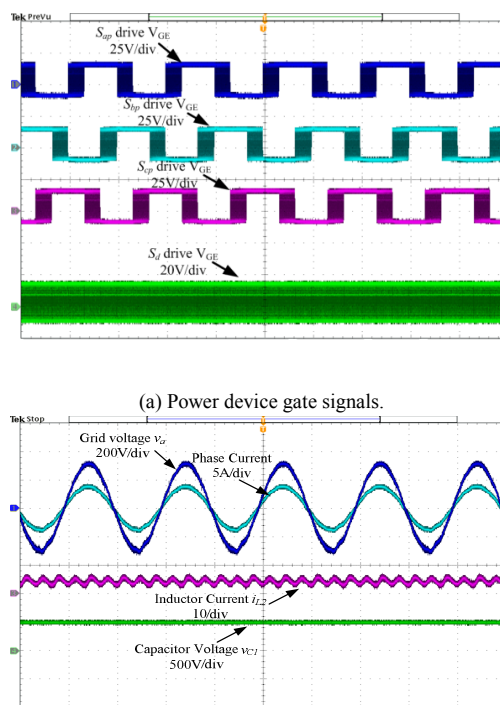


Fig. 11. Simulation results of improved modulation strategy.

A laboratory prototype rated at 2.5 kW was built to confirm the improved PWM strategy with Infineon power devices. The main control board is designed based on DSP28335. A programmable three-phase AC power supply is arranged to

simulate the power grid characteristic. A resistive load is connected to the output side.

Fig.12 shows the experiment results for Quasi-Z-source rectifier with improved modulation strategy under the output reference voltage of $V_{dc}=400V$ when the ac grid voltage is $V_{ac}=311V$. Fig.12 (a) shows the voltage waveforms of gate signals for power devices (S_{ap} , S_{bp} , S_{cp} and S_d). During each sextant, the switches in the legs of v_{max} and v_{min} are fixed. Only switches in one phase leg of v_{mid} are commutating with PWM. Fig.12(b) shows the captured waveforms of the grid voltage, grid current, intermediate capacitor voltage and the output current. By adjusting the ST to control the output voltage is 400V, the measured intermediate capacitor voltage is about 500V, which is a little lower than the theoretical values of 514 V. The value of inductor current i_{L2} is almost the same with theoretical value 4A. The peak value of input ac current suits the computation value 3.43A well. The experiment results verify the effectiveness of improved modulation again. The ac side achieves the unit power factor ($\cos\phi\approx 0.99$). Compared with existing PWM strategies, improved modulation strategy achieves the minimum intermediate dc-link capacitor voltage and equivalent switching frequency.



(b) Grid voltage, current, inductor current, intermediate capacitor voltage. ($V_{oref}=400V$)

Fig.12 Quasi-Z-source rectifier with improved modulation strategy ($v_{ac}=311V$, $f_{line}=50Hz$).

VII. CONCLUSIONS

This paper presents an improved modulation strategy for Quasi-Z-source rectifier, which can minimize the voltage stress

for switches in the rectifier and reduce their equivalent switching frequency to $1/3f_s$. Due to there is an inductor in the output, when this rectifier is applied to the V2G scenario, the output current is continuous which is good for battery lifetime. Besides, the improved modulation realizes the lowest voltage conversion ratio which is beneficial for wide range regulation. The simulation and experiment verify the proposed modulation strategy. The improve modulation method is promising in the V2G application.

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