Improved Buck-boost Power Converter of SRG Drive

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Improved Buck-boost Power Converter of SRG Drive

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Abstract

In this paper, a novel improved buck-boost power converter is proposed to improve the performance of SRG system. This new power converter originated from a conventional buck-boost converter. In the proposed converter, a buck-boost part and additional switches form a buck-boost energy conversion stage. With this energy conversion stage, it is flexible to significantly boost the magnetization voltage and demagnetization voltage thereby improving output power range and reducing power loss. Firstly, the basic structure of the proposed converter is presented and its several operating modes are analyzed. Then the control strategy of the SRG system is made to control the output voltage and the boost capacitor voltage. In the end, the simulation results on a three-phase 12/8 SRG drive demonstrate the eligibility of the proposed power converter and the feasibility of the control scheme. Compared to the conventional buck-boost converter, this improved buck-boost converter accelerates the excitation process and reduces the power loss.

Keywords: Switched Reluctance Generator Drive, Power Converter, DC-link Ripples, Voltage Control.

1 INTRODUCTION

It is well known that switched reluctance generator (SRG) has several attractive features, such as low manufacturing cost, simple and rigid structure, brushless and flexibility of control, etc [1]. Moreover, due to the

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inherent characteristics of the SRG, it has been applied in power source applications, such as aerospace power system [2], hybrid electric vehicles [3], wind turbine generators [4] and so on. However, many factors affect the control of SRG, including the nonlinear characteristic of winding inductor, back-EMF, output voltage ripples, etc. Consequently, compared with permanent magnetic generators (PMSGs), the operational control of SRGs is more difficult to achieve [5]. In particular, efficient operation of the SRG is always of importance. Some existing efficiency improvement studies for SRG include: machine design, off-line firing parameters optimization, online parameters optimization and converter topology design.

To achieve good performance, SRGs need to operate above the base speed at which phase currents are nominally constant without the need of current regulation. Nevertheless, under higher speed, the SRG may become open-loop instability caused by back-EMF. For example, the excitation and demagnetization voltage are limited by the fixed dc-link voltage in conventional SRG drive shown in Fig.1. As a result, fast excitation and demagnetization are unable to be achieved. To solve these problems, it is essential to focus on performance of power converter.

Several improved power converters have been developed for improving the SRM performance by increasing excitation and demagnetization voltages. Some researches [6,7] add additional converters to the front of asymmetric half-bridge converter. In [6], dc-link voltage can be boosted dynamically by a dc–dc boost converter, which improves the energy conversion efficiency and speed dynamic responses at high speed. In [7], a front-end circuit is added to boost excitation voltage and demagnetization voltage in SRG. Thus, system efficiency and the maximum output power under constant phase current constraints can be improved. In order to perform the phase current commutation faster, [8] presented a novel one switch per phase converter, which provides high demagnetization voltage. A buck-boost converter is presented in [9], which offers an added flexibility in motor control by separating the magnetization voltage and demagnetization voltage. And this converter can also boost demagnetization voltage significantly.

The rest of this paper is organized as follows. In section 2, the basics principles of SRG drive are introduced, then an improved power converter with a buck-boost energy conversion stage is proposed and its characteristics are analyzed accordingly. Then a voltage feedback control strategy for the proposed converter is proposed in section 3. In Section 4, the simulation results demonstrate the eligibility of the proposed power converter and the feasibility of the voltage feedback control scheme. Finally, section 5 concludes this paper.
2 IMPROVED POWER CONVERTER FOR SRG DRIVE

2.1 Basic principles of an Ideal SRG

The input power supplied by the prime mover can be written as

$$P_{in} = T_i \omega_r = \left( \sum_{i=1}^{N} T_{ei} \right) \omega_r$$

(1)

where $T_i$ is the input shaft torque, $\omega_r$ is the rotor speed and $T_{ei}$ is the phase developed torque.

Through electromechanical and electromagnetic energy conversions, $P_{in}$ will establish the winding back-EMF [5], thus the voltage equation (the mutual inductance is neglected) for each phase of SRG is given by

$$u_k = i_k R_k + \frac{d\phi_k}{dt} = i_k R_k + \frac{\partial \phi_k}{\partial i_k} \frac{di_k}{dt} + \omega \frac{\partial \phi_k}{\partial \theta_k}$$

(2)

From (2), the minimize of phase current can be written as

$$\frac{di_k}{dt} = \frac{u_k - i_k R_k - \omega \frac{\partial \phi_k}{\partial \theta_k}}{\frac{\partial \phi_k}{\partial i_k}}$$

(3)

where $e_\omega = \omega \frac{\partial \phi_k}{\partial \theta_k}$ is the back-EMF and $L_k = \frac{\partial \phi_k}{\partial i_k}$ is the incremental inductance (slope of the magnetization curve at the position $\theta$).

Also, from (2), the transient power of phase can be written as

$$P_k = u_k i_k = i_k^2 R_k + i_k \frac{\partial \phi_k}{\partial i_k} \frac{di_k}{dt} + i_k \omega \frac{\partial \phi_k}{\partial \theta_k}$$

$$= i_k^2 R_k + \frac{1}{2} \frac{d}{dt} \left( L_k i_k^2 \right) + T_k \omega$$

(4)
where \( i^2_k R_k \) is the copper loss in phase winding; \( \frac{1}{2} \frac{d}{dt}(L_k i^2_k) \) is the derivative of stored magnetic energy and \( T_k \omega \) is the instantaneous mechanical power.

### 2.2 Problems of existing converters

**Asymmetric Half-Bridge converter**: its topology is exposed in Fig.1. This configuration has 2N switches and its fundamental advantage is its control flexibility, having independent phase control and enabling phase overlap control. Its excitation and demagnetization voltage are fixed by the DC voltage source, hence the span of excitation or demagnetization decreases with the increasing of speed [10]. In this way, excitation current needs more energy to reach the desired value and generating period is prolonged.

**Conventional buck-boost converter [9]**: thanks to its elevator circuit, this converter shown as Fig.2 offers a greater control flexibility by separating the magnetization and demagnetization voltage supplied by the power source. This converter uses only N+1 switches, but does not provide the freewheeling mode operation. This means that soft chopping mode is missing. That means, only the excitation voltage can be boosted.

### 2.3 Proposed converter

According to the above problems of AHB and conventional buck-boost converter, in this paper, a new improved power converter of SRG drive with a buck-boost energy conversion stage is proposed in Fig.3. The proposed converter is derived from the conventional buck-boost converter. Compared with the conventional buck-boost converter, the proposed converter can provide the freewheeling mode operation and boost both excitation voltage and demagnetization voltage. As shown in Fig.3, the proposed converter mainly consists of three parts: buck-boost part, the common part and the phase circuit part. The common part consists of common switches \( S_2, S_3 \) and diode \( D_2 \). Excitation current is controlled by \( S_2 \) and \( S_3 \). When \( S_2 \) is turned off and \( S_3 \) is turned on, the phase winding is magnetized by boost capacitor \( C_b \); when \( S_2 \) is turned on and \( S_3 \) is turned off, the phase windings is magnetized by both boost capacitor \( C_b \) and output capacitor \( C_o \). Boost capacitor \( C_b \) can be charged by inductor \( L \) or by phase windings. Basic operation modes of the proposed converter are presented as below.

### 2.4 Operation modes of the improved buck-boost converter

**Excitation mode 1**: From Fig.4, it can be found that when both switches \( S_3 \) and \( S_a \) are turned on, switch \( S_2 \) is turned off, phase A runs in
the boost capacitor excitation mode. In other words, the phase winding is energized by the boost capacitor voltage $U_{cb}$.

**Excitation mode 2:** From Fig.5, it can be seen that when both switches $S_2$ and $S_a$ are turned on, switch $S_3$ is turned off, phase A runs in the dual-capacitor excitation mode. The phase winding is excited by $C_b$, $C_o$ in parallel and as a result, phase voltage equals to $U_{co} + U_{cb}$.

**Demagnetization mode 1:** From Fig.6, it can be seen that when both switches $S_2$ and $S_a$ are turned off, switch $S_3$ is turned on, phase A runs in the single-capacitor charging mode. The energy stored in phase A winding is delivered to the output capacitor $C_o$ through diode $D_a$. In this condition, if the boost capacitor voltage $U_{cb}$ is below reference value, reduced voltage of capacitor $C_b$ can only be real-timely compensated from inductor $L$.

**Demagnetization mode 2:** From Fig.7, it can be seen that when switches $S_2$, $S_3$ and $S_a$ are turned off, phase A runs in the dual-capacitor charging mode. The energy stored in phase A winding is delivered to the output capacitor $C_o$ and the boost capacitor $C_b$ in parallel through $D_a$. That means, no matter the value of $U_{cb}$, the boost capacitor $C_b$ absorbs power from phase current.

**Demagnetization mode 3:** From Fig.8, it can be seen that when switch $S_a$ is turned on, both switches $S_2$ and $S_3$ are turned off, phase A runs in the zero voltage mode.

In the SRG system driven by the improved buck-boost converter, the turn-on angle of incoming phase equals the ending angle of outgoing phase. Two possible overlap modes are analyzed as below.

**Overlap mode 1:** From Fig.9, it can be seen that when both switches $S_2$ and $S_b$ are turned on, both switches $S_3$ and $S_a$ are turned off, phase B runs in excitation mode 2 and phase A runs in zero voltage mode. Energy stored in capacitor $C_o$ is consumed by $R_L$ and $i_b$. By neglecting the condition of switch $S_i$, change rate of $U_{co}$ is formulated as

$$\frac{dU_{co}}{dt} = -\frac{i_L + i_b}{C_o} < 0$$ (5)

Change rate of $U_{cb}$ is formulated as

\[
\frac{dU_{Cb}}{dt} = -\frac{i_b}{C_d} < 0
\]  

**Overlap mode 2**: From Fig.10, it can be seen that when both switches \( S_3 \) and \( S_b \) are turned on, both switches \( S_2 \) and \( S_a \) are turned off, phase B operates in excitation mode 1 and phase A operates in demagnetization mode 1. Capacitor \( C_b \) is discharged by \( i_b \). By neglecting the condition of switch \( S_1 \), change rate of \( U_{Cb} \) is the same as (6)

Charging current of output voltage is \( i_{Co} = i_A - i_L \), thus the output voltage is determined by the difference between \( i_A \) and \( i_L \). When \( i_A > i_L \), \( C_o \) is charged and hence \( U_{Co} \) increases. When \( i_A > i_L \), \( C_o \) is discharged and hence \( U_{Co} \) decreases. Based on the analysis above, the change rate of \( U_{Co} \) can be formulated as

\[
\frac{dU_{Co}}{dt} = \frac{i_A - i_L}{C_o}
\]  

3 VOLTAGE FEEDBACK CONTROL

With additional elements, the control strategy of the proposed converter is more complicated than that of the conventional buck-boost converter. The voltage feedback control strategy is shown in Fig.11, in which the output voltage controller and the boost voltage controller control voltage \( U_{Co} \) and voltage \( U_{Cb} \) respectively. Considering the relatively big output voltage ripple in the communication of the incoming phase and the outgoing phase, the proposed control is time-slotted. The waveforms of three phase current in the proposed converter are shown in Fig.12, where the region \( \theta_{on} < \theta < \theta_{end} \) can be divided into three sub-regions. Region 1: \( \theta_{on} < \theta < \theta_{ov} \); Region 2: \( \theta_{ov} < \theta < \theta_{off} \); Region 3: \( \theta_{off} < \theta < \theta_{end} \).

3.1 Output voltage controller

SRG needs to generate the output voltage robustly. The output voltage controller is employed to control the output voltage \( U_{Co} \). The output voltage \( U_{Co} \) changes with load resistor \( R_c \) and charging current. In the outer loop, the output voltage \( U_{Co} \) is the control objective. According to the difference between reference output voltage \( U_{Co}^* \) and actual output voltage \( U_{Co} \), required phase current \( I_{ref} \) is generated by a PI regulator. Control parameters of this PI regulator are given as
\[ G_{cU_0}(s) = 0.3 + \frac{1.5}{s} \]  

(8)

In the inner loop, when operating in overlap conduction (region 1), the SRG has two operation states including overlap mode 1 and overlap mode 2. If \( S_2 \) and \( S_3 \) are turned on, capacitor \( C_o \) and capacitor \( C_p \) will be discharged by phase B, therefore \( U_{cO} \) falls according to (5). If \( S_3 \) and \( S_6 \) are turned on, capacitor \( C_o \) will be charged by phase A, therefore \( U_{cO} \) raises when \( i_g > I_L \) or falls slowly when \( i_g < I_L \) according to (7). Based on this analysis, the output voltage ripple in region 1 can be formulated as

\[ \Delta U_{cO} = \frac{1}{\omega C_o} \int_{\theta_o}^{\theta_{on}} (i_g - I_L) d\theta \]  

(9)

where \( i_g \) is transient charging current for \( C_o \) and can be expressed as

\[ i_g = s_3 \sum_{k=A,B,C} (1-s_k)i_k + (1-s_2)(1-s_3) \sum_{k=A,B,C} (1-s_k)i_k - (s_2+s_3) \sum_{k=A,B,C} s_2i_k \]  

(10)

where \( s_k \) stands for the state function of \( S_k \) (k=2,3) and is defined as

\[ s_k = \begin{cases} 1, & \text{if } S_k \text{ is on} \\ 0, & \text{if } S_k \text{ is off} \end{cases} \]  

(11)

The RMS of charging current for \( C_o \) can be expressed as

\[ I_g(t) = \frac{1}{\theta_{on}(k+1)-\theta_{on}(k)} \int_{\theta_{on}(k)}^{\theta_{on}(k+1)} i_g d\theta \]  

(12)

where \( \theta_{on}(k) \) and \( \theta_{on}(k+1) \) are the turn-on angle of previous stroke and current stroke, respectively.

In order to minimize the ripple of \( U_{cO} \), \( I_g \) is the control objective according to (9). As illustrated in Fig.13, the average charging current reference \( I_g^* \) is calculated by \( I_{ref}^* \), \( I_g^* = K I_{ref} \), where \( K = 10 \). By measuring the difference between \( I_g^* \) and \( I_g \), the duty cycle of \( S_3 \) is generated by a PI-type regulator \( G_{ig}(s) \). \( S_2 \) and \( S_3 \) alternately switch on and off. Take excitation of
phase B as an example, phase A is the outgoing phase. $S_B$ is turned on.

Control parameters of $G_{I_g}(s)$ is given as

$$G_{I_g}(s) = 0.045 + \frac{0.3}{s} \quad (14)$$

When operating in single phase current excitation conduction (region 2), both $S_2$ and $S_b$ are on, thus the winding current of phase B is built by both the capacitor $C_o$ and the capacitor $C_b$. When operating in single phase current hysteresis conduction (region 3) shown in Fig.14, the switching signal for $S_b$ is equal to the product of the commutation signal $C_b$ and the chopping signal.

### 3.1 Boost voltage controller

As can be seen in Fig. 11, $U_{cb}$ is the control objective of this boost voltage controller. According to above analysis, the boost capacitor voltage $U_{cb}$ is affected by duty cycle of $S_1$ and operational state of SRG. When SRG start-ups, source voltage $U_{co}$ delivers energy to $U_{cb}$ by controlling the duty cycle of $S_1$. The actual voltage $U_{cb}$ is compared with reference $U^*_{cb}$, and the difference $\Delta U_{cb}$ is processed by a PI regulator $G_{CCB}(s)$ to generate the switching pulse to $S_1$. As a result, energy is delivered from inductor $L$ to $C_b$, and hence the boost capacitor voltage $U_{cb}$ is built. Control parameters of $G_{CCB}(s)$ is given as

$$G_{CCB}(s) = 0.5 + \frac{0.01}{s} \quad (15)$$

The rate of change of voltage $U_{cb}$ is also related to the operating condition of SRG. Region 1 and 2: capacitor $C_b$ is discharged by phase current and meanwhile compensated by inductor $L$. Hence, voltage $U_{cb}$ can be kept stable. Region 3: SRG operates in current chopping mode. When operating in demagnetization mode 1 or demagnetization mode 3, no power delivers through capacitor $C_b$. When operating in demagnetization mode 2, capacitor $C_b$ is charged by phase current and consequently $U_{cb}$ raises. Based on the above analysis, an additional hysteresis controller shown in Fig.14 is selected to control $U_{cs}$. In region 3, when $S_b$ is off, $S_3$ is modulated according to the difference between $U_{cb}$ and $U^*_{cb}$. If $U_{cb} \geq U^*_{cb} + \Delta U_1$, $S_3$ is turned on and no energy is delivered to $C_b$; if $U_{cb} \leq U^*_{cb} - \Delta U_2$, $S_3$ is turned off and energy is delivered from phase current to $C_b$, where $\Delta U_1$ and $\Delta U_2$ are the hysteresis bands. In excitation span, the energy absorbed by phase wingding
from the capacitor $C_b$ is larger than the energy which delivered from the inductor $L$ to the capacitor $C_b$. Therefore, the capacitor voltage $U_{cb}$ requires a higher value than the reference $U_{cb}^*$. $\Delta U_1$ is set as -1V and $\Delta U_2$ is set as -1.6V.

4 SIMULATION RESULTS

In order to test the proposed converter and the proposed control strategy, the 12/8 SRG model is built in MATLAB/Simulink. The SRG driven by conventional buck-boost converter is also described as the comparison.

4.1 Simulation verifications

Fig. 15 shows the waveforms of phase current $i_k$, the output voltage $U_{co}$, the boost capacitor voltage $U_{cb}$ of the proposed converter and the conventional buck-boost converter respectively. The load resistor $R_L$ is 30 $\Omega$, the turn-on angle $\theta_{on}$ is fixed at 20°, the ending angle $\theta_{end}$ is fixed at 35°. The boost capacitor voltage reference $U_{cb}^*$ is set to 100V and the required output voltage $U_{co}^*$ is set to 60V.

From the waveforms of $U_{cb}$ as shown in Fig.15(a) and Fig.15(c), the proposed control method makes $U_{cb}$ stable periodically. Where the $U_{cb}$ drops in excitation region and rises in current hysteresis region. This proves the effectiveness of boost voltage controller.

Fig. 15(a) and Fig. 15(b) conduct comparisons at 1000r/min. From Fig.15(a), the output voltage ripple of the proposed converter is 0.39V; from Fig.15(b), the output voltage ripple of the conventional converter is 1V. The reason for this distinction is that $U_{cb}$ of conventional converter delivers energy to phase wingdings consistently and absorbs energy from $U_{co}$. In particular, a greater rate of change of output voltage occurs in the conventional converter when it operates in excitation mode. Fig. 15(c) and Fig. 15(d) conduct comparisons at 600r/min. It can also be seen that the output voltage ripple generated by the conventional converter is much higher than the proposed converter. In summary, additional elements such as switches $S_2, S_3$ and diode $D_2$ provide the condition to reducing voltage ripple.

4.2 Loss analysis in different converters

Power loss of converter affects the efficiency of SRG system.
The transient conduction loss of the IGBT can also be calculated according as

\[ P_{\text{con,IGBT}} = i_{CE}(t)v_{CE}(t) \]  

(15)

The switching energy loss of the IGBT can be calculated as [11]

\[
\begin{align*}
E_{\text{on}} &= \int_{0}^{t_{\text{on}}} i_{CE}v_{CE} dt \\
E_{\text{off}} &= \int_{0}^{t_{\text{off}}} i_{CE}v_{CE} dt
\end{align*}
\]

(16)

The switching loss of the IGBT can be calculated as

\[ P_{\text{switch,IGBT}} = (E_{\text{on}} + E_{\text{off}})f_{\text{switch}} \]  

(17)

The conduction loss of the power diode can be calculated as

\[ P_{\text{con,diode}} = i_{d}(t)v_{F}(t) \]  

(18)

The switching loss of the power diode can be calculated as

\[ P_{\text{switch,diode}} = E_{rr}f_{\text{switch}} \]  

(19)

where \( E_{rr} \) is the loss in a single turn-off pulse of the diode.

Since conventional buck-boost converter can not provide the freewheeling mode operation, when operating in current hysteresis control, switching frequency of IGBT in conventional buck-boost converter is much higher than this frequency in the proposed converter. When operating in 1000r/min, this frequency in the proposed converter is 1.7kHz while in the conventional converter is 9.8kHz. Based on this conclusion, the switching losses of the IGBT driven by the conventional converter are also much higher than the proposed converter.

Table.1 compares power losses in conventional buck-boost converter and power losses in proposed converter at 1000r/min. In our comparison, the parameters are set as the same as section 4.1. It can be seen that the total losses of the conventional buck-boost converter are 61.5% higher than the proposed converter. It is worth noting that the switching losses of the former are almost twice higher than the latter. Conventional buck-boost converter and proposed converter have relatively performance in the conduction losses of both IGBTs and diodes. The switching losses of the diodes can be neglected because of very small. In sum up, the reduced switching losses of IGBTs are an important reason for the superiority of the proposed converter.
As the speed increases, the conduction region of phase currents becomes narrow and every loss of converters decrease accordingly. The Fig. 16 shows the total losses when rotor speed is changed from 400 r/min to 1000 r/min. It can be observed that the total losses of proposed converter is much lower than conventional buck-boost converter at several speeds.

4.3 Excitation interval

Excitation interval (θ_{on} - θ_{off}) is an important factor in the performance of SRG. If the turn-on angle and the ending angle are fixed, reduced excitation interval indicates increased generation interval. Hence, large generation interval results in more output power. Excitation interval depends mainly on magnitude of average phase voltage. In conventional converter, the average phase current equals the boost capacitor voltage \( U_{Cb} \). As for proposed converter, the average phase voltage can be formulated as

\[
U_{exc} = \frac{1}{\theta_{off} - \theta_{on}} ( \int_{\theta_{on}}^{\theta_{off}} [s_2 (U_{Cb} + U_{Co}) + (1 - s_2)U_{Ch}]d\theta + \int_{\theta_{on}}^{\theta_{off}} (U_{Cb} + U_{Co})d\theta )
\]

\[
= U_{Cb} + \frac{1}{\theta_{off} - \theta_{on}} ( \int_{\theta_{on}}^{\theta_{off}} s_2 U_{Cc}d\theta + \int_{\theta_{on}}^{\theta_{off}} U_{Cc}d\theta )
\]

It can be found from (19) that the average phase voltage of the proposed converter (\( U_{exc} \)) is higher than that of the conventional buck-boost converter (\( U_{Ch} \)).

Table.2 compares the excitation interval between the conventional buck-boost converter and the proposed converter. It can be found that the excitation interval of the proposed converter is shorter than the conventional buck-boost converter.

Fig.17 validates excitation interval decreases as \( U_{Cb} \) increases in proposed converter. Because of (19), \( U_{Cb} \) and \( U_{exc} \) are positively correlated.

4.4 Output power range

Fig.18 shows comparison on energy conversion cycles between conventional converter and proposed converter. The turn-on angle, the ending angle, speed, voltage \( U_{Cb} \) and \( U_{Ch} \) are the same among both converters. In this section, simulation of SRG operates at 400 r/min.
Other control parameters for both converters are regulated to obtain the same peak value of phase current. From Fig.18, the area enclosed by flux linkage curve of the proposed converter is greater than that of the conventional converter. From Fig.19, it can be seen that more output power can be obtained from the proposed converter. The reason is that higher average excitation voltage results in longer generation span according to (20). The proposed converter needs less energy in excitation period and generates more energy to dc-link. Moreover, output power ripple of the former is lower than the latter.

5 CONCLUSIONS

In this paper, an improved power converter with a buck-boost energy conversion stage for driving SRG has been proposed. With the energy conversion stage, the excitation process and demagnetization process can be shortened. Furthermore, power loss can be reduced and the output power range can be improved. Then the control strategy of the SRG system is made to control the output voltage and the boost capacitor voltage. The output voltage ripple is considered in the control strategy. In addition, with this control scheme, the boost capacitor voltage can be flexibly controlled. In the end, the simulation results demonstrate the eligibility of the proposed power converter and the effectiveness of the control scheme. Compared to the conventional buck-boost converter, the proposed converter accelerates the excitation process. The power losses are decreased despite the additional elements in the proposed converter. It can also be found that the output power range is improved because of the increased average excitation voltage.

Competing Interests
The authors declare that they have no conflict of interest.

References


**Figure Captions**

Fig. 1 Asymmetric Half-Bridge converter

Fig.2 Conventional buck-boost converter

Fig. 3 Improved buck-boost converter

Fig. 4 Excitation mode 1

Fig.5 Excitation mode 2

Fig. 6 Demagnetization mode 1

Fig. 7 Demagnetization mode 2
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Fig. 9 Overlap mode 1

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Fig. 11 Structure of the proposed voltage feedback control strategy

Fig. 12 Typical current waveforms in the proposed converter

Fig. 13 Diagram of phase current control scheme (region 1)

Fig. 14 Diagram of phase current control scheme (region 3)

Fig. 15 Simulation results in a three-phase 12/8 SRG (a) Proposed converter at 1000rpm

Fig. 15 Simulation results in a three-phase 12/8 SRG (b) Conventional converter at 1000rpm

Fig. 15 Simulation results in a three-phase 12/8 SRG (c) Proposed converter at 600rpm

Fig. 15 Simulation results in a three-phase 12/8 SRG (d) Conventional converter at 600rpm.

Fig. 16 Loss variation with speed

Fig. 17 Excitation interval variation with $U_{cb}$ in proposed converter

Fig. 18 Comparison on energy conversion cycles

Fig. 19 Comparison on output power (a) Proposed converter

Fig. 19 Comparison on output power (b) Conventional converter

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Figure 1
Asymmetric Half-Bridge converter

Figure 2
Conventional buck-boost converter
Figure 3

Improved buck-boost converter

Figure 4
Excitation mode 1

![Excitation mode 1 circuit diagram]

Figure 5

Excitation mode 2

![Excitation mode 2 circuit diagram]
Figure 6
Demagnetization mode 1

Figure 7
Demagnetization mode 2
Figure 8

Demagnetization mode 3

Figure 9
Overlap mode 1

Figure 10

Overlap mode 2

Figure 11
Structure of the proposed voltage feedback control strategy

![Figure 12](image1)

Typical current waveforms in the proposed converter

\[ \theta_{on} < \theta < \theta_{ov} \]

![Figure 13](image2)

Diagram of phase current control scheme (region 1)

\[ \theta_{off} < \theta < \theta_{end} \]

![Figure 14](image3)
Diagram of phase current control scheme (region 3)

**Figure 15**

Simulation results in a three-phase 12/8 SRG (a) Proposed converter at 1000rpm

Simulation results in a three-phase 12/8 SRG (b) Conventional converter at 1000rpm

Simulation results in a three-phase 12/8 SRG (c) Proposed converter at 600rpm

Simulation results in a three-phase 12/8 SRG (d) Conventional converter at 600rpm.
Figure 16

Loss variation with speed

Figure 17

Excitation interval variation with
Figure 18

Comparison on energy conversion cycles
Figure 19

Comparison on output power (a) Proposed converter

Comparison on output power (b) Conventional converter