A Resonant Switched Reluctance Motor Drive for Marine Propulsion

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Abstract: - Switched reluctance motors have high efficiency, high power density, high fault tolerance, and low manufacturing cost. They have a high potential to be applied in electric marine propulsion. Efficiency of power conversion is one of the important items. A resonant converter is proposed for switched reluctance motor drive. All high frequency switches in the converter are operated under zero-voltage switching condition. The zero-voltage switching feature provides low switching loss. Operation of the proposed circuit is provided in this paper.

Key-Words: - Soft-switching, zero-voltage, motor drive, propulsion, switched reluctance motor

1 Introduction
As the very high flexibility of power transmission and architecture of power system, electric propulsion system is a trend for marine propulsion. Both DC and AC machines have been using as electric marine propulsion for many years, particularly DC brush-type machines. The DC machines have the advantages of high starting torque and braking torque, wide speed range feature with smooth regulation, and good reversion ability. However, power density of this type of machine is low while power density is one of the main concerns of modifying electric ship. The spike from the brushes of the machines also leads to their low reliability and high maintenance costs.

Recently, electric marine propulsion systems with other types of machines, such as permanent magnet (PM) brushless motors and high temperature superconductor (HTS) motors, have been proposed [1-3]. These kinds of motor provide high torque, high efficiency, high reliability, a level of fault tolerance, and high power density particularly HTS motors. These features are very suitable for propulsion in marine purposes. Because of the need of high magnetised permanent magnet in PM brushless motors and the need of super-conductor in HTS motors, manufacturing costs of these machines are high.

Other than the machines mentioned above, switched reluctance motors (SRMs) [4-5] are also well suited for electric marine propulsion. Fig. 1 shows a 4-phase 6-pole 8/6 switched reluctance motor. Mechanical power is produced by the change of reluctance between the yokes of the stator and the rotor. This kind of machines has no copper wire or permanent magnet. Moment of inertia of their rotors is low. Their manufacturing costs are comparatively low.

Efficiency is a fact of power density of electrical power converters. If the efficiency of the converter is the higher, the cooling system is the smaller and the power density is the higher. Soft-switching techniques have been widely used in power converters. As the ratings of IGBT become higher and higher, it is possible to apply soft-switching techniques in power conversions [6] in electric marine propulsion. In this paper, a resonant converter for switched reluctance motor drive is proposed. All high frequency IGBTs are operated under zero-voltage condition. Resonant voltages of the high frequency switches are clamped by active-clamp circuits. The zero-voltage switching feature can also avoids producing high EMI that may affect operations of other electrical equipments like sensors and radars.

Fig. 1 8/6 switched reluctance motor.
2 Operation Principles of the Resonant SRM Drive

Fig. 2 shows the circuit diagram of the resonant SRM drive for a 4-phase SRM. The SRM is controlled by pulse-width modulation method. $Q_1$ to $Q_4$ are the commutation transistors. To reduce acoustic noise of the SRM, soft-chopping method is used in this converter. Hence, switching frequency of the commutation transistors is low so that switching loss of these transistors is also low. Soft-switching technique is not applied on these transistors to reduce manufacturing cost. $Q_a$ and $Q_b$ are the chopping transistors and $Q_{xa}$ and $Q_{xb}$ are the auxiliary transistors. Their switching frequency is high. They are all switched under zero-voltage condition. The speed of the machine is controlled by the change of the duty ratio of the gate signal of the chopping transistors.

$C_r$ is a resonant capacitor and $L_r$ is a resonant inductor. They resonate to provide zero-voltage switching for $Q_a$. $Q_x$, $D_x$ and $C_c$ form a clamping circuit. The clamping circuit clamps the resonant voltage of $C_r$ to reduce voltage stress of $Q$. In normal design, $C_c$ is much larger than $C_r$.

Fig. 3 Per-phase equivalent circuit of the resonant SRM drive

Fig. 4 Idealised waveforms of the resonant SRM drive
Fig. 3 shows a per-phase equivalent circuit of the resonant SRM drive. In regenerating stage, the commutation transistor is switched off. The regenerating current flows through D_a and D_r to the $V_{in}$. In motoring stage, there are totally seven states of operation in one switching period of each chopping transistor. Fig. 4 shows the idealized waveforms of the SRM drive in motoring stage. The corresponding commutation transistor is on in the whole motoring stage when that phase is energised. Describing the idealized waveforms, Fig. 5 shows the per-phase equivalent circuit of each state of operation in motoring stage.

Considering the inductance of the phase winding is very large, the phase winding current is assumed to be a constant, $I_L$.

$Q_a$ is switched off at $t_0$. $Q_a$ is maintaining off. $C_r$ is charged in resonant manner with $L_r$ but it can be considered as approximately linearly charging. Once $v_{cr}$ is larger than $V_{in}$+$V_{cc}$, $D_x$ becomes forward bias at $t_1$. $C_c$ resonates with $L_r$. Since $C_c$ is much larger than $C_r$, the current of $C_c$ is very small comparing to the totally $i_{t_2}$. This current can be assumed to be zero. $C_c$ clamps $v_{cr}$ as a low voltage level. While the resonant current, $i_{cr}$, is still positive, $Q_x$ is switched on at $t_2$. $Q_x$ is zero-voltage switched on. The negative resonant current flows through $Q_x$ instead of $D_x$. Let the angular resonant frequency of $C_c$ and $L_r$, $\omega_c$, be $1/\sqrt{L_cC_c}$ and the resonant impedance, $Z_c$, be $\sqrt{L_c/C_c}$, the equations of the resonance are:

$$v_{cr} = I_cZ_r \sin \omega_r(t-t_1)+V_{cil}\cos \omega_r(t-t_1)$$

$$i_{cr} = I_c \cos \omega_r(t-t_1)-\frac{V_{cil}}{Z_c}\sin \omega_r(t-t_1)$$

where

$$V_{cil} = \frac{I_cZ_r \sin \omega \alpha}{1-\cos \omega \alpha}$$

and $\alpha$ is the duration from $t_1$ to $t_2$.

When the resonant current is still negative, $Q_x$ is switched off at $t_3$. $L_r$ resonates with $C_r$ instead of $C_c$. $C_r$ is discharged in resonant manner. Let the angular resonant frequency of $C_r$ and $L_r$, $\omega_r$, be $1/\sqrt{L_rC_r}$ and the resonant impedance, $Z_r$, be $\sqrt{L_r/C_r}$, it gives the equations:

$$v_{cr} = V_{in}+V_{cil}\cos \omega_r(t-t_3)-I_cZ_r \sin \omega_r(t-t_3)$$
\[ i_{Lr} = -I_L \cos \omega_r (t-t_s) - \frac{V_{cd}}{Z_r} \sin \omega_r (t-t_s) \] (5)

The duration of this state, \( \beta_s \), is:

\[ \beta_s = \frac{1}{\omega_r} \left( \sin^{-1} \left( \frac{V_{in}}{\sqrt{V_{cc}^2 + I_L^2 Z_r^2}} \right) - \tan^{-1} \left( \frac{-V_{cd}}{I_L Z_r} \right) \right) \] (6)

The resonance stops at \( t_4 \) while the \( v_{cr} \) reaches zero. \( D_r \) is forward bias to demagnetise \( L_r \). \( Q_s \) is switched on at \( t_5 \) while \( i_{Lr} \) is still negative. \( Q_s \) is switched on under zero-voltage condition. When \( i_{Lr} \) is positive, it flows through \( Q_s \) to the phase winding. \( i_{Lr} \) is increasing in this state and it reaches \( I_L \) at \( t_6 \). From \( t_5 \) to \( t_6 \), \( i_{Lr} \) stops increasing and maintaining equal to \( I_L \). Another switching starts at \( t_7 \).

### 3 Criteria of Soft-switching

For chopping transistor and auxiliary transistor, after one transistor is switched off, another one will be switched on after a short delay. As shown in Fig. 4, \( \delta_1 \) and \( \delta_2 \) are the short delays. To obtain zero-voltage switching condition for both transistors, certain criteria have to be met. First of all, \( Q_s \) should be switched on before \( i_{Lr} \) decreases to zero. Criteria of \( \delta_1 \) and \( \delta_2 \) to obtain soft-switching are derived:

\[ \frac{C_r (V_{cc} + V_{cd})}{I_L} \geq \delta_1 \geq \frac{1}{\omega_r} \tan^{-1} \left( \frac{1 - \cos \omega r \alpha}{\sin \omega r \alpha} \right) \] (7)

\[ \beta \leq \delta_2 \leq \beta + \frac{I_L L_r}{V_{in}} \] (8)

Fig. 6. State-plane of the state \([t_3 - t_4]\)

Also, \( v_{cr} \) in the state of \([t_3 - t_4]\) has to reach zero to provide zero-voltage switching for \( Q_s \). A state-plane diagram of this state is shown in Fig. 6. It shows that another criterion of achieving zero-voltage switching is:

\[ \sqrt{V_{cc}^2 + Z_r^2 I_L^2} \geq V_{in} \] (9)

### 4 Simulation Results of the Resonant SRM Drive

Fig. 7 Computer simulation of the resonant SRM drive
A resonant SRM drive is simulated by using circuit simulation package Saber which is especially for power electronics and machine simulation. The circuit is simulated with a 4-phase 8/6 SRM. The input voltage of the circuit, \( V_{in} \), is 13.3kV. In this computer simulation, the switching frequency of the chopping transistors and the auxiliary transistors is 10kHz. \( C_m \) is 1000\( \mu \)F, \( L_m \) and \( L_a \) are 6.3\( \mu \)H, \( C_a \) and \( C_b \) are 20\( \mu \)F, and \( C_{ca} \) and \( C_{cb} \) are 550\( \mu \)F. The SRM operates with soft-chopping and PWM method. Dwell angle of each phase of the SRM is 15° and its firing angle is 0°. The electrical output power of the SRM drive in the simulation is 4.3MW. The computer simulation results are shown in Fig. 7.

Fig. 7(a) shows the switching sequence of the commutation transistors and the simulated commutation currents of Pha and Phb referring to Fig. 2. \( i_a \) is the current of Pha and \( i_b \) is the current of Phb. The result verifies that the SRM can have normal operation when driven by the proposed resonant SRM drive.

Fig. 7(b) shows the waveforms of the collector-to-emitter voltage of \( Q_a \), i.e., \( V_{cem} \) when \( Q_a \) is switched on. It is clearly shown that when the chopping transistor is triggered to on, the device’s voltage is zero. Fig. 7(c) shows the waveforms of the drain-to-source voltage of \( Q_m \) when \( Q_m \) is switched on. The simulation results verify that the auxiliary transistors in the resonant SRM drive are switched on under zero-voltage switching.

The operation condition of the motor has also been tested at other condition and very favourable soft-switching has also been obtained.

5 Conclusion

Switched reluctance motors are a kind of potential machine for electric marine propulsion because of their low manufacturing costs, brushless structures, low moment of inertia of rotors, and high torque productions.

A resonant converter for the SRM drive was introduced. This SRM drive provides high efficiency and low EMI by the technique of zero-voltage switching for all high frequency transistors. Resonant voltages of the chopping transistors are clamped by the clamping circuit. The operation principles of the resonant SRM drive was described. Criteria of achieving soft-switching were provided. Computer simulation of the resonant SRM drive was done. The simulation results verified that both the high frequency chopping transistors and auxiliary transistors are switched under zero-voltage condition.

The proposed drive circuit for SRM is a circuit with potential to replace the classical method of SRM drive. The power level can be large with virtually no switching loss. It represents a more feasible solution for reliable and high efficiency system. One of the main advantages is that under high input voltage, the resonant voltages are still under low and clamped value rather than a few times higher than the input voltage. It therefore gives a safe operation and lower device cost for the IGBT. The thermal management of the proposed system is also therefore reduced. Even though under very adverse condition, the thermal dissipation can also be better off and under control as compared to conventional hard-switching method.

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