A Novel Power Inverter for Switched Reluctance Motor Drives

Zeljko Grbo, Slobodan Vukosavic, *Member IEEE,* Emil Levi, *Senior Member IEEE*

***Abstract* – Although apparently simpler, the SRM drives are nowadays more expensive than their conventional AC drive counterparts. This is to a great extent caused by the lack of a standardised power electronic converter for SRM drives, which would be available on the market as a single module. A number of attempts were therefore made in recent times to develop novel power electronic converter structures for SRM drives, based on the utilisation of a three-phase voltage source inverter (VSI), which is readily available as a single module. This paper follows this line of thought and presents a novel power electronic converter topology for SRM drives, which is entirely based on utilisation of standard inverter legs. One of its most important feature is that both magnetising and demagnetising voltage may reach the DC-bus voltage level while being contemporarily applied during the conduction overlap in the SRM adjacent phases. At the same time, the voltage stress across the power switches equals the DC-bus voltage. The topology is functional in all operating regimes of the drive. Principle of operation is explained in detail for a three-phase SRM drive and experimental results, obtained with a 6/4 switched reluctance motor, are included. Four inverter legs are required in this case. Some considerations, justifying the proposed converter topology from the point of view of the cost, are included.**

***Index Terms* – Voltage source inverter, semiconductor switch, switched reluctance motor.**

I. INTRODUCTION

Switched reluctance motor drives have been in the focus of research effort for more than two decades [1-3]. As a result, various motor constructions have been proposed. These primarily differ with respect to the number of phases employed, stator/rotor pole number configurations, and the mechanism of torque production. Although the torque is always produced by the doubly-salient structure of the machine, its origin may be two-fold. Torque may be generated entirely due to the variation of the winding self-inductance with rotor position (so-called short pitched SRMs). Alternatively, mutual coupling between phases (i.e. position-dependent variation of the mutual inductances) can be used to improve the torque density. Depending on the winding distribution, two types of SRMs may result, fully pitched and fractionally pitched SRMs. In fully pitched SRMs there is a negligible variation in phase self-inductance with rotor position and torque production results due to variation of the mutual inductance between adjacent phases. In terms of this subdivision, this paper concentrates on the short pitched SRMs. The development and explanation of the power electronic converter topology, as well as the experimental results, are given for a three-phase 6/4 pole SRM.

A number of power electronic converter topologies have been developed over the years exclusively for use in conjunction with SRM drives. In principle, the quest has always been for a converter with a minimum number of switches [4]. An excellent review of numerous power electronic converter configurations for SRM drives is available in [2], while some very insightful comparisons of various commonly used topologies can be found in [5,6]. However, regardless of all the developments in the SRM drives area, switched reluctance motors have not yet found broad acceptance. One of the main reasons for such a situation is undoubtedly the lack of a standardised power electronic converter, which would be readily available on the market. This contrasts with the AC drives market, where a three-phase voltage source inverter has become the standard solution and numerous manufacturers offer the complete inverter 6-pack, including the driver and protection circuits. It is precisely for this reason that a number of authors have looked recently at the potential of applying a standard VSI 6-pack as the converter for SRM drives [7-9].

The configuration proposed in [8] is applicable to both fully pitched and short-pitched SRMs, it leads to the unipolar current flow and full DC voltage is available for magnetisation and demagnetisation. The converter is a standard VSI 6-pack. However, the three-phase SRM winding has to be connected in delta, with a separate diode connected in series with each phase. Furthermore, winding delta connection makes independent phase control impossible. A quite different approach is proposed in [9] for a fractionally pitched winding SRM. The three-phase winding is star-connected and is supplied from the three-phase VSI 6-pack. The phase currents are therefore bipolar. The star point of the winding is connected to the mid-point of the split capacitor in the DC link. Although this scheme requires only one standard VSI, it makes only half of the DC link voltage available for magnetisation and demagnetisation.

The purpose of this paper is to propose a novel converter topology for SRM drives, which entirely relies on utilisation of the standard VSI legs. Similar to [9], three-phase winding is connected in star and bipolar current flow in phases is obtained. However, in contrast to [9], full DC voltage is

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available for both magnetisation and demagnetisation purposes. The converter requires a total of four inverter legs for the three-phase SRM supply. The fourth leg is utilised to connect the star point of the three-phase winding and is actively controlled. Principles of operation of the converter are at first explained. This is followed by experimental results obtained using a three-phase 6/4 SRM. The cost-effectiveness of the proposed converter configuration is assessed by comparing the component cost of the novel converter with the asymmetrical half bridge converter.

II. SRM CONVERTER REQUIREMENTS

In light of the torque production, it is possible to formulate basic requirements for the SRM drive power circuit:

a) For the purpose of the phase current control, it is necessary to modulate the phase voltage. This is especially important at low speed, when the motor back-emf is low.

b) The voltage gain of the converter should be maximum possible in order to extend the constant power operation mode and increase the maximum speed.

c) Large fall time of phase current results in negative torque and this time can be reduced if demagnetising voltage is as high as possible.

d) It is necessary, at the same time, to control current in one phase and force demagnetising of some other phase of the motor. This is crucial for reduction of the torque ripple [10].

e) Converter has to be single rail in order to reduce the voltage stress across the semiconductor switches.

f) The power converter must not require bifilar windings or rely upon the motor construction.

g) A low number of semiconductor switches is desirable.

On the basis of detailed surveys and comparisons of various converter circuits in [2,5,6], it appears that the two most frequently used converter circuits are the asymmetrical half bridge converter and the Miller converter. These circuits are illustrated in Fig. 1.

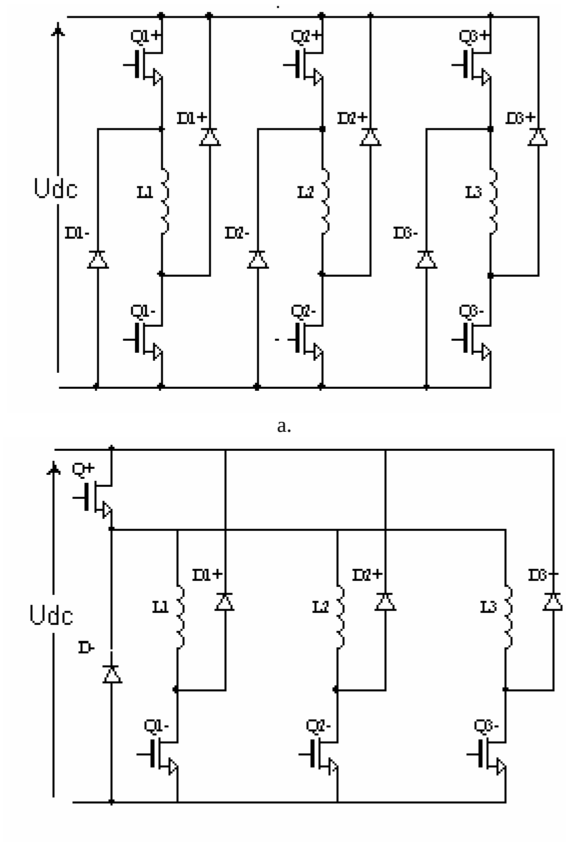
Phase current in asymmetrical half bridge converter is controlled by selecting from three possible states:

i) Both switches in a phase leg are on, and phase is energised from power supply (magnetising stage).

ii) Both switches in a phase leg are off. Phase current commutates to the diodes and decays rapidly (demagnetizing stage).

iii) Only one of the switches is off. The voltage across winding is near zero and phase current decays slowly (freewheeling).

Each phase is controlled independently and by proper selection of phase states it is possible to satisfy all the functional requirements listed above. Full DC-bus voltage is available for both magnetisation and demagnetisation. The converter requires, for a three-phase SRM, a total of six controllable switches and six diodes. Although this is the same as for a standard 6-pack VSI, converters of the structure of Fig. 1a are not available on the market as single modules and are therefore built using discrete components.



a.

b.

Fig. 1. Typical converter topologies for SRM drives: Asymmetrical half bridge converter (a.) and Miller converter (b.).

In order to reduce the number of switches and therefore bring down the converter cost, Miller converter was proposed, Fig. 1b. In each phase the following three switching states are available:

i) Both the Q+ switch and switch in phase leg are on (magnetisation stage).

ii) Switch Q+ is off and switch in phase leg is off. Phase current flows through diode D- and diode in appropriate phase leg and phase current decays rapidly (demagnetisation stage).

iii) Switch Q+ is off. The voltage across phase winding is near zero and decays slowly (freewheeling).

The Miller converter requires only four controllable switches and four diodes for a three-phase SRM drive. However, this converter is not available on the market as a single module either and therefore has to be manufactured from discrete components. The main disadvantage of the Miller converter is that motor phases cannot be controlled independently. When the switch Q+ is on, the forced demagnetisation of any of the phases is not feasible. It is shown in [5] that demagnetising voltage in Miller converter reduces to one half of the DC-bus voltage and this represents a significant drawback. Many other existing topologies suffer from similar control insufficiencies or require an unacceptable rating of semiconductor switches [5,6].

II. PROPOSED CONVERTER TOPOLOGY

The underlying idea behind the development of the novel converter topology is that it must be entirely based on utilisation of standard VSI legs (in contrast to [8]). At the same time full DC-bus voltage must be available for both magnetisation and demagnetisation purposes (in contrast to [9]). Finally, the converter should satisfy the technical requirements listed in the preceding section. The novel converter topology is presented in Fig. 2 for a three-phase SRM drive. A 6/4 SRM design is assumed but the considerations and conclusions drawn hereafter can be extended to other three-phase SRM configurations.

The converter consists of four typical inverter legs (in the case of an N phase motor the converter consist of N+1 inverter legs). One inverter leg (Q+,Q-) is common for all phases. The star point of the three-phase SRM winding is connected to this leg. The operation of the converter is analysed and explained by considering various switching states, illustrated in Fig. 3. The switching states related to the phase L1 winding are:

A) Magnetising stage:

A1) Q1- and Q+ are on, Fig. 3a (positive L1 flux).

A2) Q1+ and Q- are on, Fig. 3b (negative L1 flux).

It should be noted at this point that these two states lead to two possible directions of the phase current. This means that the current in the winding is bipolar, rather than unipolar (as the case is with standard converters of Fig. 1). Since the SRM under consideration is of short pitched design, where torque is produced entirely due to the variation of the self-inductance with rotor position, it is obvious that the same torque can be generated with both unipolar and bipolar currents. In both A1 and A2 switching states, full DC-bus voltage is available across the winding for magnetisation stage. The two possible magnetisation stages are depicted in Figs. 3a and 3b.

B) Demagnetising stage:

Switch Q- is on (A1 magnetising) or Q+ is on (A2 magnetising). The switches in off-going phase leg are off. Phase current commutates to diodes and decays rapidly. Demagnetisation of phase L1 is illustrated in Fig. 3c for the case of magnetisation with A1 method. During demagnetisation stored energy in the off-going phase is returned to the power supply and on-coming phase.

C) Freewheeling:

The winding can be short-circuited by either turning off switches (Q+,Q-) or (Q1+,Q1-). Phase current decays slowly. This state is presented in Fig. 3d, for the case of magnetisation using A1 method and turning off leg (Q1+,Q1-).

During low speed operation phase current has to be limited or controlled in order to reduce torque ripple. This can be done by alternating between states A and B or between states A and C. It is preferable to use states A and C because this results in lower switching frequency for the same current ripple.

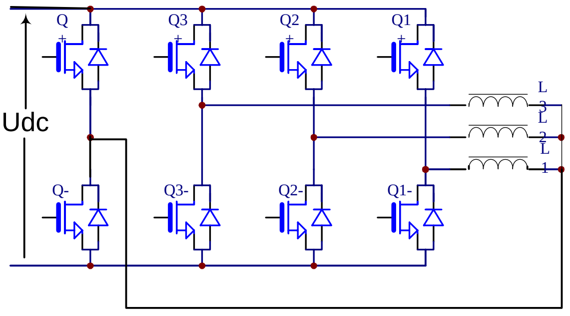
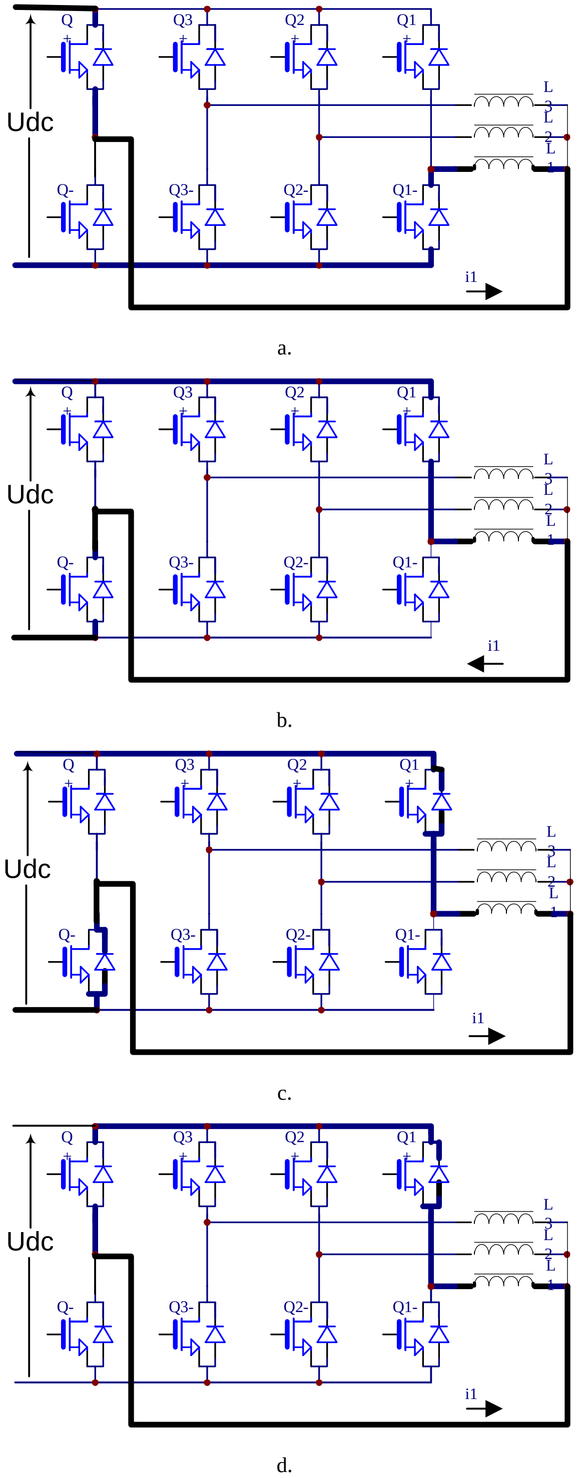


Fig. 2. The novel converter circuit for a three-phase SRM drive.



a.

b.

c.

d.

Fig. 3. Switching states of phase L1: a. Magnetisation (A1 method); b. Magnetisation (A2 method); c. Demagnetisation; d. Freewheeling.

It is important to show that at the same time it is possible to control current in the on-going phase and make forced demagnetisation in the off-going phase. This is illustrated in Fig. 4.

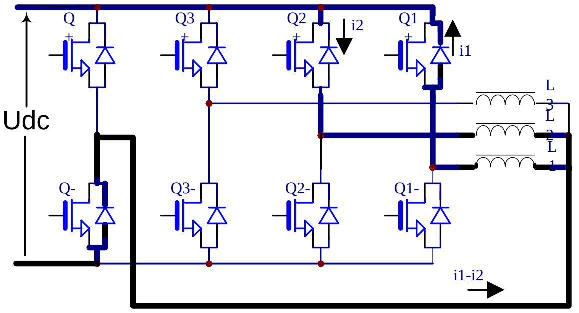


Fig. 4. Simultaneous conduction of adjacent phases.

It is assumed in Fig. 4 that phase L1 is off-going and phase L2 is on-going. It can be observed that currents of two adjacent phases have to have opposite direction. In the case of three-phase switched reluctance motor this results, as already noted, in bipolar phase current. Idealised waveforms of phase voltages and currents for all three phases, during one complete rotor revolution, are presented in Fig. 5. High-speed operation is assumed.

On the basis of the presented principles of operation of the novel converter for SRM drives the following conclusions can be drawn: the phase current is bipolar; full DC-bus voltage is available for both magnetisation and demagnetisation at high speeds; phase current waveform can be fully regulated at low speeds by combining the operating regimes of Fig. 3; the converter allows for simultaneous magnetisation of the on-coming phase and demagnetisation of the off-going phase.

It is important to note that each change of the excited phase requires the change of the state in the auxiliary (fourth) inverter leg. This requirement arises from the need for simultaneous magnetisation and demagnetisation of the two adjacent phases and leads to the bipolar phase current.

IV. EXPERIMENTAL SET-UP AND EXPERIMENTAL RESULTS

Experimental investigation is based on a three-phase 6/4 SRM with stator and rotor pole widths equal to 36°. The air-gap and the rotor length are 0.3 mm and 50.2 mm, respectively, and the per-phase winding resistance is 4 Ω. Stator winding self-inductance profile against rotor position was determined experimentally and is shown in Fig. 6.

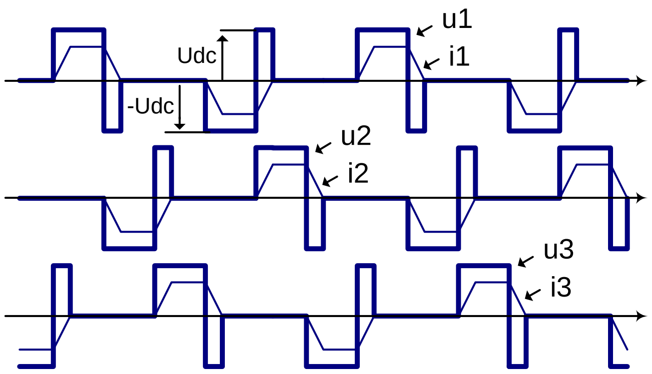


Fig. 5. Phase voltages and currents (one complete revolution).

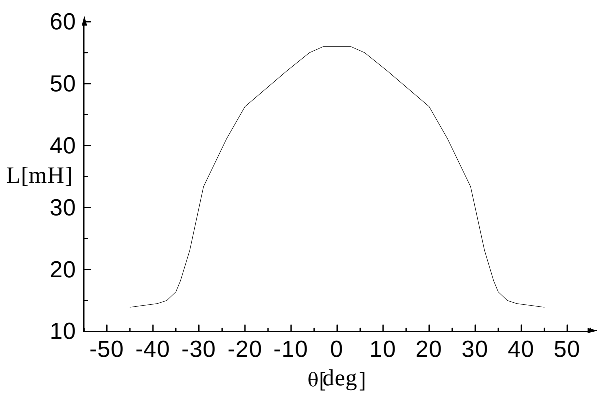


Fig. 6. Unsaturated stator phase self-inductance versus rotor position.

Fig. 6 was obtained using low excitation current (unsaturated region). Rotor position was measured using a resolver and a 12-bit R/D converter, while a Hewlett-Packard LCZ meter was employed for inductance measurement. The minimum and maximum measured inductance values in Fig.6 are 13 mH and 56 mH, respectively. Although the inductance profile of Fig. 6 departs from a trapezoidal waveform, trapezoidal approximation was used to determine the approximate value of the torque constant (41 mH/rad).

The circuit of Fig. 2 is constructed using a three-phase VSI 6-pack MOSFET module and two additional inverter-grade switches (i.e. a fully controllable switch with built-in anti-parallel diode) for the fourth leg. The control is implemented using DSP TMS320C14. An additional microcontroller 80C51 is used for communication purposes. Current controllers of hysteresis type are implemented and each motor phase is equipped with a LEM current sensor. DC-bus voltage equals 50 V in all experiments. The SRM motor is coupled to a controllable DC load, so that the load torque is adjustable. Closed-loop speed control mode of operation is investigated.

The first experiment is conducted in steady state with the SRM running at 800 rpm. Phase current and phase voltage are illustrated in Fig. 7. As can be observed from Fig. 7 and as predicted by theoretical considerations, phase current is bipolar and full DC-bus voltage is available for demagnetisation. From the phase voltage graph, it can be concluded that current regulation is accomplished by alternating between states A and C, while demagnetisation takes place using state B.

In the second experiment the motor runs at 1000 rpm. The aim is to show the existence of the possibility for simultaneous magnetisation of one phase and demagnetisation of the other phase. Fig. 8 therefore shows currents in two adjacent phases. It is easy to observe the existence of the current overlap when phase L2 is off-going and phase L1 is on-coming.

The converter is however capable of operating without the current overlap in two phases as well. This is illustrated in Fig. 9 by means of currents in two adjacent phases at 1000 rpm. It can be observed from Fig. 9 that there are intervals when currents in both phases are zero.

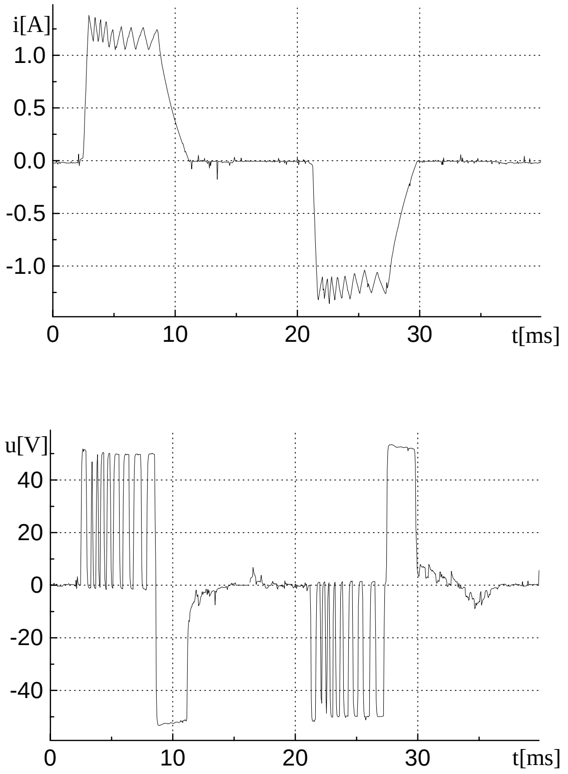


Fig. 7. Phase current and phase voltage during operation at 800 rpm.

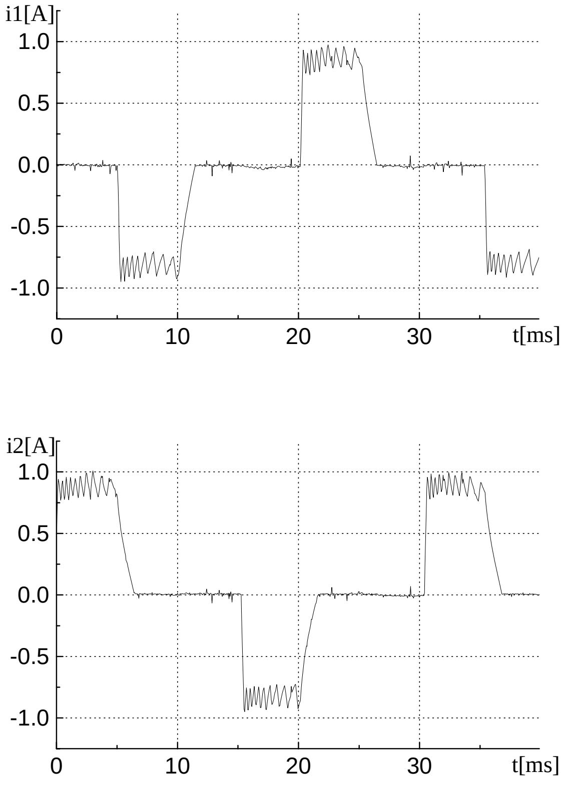


Fig. 8. Currents in two phases during operation at 1000 rpm, illustrating simultaneous conduction (current overlap) in two adjacent phases.

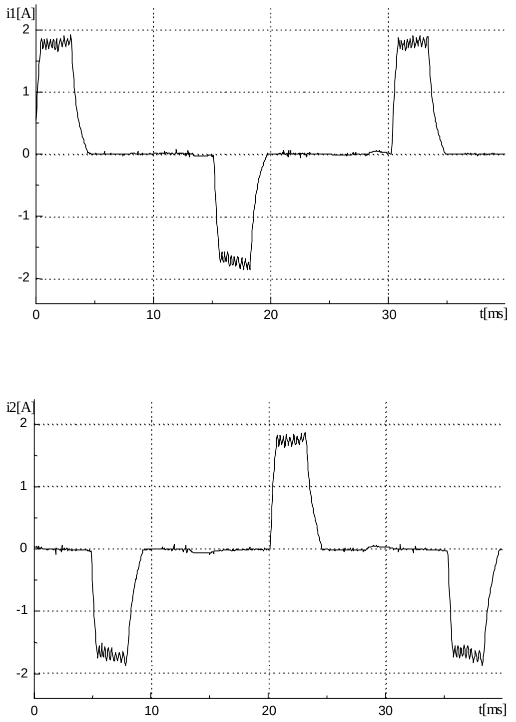


Fig. 9. Currents in two phases at 1000 rpm with reduced conduction angle, illustrating the operation without current overlap in two adjacent phases.

V. COST EFFECTIVNESS OF THE PROPOSED CONVERTER

An attempt is made in this section to evaluate the cost implications of the novel converter structure. This is of course a tremendously difficult task, since the converter price consists of two main components, component cost and manufacturing cost. Only the component cost can be investigated with any reliability, since manufacturing costs vary hugely. Every effort is made in the cost comparison to preserve objectivity. Since the proposed converter provides operating characteristics similar to the asymmetrical half bridge converter, especially in terms of the voltage available for magnetisation and demagnetisation, component cost of the novel converter is compared to the component cost of the asymmetrical converter of Fig. 3a (Miller converter will of course have a lower component cost; however it provides only one half of the DC-bus voltage for demagnetisation, in contrast to the other two converters).

In the price comparison the following design is considered: 3-4 A RMS with heat-sink temperature of 100° C, 300-400 V DC-bus voltage, 20 kHz PWM switching frequency. All the component prices are taken from a publicly available source [11] on 21 May 2004 and the components are from International Rectifier, except for the fast diodes for the asymmetrical half-bridge converter (Diode Inc.) and thermistors (Infineon Technologies). Only the cost of the SRM side converter is considered and the target number of full converters is 1,000 (hence, the prices taken for discrete semiconductor components apply to quantities of 3,000-10,000). Table I gives component prices.

TABLE I. COMPONENT PRICES (21 MAY 2004, www.Digikey.com).

Description	Code	Quantity	Unit price (USD)
3-phase IGBT VSI 6-pack module; integrated drivers & thermistor	IRAMS06UP60A-ND	1,000	10.625
IGBT with anti-parallel diode	IRG4BC10UD	10,000	1.2
Thermistor	KTY135, SOT-23	1,000	0.417
IGBT (no diode)	IRG4BC10U, IRG4BC10U-ND	10,000	0.98305
Fast diode	RS3JB-13	3,000	0.351
Driver, one IGBT pair	IR210STR	2,500	2.07

The proposed converter requires one full three-phase VSI module, two additional IGBTs with anti-parallel diodes and one additional driver for the fourth leg. Using the data of Table I, one calculates the total component price as equal to USD 15.095. The asymmetrical half bridge converter requires six IGBTs, six fast diodes, one thermistor and three IGBT drivers (one per leg). From Table I the total component cost is USD 14.6313. The comparison shows that the proposed converter is, in terms of the component cost, insignificantly more expensive (USD 0.4637 or 3.17%). However, it is obvious that the reduction in the manufacturing cost is more than likely to offset this component price difference. This is so since only one three-phase VSI module, two inverter-grade IGBTs and one additional driver for the fourth leg are required (a total of four 'components'). This contrasts with six IGBTs, six diodes and three driver circuits (a total of 15 'components') for the asymmetrical half bridge configuration.

VI. CONCLUSION

The paper proposes a novel power electronic converter topology for SRM drives. The topology is entirely based on the utilisation of standard inverter legs, utilised in three-phase VSIs. The main characteristics of the new inverter are:

- All of the available DC-bus voltage is available for both the magnetisation and demagnetisation, even during the current overlap due to conduction of the two adjacent phases.
- In the case of three-phase SRM, bipolar phase currents result.
- Voltage rating of all switches does not exceed the DC-bus voltage.
- Current rating of all switches is equal to the maximum phase current.
- Due to the small number of discrete components (assuming utilisation of a three-phase VSI 6-pack module), wiring and manufacturing is very simple.

When compared to the asymmetrical half bridge converter, the proposed converter is likely to be more cost effective, as illustrated in Section V. When compared to the Miller converter, the novel inverter does require more components and is therefore potentially more expensive. However, in contrast to the Miller converter, there is not any limitation on the available demagnetising voltage.

It is believed that the proposed concept can be extended to other types of SRM drives, with a different phase number. A particularly interesting case from this point of view is the two-phase SRM. By using two inverter legs to control two phases and by connecting the star point of the winding to the third inverter leg, is should be possible to realise a two-phase SRM drive using a single three-phase VSI 6-pack module. Similarly, in the case of a five-phase SRM drive it should be possible to use two three-phase VSI 6-pack modules, where the sixth inverter leg would again be used to connect the star point of the winding. The authors believe that these possibilities represent a potentially viable direction for future research.

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