High performance switched reluctance drives with wide field weakening range

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Abstract

For electrical vehicles, switched reluctance drives present a promising alternative - compared to asynchronous and synchronous (permanent magnet) concepts. For these applications, a very wide field weakening range is a key issue. Other requirements include high torque output from a small machine and low current ripple at the DC-side without the use of bulky filters - when powered from fuel cells or advanced Lithium-Ion-batteries. A new converter and control strategy according to these requirements is presented and compared to existing designs. The comparison is done for a drive system with a continuous power rating of 30 to 40 kW.

Introduction

Switched reluctance drives (SRD) for applications in electrical vehicles (EV) have been investigated extensively by several authors [2,3,4,5]. A simplified motor construction and lower cost – compared to conventional motors – have been stated frequently, but these points were not sufficient for a real breakthrough. In the future, two main applications in electrical vehicles are of special interest:

- An electrical starter / generator / damper [6] , mounted directly onto the crank shaft of a combustion engine. (Applicable for hybrid vehicles too, depending on peak power).
- Main traction drives for electrical cars, powered from fuel cells or advanced Lithium-Ion-batteries.

Both applications require a very wide field weakening range, which means a high starting torque combined with a wide speed range of constant power. In conjunction with the weak and load dependent DC-supply voltage of fuel cells or batteries, these requirements are hard to fulfil.

A new converter concept has been developed, enabling much better performance under these conditions and offering additional degrees of freedom for improved control strategies.

1. Comparison of drives for EV-applications

Taking into account the two important applications areas: starter/generator systems and main traction drives, both permanent magnet motor and asynchronous motor are suitable for these applications. Switched reluctance drives (SRD) have reached a status of development, where they can compete with these types. In Table 1, a simplified comparison of the main points is given:

	AM	**PM**	**SRD**
Efficiency (partial load)	+	0	+
Efficiency (full load)	0	+	0
Field weakening range	+	0	+
Motor cooling (rotor losses)	-	+	+
Fault behaviour (motor)	0	-	+
Fault behaviour (converter)	-	-	+
Torque pulsation	+	+	-
Acoustic noise	+	+	-

Table 1: Typical advantages (+) and disadvantages (-) of competing drive systems for electric vehicles

SR-Drives combine some advantages of both asynchronous (AM) and permanent magnet (PM) concepts. In addition, the fault behaviour of motor and converter is favourable. While the PM-machine may supply dangerous high voltages, high currents or undesirable breaking torque under fault conditions, the SR-machine is deenergized easily. The converter for SR-Drives represents the most reliable power circuit with respect to possible short circuits of the DC-supply. One disadvantage is the higher acoustic noise of typical SR-machines, which has to be reduced mainly by a good mechanical design. The important points „torque pulsation, maximum torque and efficiency“ can be improved significantly by a new converter concept with flexible control, which will be shown here.

2. Converter circuits

Many converter circuits for SRD have been proposed. Most of them are restricted to motoring operation – excluding generator operation i.e. electrical breaking [1,7]. The majority of converter publications is focused on cost reduction of different converter circuits. In order to get a relative number for cost comparison of converter circuits, the number of switches and their switching power are summed up. This gives a rough approximation, if the following conditions are fulfilled:

a) Large discrete power devices with a relative high voltage rating – compared to the technological limits – are used
b) The expense for the housing of these discrete devices, their associated gate drivers, snubbers and mechanical parts represent a high percentage of the total converter cost.

For modern power converters with a high degree of monolithic integration using IGBT-chips, neither a) nor b) are true. In addition, the switching power of the semiconductor devices is not a significant figure, especially in the standard voltage range below approx. 1000 V. A better representation for the expense of the converter is then given by:

1. The required total silicon area
2. The sum of the semiconductor power losses
3. The amount of passive filter components needed

Here , the first point is the most important one, while the second point has to be considered in addition - especially if the cooling system or the total efficiency of the converter are predefined. The third point should not be neglected for applications with strong EMI-restrictions.

Fig. 1 shows the standard converter circuit for SRD, which is used in the majority of applications. Each phase (A,B,C) of the motor is controlled separately by means of a pair of one quadrant (1Q) choppers. The separate control is necessary in order to achieve low torque ripple and high average torque from a given machine. In addition, this circuit can be operated in both directions of energy flow at the DC-side (motoring and regenerating).

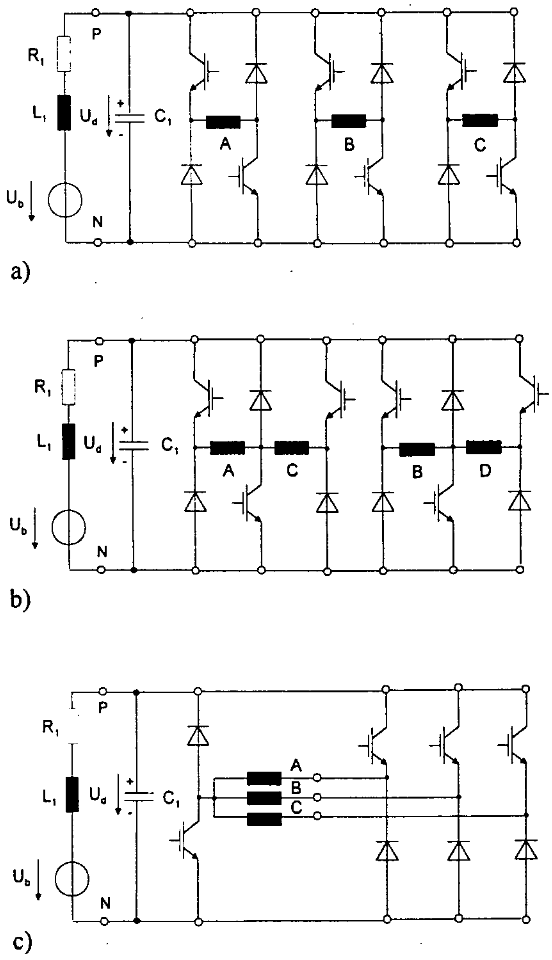


Fig. 1: Basic converter configurations for SRD

If a machine with more than 3 phases is used, some IGBT-switches may be shared between groups of 2 phases(Fig. 1b),[7].This will not disturb the separate control of the phases significantly, if the shared switches are not supplying consecutive phases. The expense for the converter, however, will not be reduced considerably by this measure, because the silicon area (point 1) will be reduced by the area of a few gate drivers, only. The sum of the semiconductor power losses (point 2) will remain unchanged. This is owing to the fact, that the shared semiconductors will have to carry double the average current compared to the other devices.

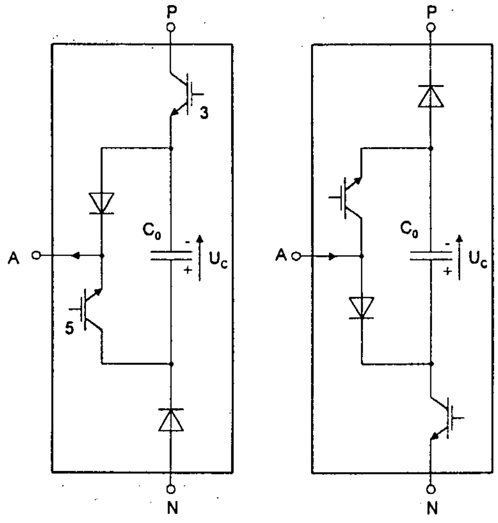
A configuration according to Fig. 1c, [1], with one common 1Q-chopper for all the phases is more advantageous, because it minimizes the number of motor terminals and interconnections. Unfortunately, the separate control of the phase currents will now be disturbed seriously, limiting the application to low power, low quality drives in a range below 1 kW.
In conjunction with the new converter concept presented here, a similar configuration without these drawbacks becomes possible.

3. New converter concept with flexible control

The new topology given here, represents the result of intensive analysis of the typical properties and significant drawbacks of SR-Drives in this application field. In order to achieve great improvements," some expenditure" at the electronic side (converter and control) is a necessary and favourable measure. The solution presented here, was chosen finally, because it offers very flexible control and extreme improvements in conjunction with moderate expenditure.

The new converter concept replaces one, several or all the 1Q-choppers by compatible subsystems (Fig. 2), which exhibit additional switching states and internal energy storage. The subsystems feature:

1. One additional switching state, where the output voltage is higher (positive) and another additional switching state, where the output voltage is lower (negative) than it is possible with conventional 1Q-choppers.
2. One unipolar capacitor for storing energy independent of the DC-Bus - being small compared to the DC-Bus-Capacitance (C_1).



a) b)

Fig. 2: Converter subsystems for the new concept

a) For positive load current
b) For negative load current

A good choice is, to replace the three 1Q-choppers (at the right side in Fig. 1c) by new subsystems, only. This version will be described here.

Table 2 gives an overview of the four switching states of the new subsystem. (Fig. 2a.).

Switching states Number 2 and 4 are the common states known from 1Q-choppers and Number 1 and 3 are the additional states. The semiconductors can be "state of the art" IGBT, which do not need reverse blocking. Only the blocking voltage of these devices must be higher, depending on the chosen voltage (U_C) of the unipolar capacitor (C_0). For applications with DC-link voltages (U_d) of 200 ...400 V or lower, the voltage rating of the IGBT and the diodes (in the range 600...1200 V typical), does not affect the silicon area, the semiconductor conduction losses or their cost, significantly.

The maximum voltage of the unipolar capacitor (C_0) can be controlled in a wide range by variable switching times- without increasing the switching frequency. The voltage is selfstabilizing even under open loop control (fixed switching patterns).

State	**Switches**		**Output voltage**	**Stored Energy**
No.	**3**	**5**	**U_A**	**sign(dW/dt)**
1	0	0	$-U_C$	+1
2	0	1	0	0
3	1	1	$+U_C+U_d$	-1
4	1	0	$+U_d$	0

Table 2: Switching states referring to subsystem 2a

The number of IGBT required, increases from six to seven only, for a 3 phase machine. This is owing to the fact, that the simpler basic topology similar to Fig. 1c is applicable now – without loosing the separate control of each phase. Because the four switching states per motor phase are fully sufficient for independent control of the motor currents, it is possible to change the state of the common 1Q-chopper, only , when changing between motoring and regenerating.

Briefly summarized, the following essential advantages can be realized:

a) Increasing the torque of a given machine by a factor of 2 or more - including the maximum speed range.
b) Increasing efficiency of a given machine significantly.
c) Decreasing torque ripple or DC-side current ripple, by improving current waveform.

d) Controlled stabilization of power and torque up to the maximum speed, despite the large DC-voltage variation of the weak supply.

All these advantages can be achieved by appropriate control of the switching patterns at fundamental frequency. Pulse width modulation with increased switching frequency is not necessary – but possible. The optimization criteria do not have to be fixed in the development phase or production process. On the contrary, it is possible to use advanced control schemes adapting the drive system to different load conditions and varying priorities during operation [6].

4. Results of measurements and simulations

For the purpose of testing, an existing SR-machine SR 301 was used, [5]. This machine was designed and tested thoroughly for application as a main traction drive of electrical vehicles (see [3]). The extensive measurement results of this machine at different operating points have been used and the machine parameters have been checked in order to validate the new machine model. This machine model has been used – embedded in a Simplorer simulation program – in order to calculate the results, presented here. The machine model is very precise, which can be checked by comparing the measurement results given in [3,5] with the results of the conventional converter, which are presented here for comparison.

4.1 Motor operation at max. speed

The operation with the conventional converter is shown in Fig. 3 (n=9000/min). The motor current waveform is characterized by an unfavourable small duty cycle and phase shift. This is owing to the facts, that the small time span near the unaligned rotor position must be used to build up the motor current and the decay of the motor current must be finished early enough, to assure demagnetization. Therefore the achievable torque M = 37 Nm is very near the boundary of stability (self excitation). Fig. 4 shows the improved waveforms, if increased torque is given priority. More than double the torque is achieved, without reaching the boundary of stability. The waveform of current is closer to the ideal, leading to reduced torque ripple and DC-input current ripple. The improved waveform may be seen from the fact, that 2 times the torque is achieved with 1.5 times the peak current.

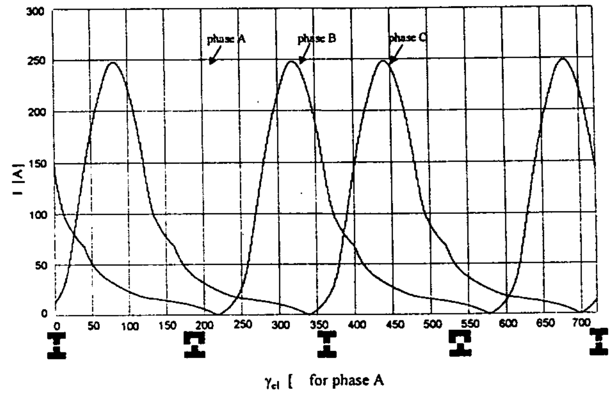


Fig. 3: Convent.; n=9000/min;**M=37Nm**; U_d=215 V

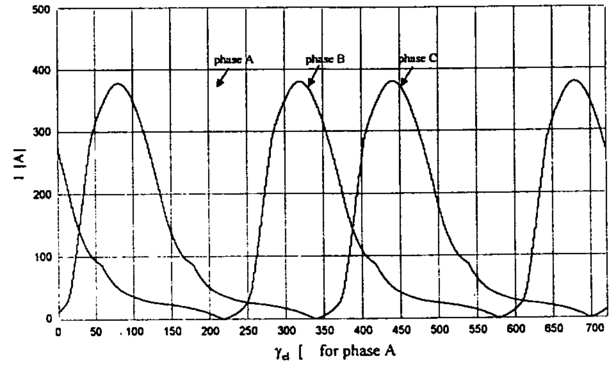


Fig. 4: New; n=9000/min; **M=75 Nm**; U_d=215 V

4.2 Motor operation in the constant power speed range

Fig.5 shows motor operation at 6750/min, which is well within the constant power speed range.

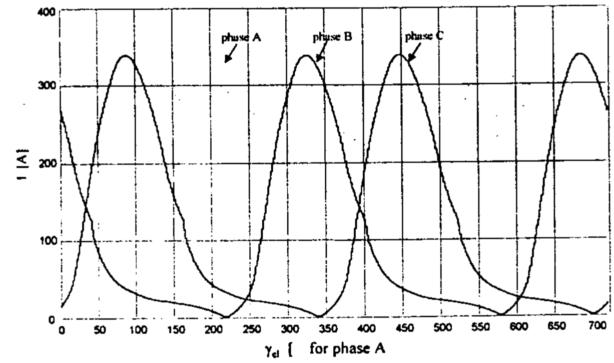


Fig.5: Convent.; n=6750/min; **M=75Nm**; U_d=215 V

Fig. 6 shows the improved operation at the same speed, if reduced torque ripple is given priority. For simplicity, a pulse pattern at fundamental frequency, (no increased switching frequency of the IGBT) is shown.

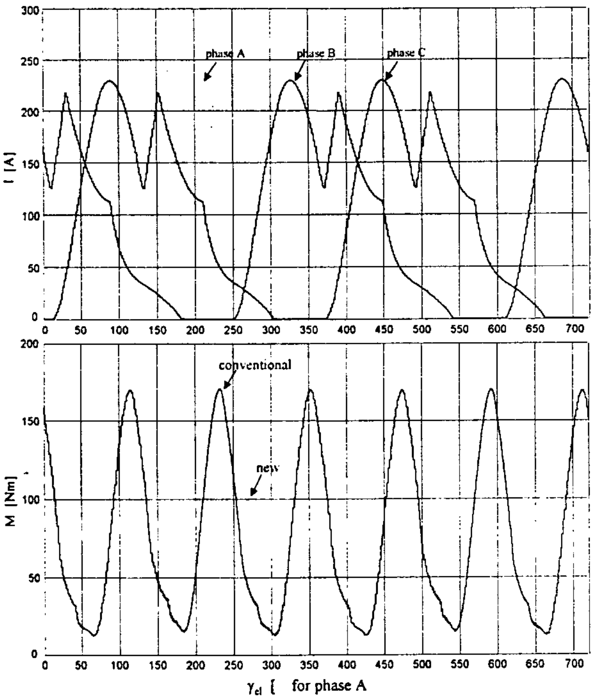


Fig. 6: New; n=6750/min; **M=75 Nm**; U_d=215 V

Amplitude and frequency of torque ripple have been improved. Obviously, even better results could be achieved, if PWM-operation with increased switching frequency would be used. This is not necessary in this speed range, however.

Fig. 7 gives a comparison of these operating points in the ψ-i-area at of the machine.

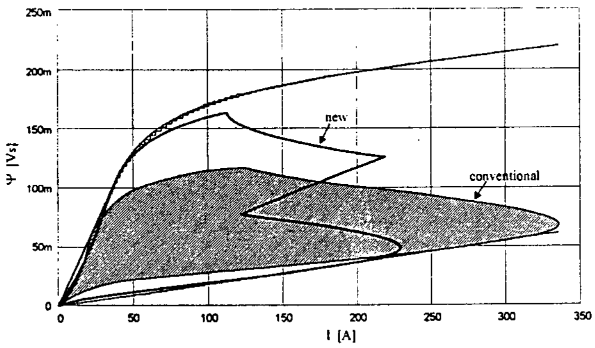
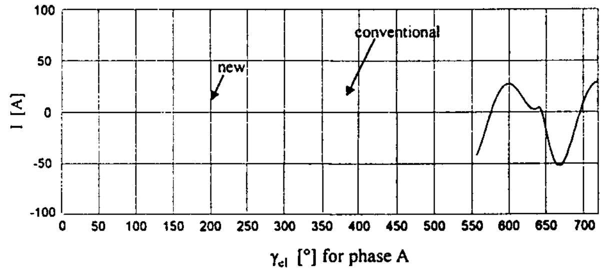


Fig. 7: ψ-i-plot; n=6750/min; **M=75** Nm; U_d=215 V

By comparing the effective motor currents, it turns out, that copper losses have been reduced by approx. 40 %. This reduces motor temperature and increases efficiency considerably.

Fig. 8 gives a comparison of DC-input current based on equal input power. This result was achieved using a switching pattern with fundamental frequency similar to Fig.6. The switching angles, however, are slightly differing because minimum torque ripple and minimum current ripple do not coincide

Fig. 8: DC-Input ripple current ; C_1= 1000 µF



L_l= 2 µH, R_l= 80mΩ, C_0 = 180µF

n=6750/min; **M=75 Nm**; U_d=215 V

4.3 Regeneration at max. speed

When energy flow is reversed – for instance at regenerative braking – even greater improvements can be achieved.

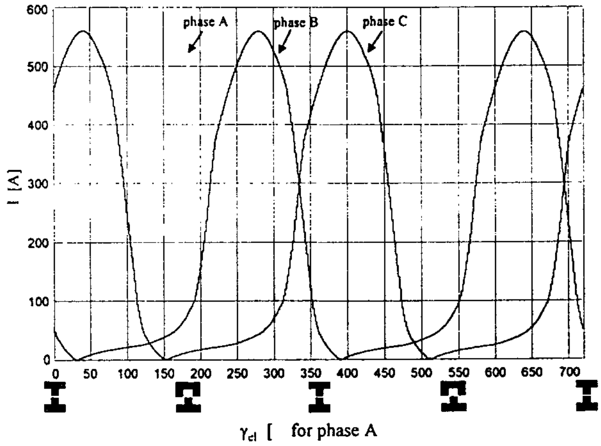


Fig. 9: New; n=9000/min;**M= - 117 Nm**;U_d=215 V

An operating point at max. speed is given in Fig. 9, showing that the torque is approximately tripled - compared to the conventional limit - and the waveform is improved, as described for motor operation, already.

4.4 Motor operation at low DC-voltage

Because of the load dependent and weak DC-supply, operation at low DC-voltage is of major concern :

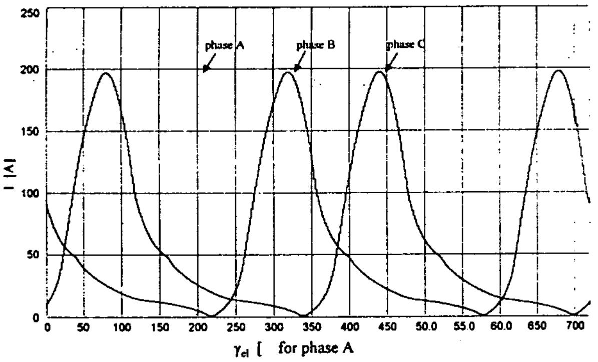


Fig.10: Convent.:n=9000/min;**M=22 Nm**;U_d=172 V

While the conventional drive system looses approx. 40 % of the max. torque at –20 % DC-voltage, the new system can stabilize power and torque even under these bad conditions. This advantage, too, can be achieved by appropriate control of the switching states and covers the whole speed range. The conventional system can guarantee the stable max. torque in the very low speed range only, where PWM-operation is feasible.

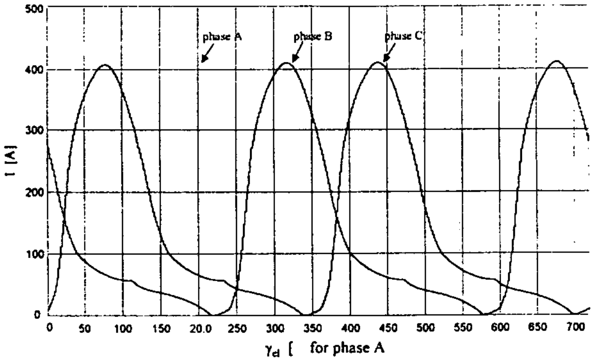


Fig. 11: New; n=9000/min; **M=72 Nm**; U_d=172 V

In Fig.12 an overview of different operating points (motoring) is given. Using the present SR-machine and choosing a maximum value U_c=350V, at least double the torque can be achieved throughout the whole field weakening range up to max. speed.

5. Conclusion

A new converter concept for high performance SR-Drives - especially for electrical vehicle applications - has been given. It offers very flexible control, great improvements in torque output and other advantages. In applications, where the high performance is not needed, it may be used for cost reduction, alternatively. Further development work will include closed loop control in realtime and an improved machine design better adjusted to the new possibilities.

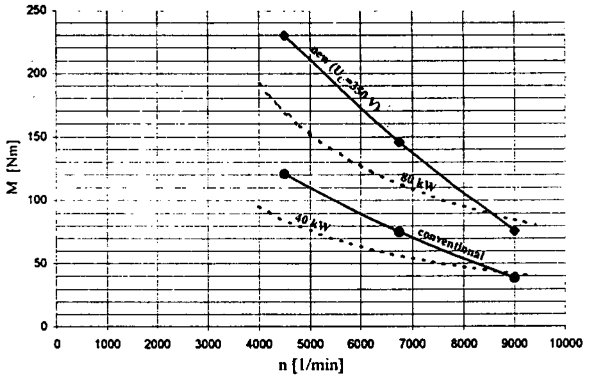


Fig. 12: Comparison of max. torque versus speed

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