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Low Cost High-side Gate Drive Power Supply for Switched Reluctance Machines

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Abstract – The applications of switched reluctance machines in electrical vehicles, as well as in wind and hydro turbines, are gaining increasing attentions from the industries because of their low cost, low inertia and simple construction. In this paper, a low cost high-side power supply for the gate driver of switched reluctance machine is presented. With the use of a bootstrap technology, the high-side circuit acquires energy from the power supply of the low-side when the high-side switch is turned off. The acquired energy is utilized to support the high-side gate driver and current sensor when the phase winding is excited with the DC-link voltage. The circuit requires only a power diode and capacitor for each high-side power electronic switch. Comparing with traditional isolated power supply solutions, the cost and size of the proposed method are reduced. The necessary control algorithm of the gate drive to sustain the high-side voltage is also presented in this paper. Although it slightly increases the computational burden of the controller, it imposes no limit on the control of the phase winding of the machine with proper selection of the bootstrap capacitor. The guideline on the selection of the power electronic components is derived based on the parameters of the switched reluctance machine. Experimental results prove that the proposed scheme is practically feasible, for normal operations of SRM.

Keywords - Reluctance machine, high-side power supply, gate drive

I. INTRODUCTION

Switched reluctance machine (SRM) has been gaining increasing attention from the industries for decades. Because of its low moment of inertia, simple construction, low maintenance cost [1], and fault tolerant operation [2], [3], SRM is considered as a strong competitor to induction and DC machines for variable speed applications. Because of the rise of fuel costs in recent years, alternative energy supplies such as wind and solar sources are being studied extensively. SRM is suitable for wind [4] and hydro turbines which require a wide range of operating speed.

Traditional topology of the power electronic converter of SRM is built from asymmetrical half-bridges (Fig. 1). Many variants are derived from this configuration [1], [5], [6]. As the half-bridge consists of a power electronic switch connecting to the high-side of the DC-link, and most switches require a positive voltage bias for proper operation, a dedicated floating power supply circuit for the high-side is required for each bridge. Charge-pump [7], [8], and inductive transformer [9] are reported to deliver energy to the high-side from the low-side power source. This topology has no limit on the control of the high-side switch, at the expense of extra gate driver, MOSFET, and opto-coupler, with large parasitic capacitance. Bootstrap, as a simple and low cost alternative, can be utilized to provide energy to the high-side circuit. The major drawback of bootstrapping is the limit on the maximum ON time of the high-side switch. Relatively few literatures describe the operation of SRM with bootstrap power supply. Reference [10] proposes an algorithm to protect the power drive with bootstrap circuit and SRM from overloading when the rotor speed is low. However, it imposes a lower limit on the operating speed of the SRM and such limits are undesirable for variable speed applications.

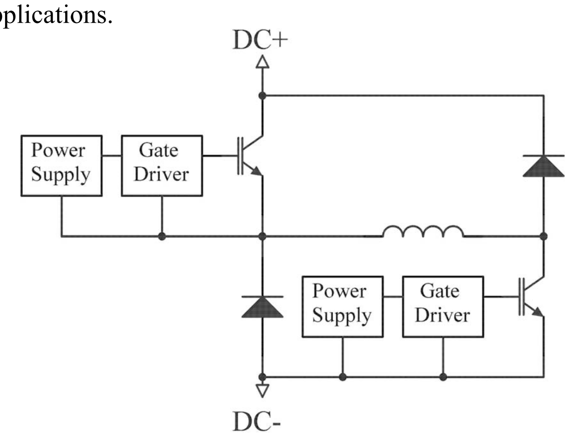

Fig. 1: Gate drivers and high-side power supply of asymmetric half-bridge for SRM

This paper presents the use of bootstrapping on the power drive of SRM built from an asymmetrical half-bridge. In this paper the principles of operation of bootstrap are explained and the associate control algorithm is also described. Experimental results are provided to prove the effectiveness of the bootstrapping circuit. Based on the basic parameters of SRM, the selection of the components of the bootstrap supply is discussed..

II. PRINCIPLES OF OPERATION

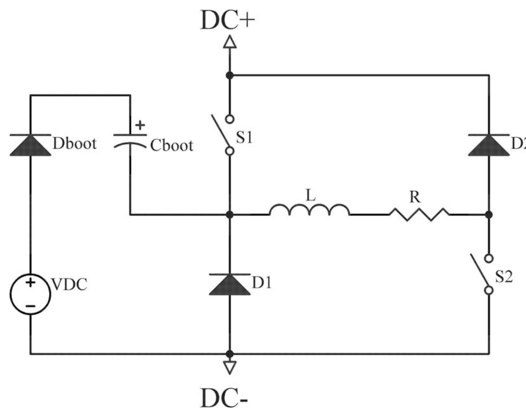

Fig. 2: Bootstrap supply circuit for SRM

The proposed bootstrapping circuit and associated asymmetric half-bridge are shown in Fig. 2. The bootstrap circuit consists of a low voltage power source VDC, bootstrap diode D_{boot}, and bootstrap capacitor C_{boot}. S_1, S_2, are the power electronic switches and D_1, D_2 are the diodes of the asymmetric half-bridge. L and R respectively represent the inductance and resistance of winding. For simplicity, the gate driver circuits for the power electronic switches are not illustrated in the figure. It should be noted that the power source VDC may also be used to supply power to the low-side gate driver.

2.1. Stage of operation

2.1.1. Stage 1: Charging C_{boot}

Initially, the bootstrap capacitor is not charged and there is no current following in the phase winding. When the low-side switch S_2 is closed, the power source charges the capacitor through the bootstrap diode and winding. The equivalent circuit of this stage is shown in Fig. 3.

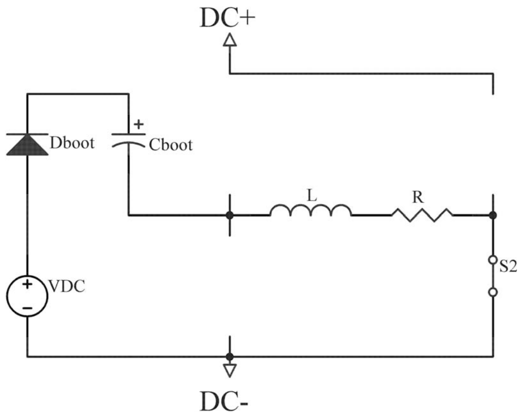

Fig. 3: Stage 1: Charging C_{boot}

2.1.2. Stage 2: Freewheeling/de-energizing winding

As the capacitor is fully charged, the power diode D_1 is forward biased to carry the winding current. Thus, the phase winding freewheels. At the same instant, the bootstrap diode ceases to conduct. The high-side gate driver is supplied with the charge stored in C_{boot}. The circuit representation of this stage is shown in Fig. 4.

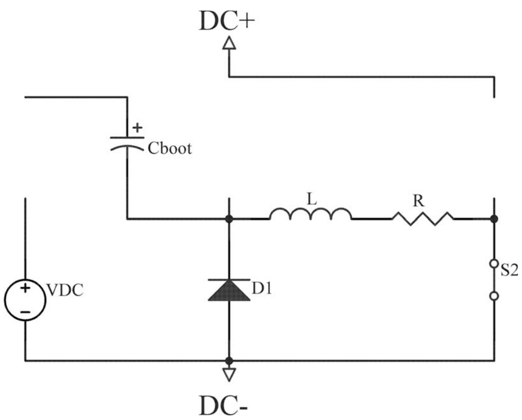

Fig. 4: Stage 2: Freewheeling/de-energizing winding

It should be noted that if S2 is switched off in this stage, the winding begins to de-energize and the winding current flows through the diodes D_1 and D_2.

2.1.3. Stage 3: Energizing winding

If S_1 and S_2 are closed to energize the phase winding, D_1 stops conduction. D_{boot} is reversely biased and C_{boot} supplies the power to the high-side gate drive circuit, as shown in Fig. 5.

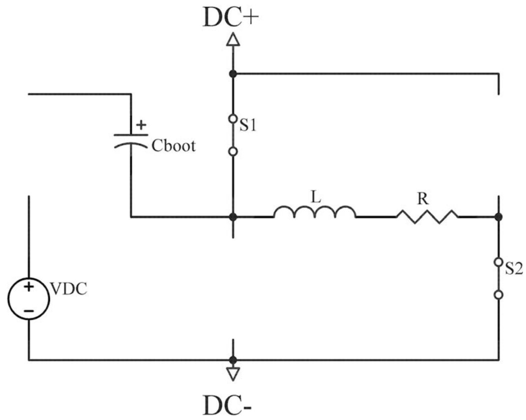

Fig. 5: Stage 3: Energizing winding

2.1.4. Stage 4: Freewheeling/de-energizing winding and charging C_{boot}

If the high-side switch is off, the voltage of C_{boot} is lower than the voltage of the power source VDC and there is phase current, the operating stage is changed from either 2 or 3 to 4. D1 conducts to handle the freewheeling current of the winding, whereas VDC charges C_{boot} via D_{boot}. The equivalent circuit is depicted in Fig. 6.

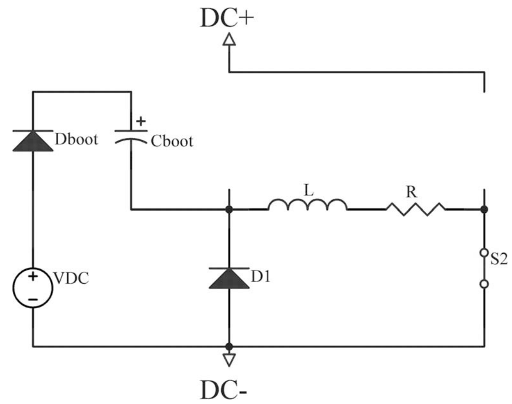

Fig. 6: Stage 4: Freewheeling/de-energizing winding and charging C_{boot}

Similar to stage 2, if the switch S_2 is off, the winding begins to de-energize via the diodes D_1 and D_2, provided that the winding current is continuing to flow. The charging state of C_{boot} in this stage is independent of the state of S_2.

2.2. Control algorithm

From the operation stages described earlier, one may notice that charging of the capacitor C_{boot} is necessary for the starting up of the circuit. When there is current flowing through the phase winding and switch S_1 is opened, the voltage of the bootstrap capacitor C_{boot} charges up to a level which is close to the supply voltage VDC. When S_1 is on or no current flows through the winding, the loading of the gate drive circuit consumes the energy stored in C_{boot} and its voltage decreases accordingly. Hence, a control algorithm of the SRM with the bootstrap taken into consideration is derived. When the circuit is powered up, the high-side switch S_1 is off, and S_2 is on for a period of time. To provide excitation to the winding, both switches are turned on. When freewheeling is required to control the current, S_1 is switched off. To de-energize the winding, both switches are off. If the rotor speed is low, the phase current is zero and the phase is not in the active region, S_2 switches on.

The scheme maintains the voltage of the bootstrap capacitor to the required level, and puts no limitation on the control of the SRM winding, provided that the bootstrap capacitor is sufficiently large to supply the gate drive circuit during the energizing period.

III. EXPERIMENTAL RESULTS

The proposed bootstrap circuit and control algorithm are implemented experimentally. The details of the circuit and SRM are listed in Table 1 and Table 2, respectively.

Table 1 Details of bootstrap circuit

Loading of high-side gate driver	3 mA
Bootstrap capacitor C_{boot}	470 μF
Bootstrap diode D_{boot} forward voltage	0.3 V-0.6 V
Low voltage power source VDC	15 V

Table 2 Parameters of the SRM

Rated voltage	270 Vdc
Rated current	10 A
Unaligned bulk inductance	0.0189 H
Aligned bulk inductance	0.141 H
Winding resistance	1.2 Ω

The high-side supply voltage and phase current during the start up of the bootstrap circuit are displayed in Fig. 7.

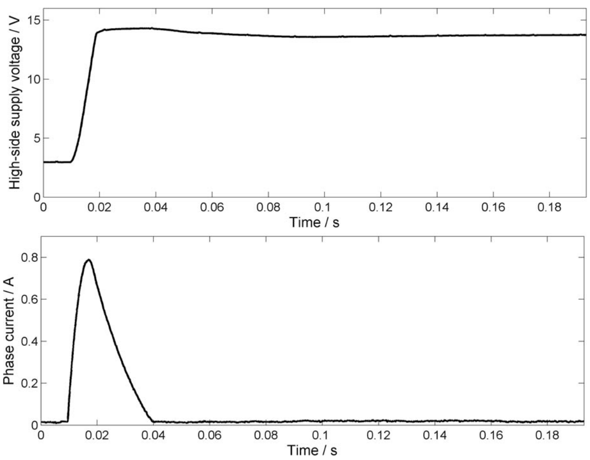

Fig. 7: Experimental start-up waveforms of the bootstrap

From the high-side supply voltage waveform, it can be seen that the bootstrap capacitor charges up rapidly within 10 ms after the low-side switch S_1 switches on at t=0.01 s. As the capacitor voltage reaches the voltage of the low voltage power source, the voltage remains constant and the phase current starts to decrease due to the winding resistance.
The voltage of the bootstrap capacitor and phase current when the IGBTs are controlling the phase current are shown in Fig. 8. From 0.017 s to 0.035 s, both IGBTs are on to excite the phase winding. Within this period, the high-side supply voltage drops linearly because the gate driver is consuming the energy stored in the capacitor. Between 0.035 s and 0.055 s, the high-side IGBT S_1 performs PWM switching and S_2 remains on to control the phase current. At the same time, the capacitor is charged up gradually. For the period from 0.055 s to 0.13 s, both IGBTs are off to de-energize the phase winding. The high-side supply voltage rises to and maintains at VDC when there is current flowing through the winding. Afterwards, the IGBTs remain off in the inactive region of the phase. Hence, the voltage drops linearly until the recharging stroke in the next cycle.

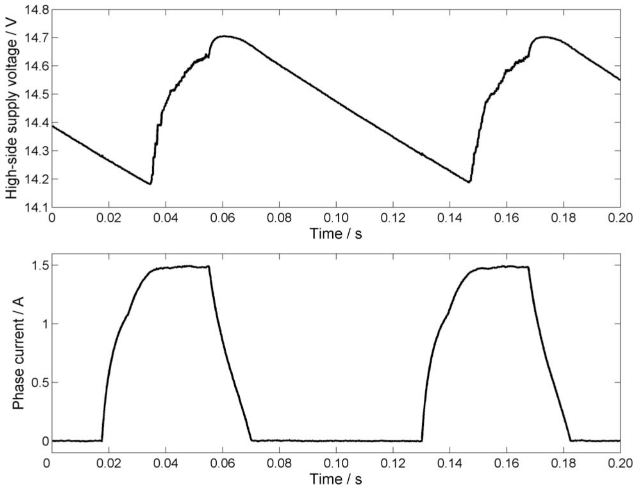

Fig. 8: Voltage and phase current during operation

The figures show that the bootstrap circuit and algorithm can maintain the high-side supply voltage under normal SRM operation with current control, while meeting the energy demand of the gate drive circuit.

IV. COMPONENT SELECTION

4.1.Selection of bootstrap capacitor

To select the bootstrap capacitor, the variation of the voltage between successive strokes has to be evaluated first. Between successive strokes, the voltage drop of the capacitor is:

$$\Delta v_{boot} = \frac{i_{load}\theta_{stroke}}{C_{boot}\omega} \quad (1)$$

where i_{load} is the loading current of the high-side gate drive, θ_{on} is the stroke angle, C_{boot} is the capacitance of the bootstrap capacitor, and ω is the rotor speed. According to the design of the gate drive circuit, the permissible voltage drop and loading current are specified. Stroke angle is calculated from the geometry of the SRM. When the capacitance is specified, the minimum rotor speed can be calculated. If the rotor speed is lower than the threshold, the low-side switch has to switch on in the inactive region of the phase. In general, the minimum rotor speed is inversely proportional to the capacitance. It should also be noted that the minimum capacitance should be able to sustain the voltage during the maximum on period T_{on} of the high-side switch.

$$\Delta v_{boot} = \frac{i_{load}}{C_{boot}} T_{on} \quad (2)$$

where the maximum on period is calculated as:

$$T_{on} = \frac{\lambda_{ph\max}}{V_{dc\text{-}link}} = \frac{L_a i_{ph\max}}{V_{dc\text{-}link}} \quad (3)$$

where; $\lambda_{ph\ max}$ is the maximum flux-linkage of the SRM, which is the product of the aligned phase inductance L_a and maximum phase current $i_{ph\ max}$; $V_{dc\text{-}link}$ is the dc-link voltage.

As for the voltage rating of the bootstrap capacitor, it is equal to the voltage of the low voltage power source.

4.2. Selection of bootstrap diode

The bootstrap diode should be able to withstand the inrush current during the start-up process of the circuit. To calculate the inrush current, the electrical equations of stage 1 are described:

$$VDC = L\frac{di_{ph}}{dt} + v_{boot} + i_{ph}R \quad (4)$$

$$i_{ph} = C_{boot}\frac{dv_{boot}}{dt} \quad (5)$$

After solving (0), and (0) with the initial values of phase current i_{ph} and capacitor voltage v_{boot} set to zero, the peak current during start-up is:

$$i_{ph_{peak}} = VDC\, C_{boot} e^{-at_p}\left(b + \frac{a^2}{b}\right)\sin(bt_p) \quad (6)$$

where $a = \frac{R}{2L}$, $b = \frac{\sqrt{4LC_{boot} - R^2C_{boot}^2}}{2LC_{boot}}$, and $t_p = \frac{1}{b}\tan^{-1}\left(\frac{b}{a}\right)$.

The non-repetitive surge rating the bootstrap diode should be larger than the peak current. For the voltage rating, it is the sum of voltages of the DC-link voltage and the low voltage power supply.

V. CONCLUSION

This paper develops a low-cost bootstrap circuit to supply energy to the high-side gate driver circuit from the low-side power supply. The circuit consists of a low-voltage capacitor and a high voltage diode only. The principle of operation of the circuit is analysed. Hence, a control algorithm is derived. The algorithm imposes no limitation on the control of the SRM. Experimental results of the circuit are also presented to prove the effectiveness of the circuit. A guideline on the selection of the bootstrap components is derived based on the basic parameters of the SRM.

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