A Novel Soft-Switching Converter for Switched Reluctance Motor Drives

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Abstract: - A high efficiency converter for switched reluctance motor (SRM) drive is developed in this paper. In the proposed converter, the power semiconductor device with shorter switching time is employed to implement its high-speed PWM switches. And the soft-switching control is employed for further reducing their switching losses. To achieve this, an auxiliary resonant circuit is added to the PWM switch, and its zero-voltage-transition (ZVT) soft switching is obtained by applying suitable switching signals to the main and auxiliary switches. No extra voltage and/or current sensors are required. Having derived the governing circuit equations, a design procedure is proposed to systematically find the constituted components of the auxiliary branch. As to the low-speed commutation switches, they are realized using the power device having low on-state voltage. Owing to the ability of making PWM switching control, the SRM motor drive with the proposed converter possesses good driving performance. The performance of the designed converter is demonstrated by some simulation and experimental results. An approach for measuring the energy conversion efficiency of a SRM drive is also proposed.

Key-Words: Switched reluctance motor (SRM), Soft-switching converter, Zero voltage transition (ZVT), PWM, Efficiency measurement, High-efficiency converter.

1 Introduction

Switched reluctance motor (SRM) possesses many advantages, such as rigid mechanical structure, brushless operation, higher conversion efficiency and power density [1]. Moreover, its converter circuit is simple and free from shoot-through fault [1-4]. However, in addition to the generation of large acoustic noise and large torque ripple, its developed torque characteristic is quite nonlinear. These factors may limit the capability of a SRM in high-performance applications. During the past decades, many researches have been done to improve the performance of a SRM drive. These include: motor design [2], converter circuit [3,4], voltage boosting circuit [5,6], current waveform programming [7,8], commutation tuning [9]. And other related issues, such as noise reduction, equivalent circuit development, current and speed controls, sensorless control, digital simulation, etc.

As generally recognized, the driving performance of a SRM motor drive is significantly affected by its employed converter and switching control. The whole motor drive performance is also affected by the converter efficiency, particularly for the battery-powered motor drive system. The conventional hard-switched converters possess inherent disadvantages of generating large switching losses, switching stresses and electromagnetic magnetic interference (EMI). These problems can be effectively reduced employing soft-switching technique to let the switches have zero voltage and/or zero current switchings. Soft-switching converters can be broadly categorized into resonant converters and zero voltage (current) (ZV(C)T) transition converters. The former types of converters possess larger limitations in circuit configuration and PWM switching control. As to the latter, the circuits can be formed from the conventional ones by adding simple auxiliary resonant branch. And the soft switching can be obtained by applying suitable switching signals to the main and auxiliary switches.

Recently, there have been some soft-switching converters being specifically developed for powering SRMs. For the three-phase SRM soft-switching converter developed in [10], an auxiliary branch consisting of a LC resonant circuit and an auxiliary switch is used to let the main switches have ZVS at turn off. The converter presented in [11] is basically an improved circuit configuration of the one in [10]. In which, the auxiliary switch is not necessary. However, these types of converters suffer from the limitations: (i) the PWM switching control can not be performed; and (ii) the switching frequency of converter is limited, since it must be synchronized to the resonant frequency of auxiliary branch. In [12], a current-controlled quasi-resonant unipolar converter using thyristors for SRM is presented. Obviously, the PWM current control performance is also limited. Another group of soft-switching converters [13,14] developed for SRM belong to resonant DC link converters. The one in [14] has limited switch voltage stress through using the actively clamped resonant DC link. These converters also lack of PWM switching control capability. In [15], the ZVT switching technique [16,17] is applied to let the switches in a Miller converter possess ZVS soft-switching characteristics. However, only simulation results are presented.

In this paper, a converter with high efficiency for SRM is designed and implemented. First, a SRM drive powered using hard-switched modified Miller converter is established. Then the proposed converter is introduced. It is formed from the conventional Miller's converter via suitable modifications in circuit and switching control. Each PWM switch is augmented by an auxiliary branch, and the ZVT soft switching is achieved by applying suitable switching signals to the PWM main and auxiliary switches. No additional sensors are required for making the soft-switching control. Having analyzed and derived the governing equations of the converter in various modes, the quantitative design for the auxiliary branch is made. As to the commutation switches, they are implemented using power devices with lower on-state voltage. In making the performance evaluation of the developed converter, an efficiency measurement approach is introduced. The simulation and experimental results show that higher energy conversion efficiency of the SRM drive with the designed converter is obtained, and the driving control performance remains unchanged.

2 Establishment of the SRM Drive

Fig. 1 shows the established SRM drive powered by the hard-switched 2(n+1)(n is the phase number of motor) Miller converter, which uses two PWM switches to lessen their power burden. The SRM, which is manufactured by TASC Drives Ltd., is rated as 8/6 4-phase, 1500rpm, 4kW. The DC-link voltage is set as V_i=310V. The permanent magnet synchronous generator (PMSG) equipped with switched resistance is served as the dynamic load of the motor. For the converter, the four lower switches are used for making exciting commutation of armature phase windings. Their switching frequency is low, and the choice of power switch is emphasized in having low on-state voltage. The MOS-controlled thyristor (MCT) may be a better choice. However, it is not popularly available commercially. Thus the IGBT IXGH41N60 (600V/75A, 0.45 μs, 1.6V/41A) manufactured by IXYS Company is adopted for implementing these commutation switches. As to the upper two switches, since they are in charge of PWM switching control, the power switch with shorter switching time is preferable for reducing the switching losses. Thus the IGBT IXGH39N60BD1 (600V/75A, $0.2\mu s$, 1.8V/39A) is adopted here. And moreover, the ZVT soft-switching control will be employed for further reducing their switching losses. The control system shown in Fig. 1 is cascade-configured consisting of speed and current loops. And the current-controlled PWM scheme is employed to obtain good winding current tracking waveform. The commutation signals ($S_1 \sim S_4$) for lower switches are yielded from the quadrature Hall sensing signals H_A and H_B. For ease of implementation, both the speed and current controllers are chosen to be the PI types:

$$G_{c\omega}(s) = 0.5 + \frac{1.1}{s},\ G_{ci}(s) = 510 + \frac{10^7}{s} \qquad (1)$$

Having established the motor drive, some measured results are provided to show its correctness and performance. Figs. 2(a) and 2(b) show the measured winding currents and their commands of phase 1 at ($\omega_r = 700rpm,\ R_L = 22\Omega$) and ($\omega_r = 1400rpm,\ R_L = \infty\Omega$), respectively. Fig. 3(a) shows the rotor speed responses and current commands due to step command change (700rpm→800rpm, R_L=22Ω) and step load resistance change (R_L=22 Ω → 13.2 Ω, $\omega_r = 700rpm$). Fig. 3(b) shows the results corresponding to $(1400rpm \to 1500rpm, R_L = \infty\Omega)$ and ($R_L = \infty\Omega \to 304\Omega,\quad \omega_r = 1400rpm$). The results shown in Figs. 2 and 3 indicate that the established SRM drive can normally be operated and possess satisfactory performances in winding current tracking waveform and speed dynamic responses.

3 The Proposed Converter for SRM Drive

Circuit configuration of the proposed soft-switching converter is drawn in Fig. 4(a), which is formed from the modified Miller's converter shown in Fig. 1 by augmenting an auxiliary resonant branch circuit for each PWM switch to reduce its switching losses. Each auxiliary branch consists of a switch, a diode and a LC resonant circuit. The control system block diagram of the proposed soft-switching converter is shown in Fig. 4(b), which is obtained from Fig. 1(b) by slight modification. The ZVT soft-switching is obtained by suitably delaying the turn-on instant of the PWM switching signal of the main switch, and within the delay period the switching signal is applied to the auxiliary switch.

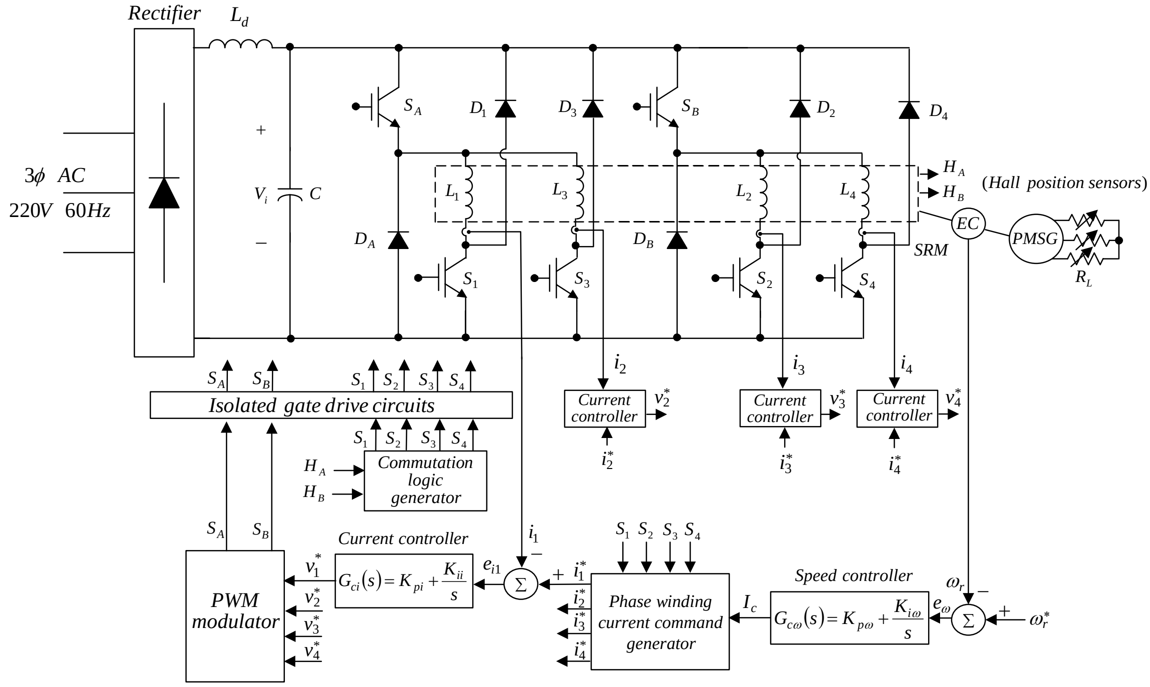
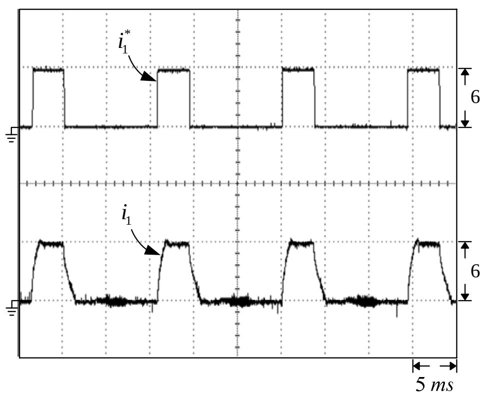
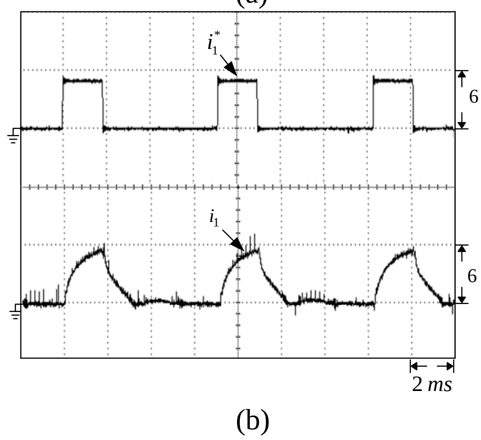


Fig.1 Configuration of the established hard-switching converter-fed SRM drive



(a)



(b)

Fig. 2 Measured winding currents and their commands: (a) $\omega_r = 700rpm,\ R_L = 22\Omega$; (b) ω_r =1400$rpm,\ R_L = \infty$

The mechanism for generating the delayed switching signals for main PWM switches (S_A and S_B) and auxiliary switches (S_{Ar} and S_{Br}) is shown in Fig. 4(c). Since the delay time is very short compared with the PWM switching period, the performance of the soft-switching converter is almost the same as those of conventional converter.

3.1 Circuit Operation and Governing Equations

The analysis is made for the particular phase winding, which is being performed the current-controlled PWM switching by the upper switch S_A or S_B. The following assumptions are reasonably made: (i) during the PWM switching period, the commutating diode $(D_1 \sim D_4)$ is off, and one of the lower switch is on. This leads to the circuit configuration shown in Fig. 5(a); (ii) since the switching period is very short, within which the input voltage and winding current are all assumed to be constant, i.e., $i_o = I_o$ and $v_i = V_i$. Hence, the equivalent circuit of Fig. 5(a) is drawn in Fig. 5(b); (iii) all the constituted components are lossless; and (iv) the resonant capacitance C_r is the sum of the parasitic capacitance of main switch S and the externally added capacitance.