Analysis of a Rolling Rotor Switched Reluctance Motor with Power Electronic

M. Franke, M. Brutscheck, H. Mrech and U. Schmucker

***Abstract* — This paper describes the investigation and development of the power electronics of a rolling rotor switched reluctance motor (RRSRM). The architecture of the RRSRM is determined by a heterogeneous system structure and consequently, the mode of operation is strongly affected by the interconnections between the different physical domains. Therefore, the analysis of the RRSRM and the power electronics design are carried out by means of a multi-domain system architecture. This new approach allows an interdisciplinary simulation and consequently the design of the overall transmission. The overall power transmission of the rolling rotor motor consists of the power electronics, the electric and magnetic fields as well as the mechanical elements. Moreover, these other physical domains interact with a magnetic field that has highly nonlinear properties. Therefore, the development of the power electronics uses a complete mathematical model of the rolling rotor switched reluctance motor. This paper describes the basic principles of the power electronics and its applications. For this purpose, different setups and functions of the direct current power controller are described. Furthermore, the range of applications as well as thier advantages and disadvantages are examinedinstructions. These investigations are used for optimal mode of operation of RRSRM and optimal design of power transmission.**

***Keywords* — Direct Current Power Controller, Energy Converter, Multi-domain System Architecture, Rolling Rotor Switched Reluctance Motor.**

I. INTRODUCTION

THE analysis of electrical machines is a very important research area and modelling and simulation support this action. New design methods allow the investigation of new drive concepts and make it possible to develop better technical systems [1]. Multiphysical modelling leads to interdisciplinary simulation. Electrical machines consist of electrical, magnetic and mechanical domains which interact strongly. Therefore, the described investigation of power electronics uses multiphysical modelling of electrical machines. The implementation of RRSRM is based on the fundamental knowledge of the properties of the magnetic field. Therefore, the mathematical description and the interactions must be also examined among other domains. The nonlinear behaviour of the magnetic domain has a strong effect on the performance of the overall drive concept and consequently on the power electronics [2]. A complete simulation model should contain electrical as well as mechanical parts. This modelling concept can be used to improve the overall efficiency of electrical machines.

The mode of operation of the energy converter affects the function of electrical machines fundamentally. Furthermore, the function of electrical machines has retroactivity to the power electronics. Therefore, these dynamical processes are analysed within a heterogeneous simulation environment [3].

II. THE FUNCTION AND CONSTRUCTION OF AN RRSRM

The fundamental structure is characterised by the moving rotor which is rolling in the stator. This property has strong effects on the applicability of this electrical machine. The important parts and the functional construction of a 4-pole rolling rotor switched reluctance motor are illustrated in Fig. 1.

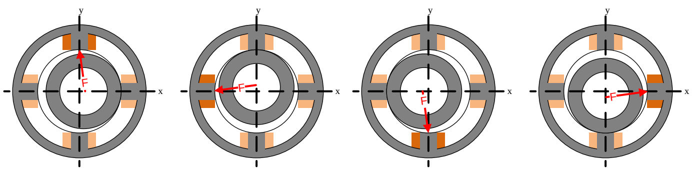

Fig. 1. Power Sequence of the RRSRM.

Here, the essential diameters of the rotor and stator can be seen, which are used to customise a gear transmission with possibly high gear ratios. Therefore, an RRSRM can be used in a direct drive manner. The rolling rotor switched reluctance motor belongs to the category of reluctance motors. A salient feature of this electrical machine - having a rotor that has no bearing - characterises it as an RRSRM. This property affects the magnetic field as well as the overall behaviour within all available domains. The fundamental construction is characterised by the rolling rotor, made of iron, and the stator having lumped windings. The rotor is forced to move to the switched coil. If the windings are switched alternately, a torque is produced. Here, the rotor is moved to the activated coil to reduce the magnetic resistance as illustrated above. This behaviour generates a time varying magnetic field and creates flux variations which lead to a torque ripple. Furthermore, this changing magnetic field influences the power electronics and the mechanics. These properties have advantages as well as disadvantages which

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delimit the field of application for this machine [1].

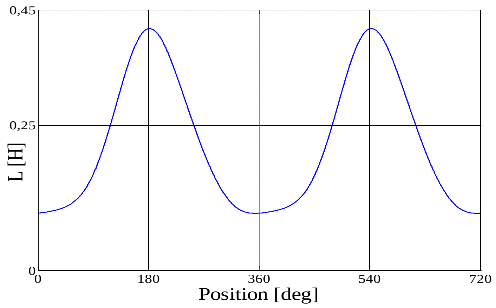

Fig. 2. Varying inductance in an RRSRM

Main feature of the RRSRM is the varying inductance at the moving rotor as can be seen in Fig. 2. For this purpose, the development of the power electronics involves the changing parameters of the motor and the basic principles of the power converters [3].

III. POWER CONVERTER FOR AN RRSRM

The design of an energy converter for a rolling rotor switched reluctance motor depends on its mode of operation. Therefore, conventional power converters of electrical machines cannot be used [2]. The function and the design of machines can be different and therefore, the power converter must be individually developed for each machine type. The design concepts of a RRSRM have to be investigated to meet the required specifications.

Following assumptions are given:

- The produced torque of reluctance machines does not depend on the sign or values of flux linkage or current, but only on the sign of $dL/d\varphi$.
- The function and the direction of the RRSRM is determined by the alternate switching of the lumped windings.
- The current rise and current decrease in the different phases must be realised very fast.

The turn on procedure of one winding has to be started if the inductance value rises and must be turned off if the inductance value is maximal. Although these properties are similar to some other machine requirements, many details are different to conventional controllers.

A. One-Quadrant Chopper

The requirements specified above may be obtained with direct current power controllers. For this purpose, accordant investigations are executed. The one-quadrant chopper is a simple direct current power controller and is labelled as buck converter. This means that the output voltage U_A is always less than the input voltage U_S. The fundamental structure can be seen in Fig. 3 [4].

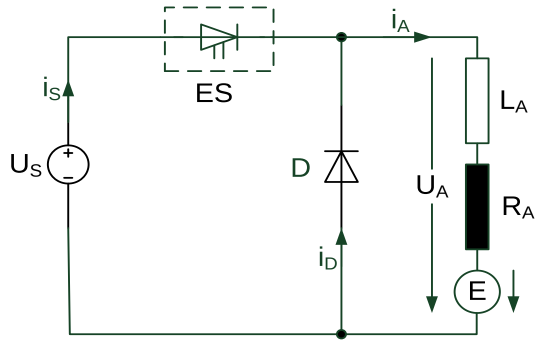

Fig. 3. One-Quadrant Chopper

The one-quadrant power converter is used for one phase and can be operated in continuous and discontinuous mode.

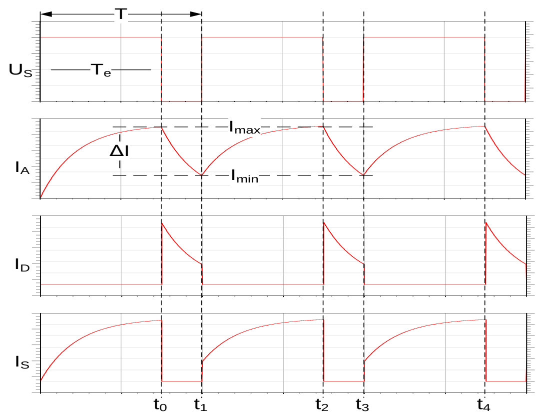

Fig. 4. Elapsed Time of One-Quadrant Chopper in Continuous Mode

The continuous mode operates with a current which never falls to zero as is illustrated in Fig 4. The third diagram shows the current through the diode in the free-wheeling circuit. The fourth chart illustrates the current of the source. The relative duty cycle can be seen in the first window of Fig. 4 and it is labelled as λ. It is described as follows:

$$\lambda = \frac{T_e}{T} \tag{1}$$

If the electronic switch (ES) is turned on the direct current is increased with following time constant τ.

$$\tau = \frac{L_A}{R_A} \tag{2}$$

At the time t_0 the load current has approximately the value I_{max} and ES is opened. The current I_A directly commutates over the diode in the free-wheeling circuit. The current through the free-wheeling diode during the time $t > t_0$ and $t < t_1$ is described by Equation (3).

$$I_A(t) = \left(I_{\max} + \frac{E}{R_A}\right)e^{-\frac{t-t_0}{\tau}} - \frac{E}{R_A} \tag{3}$$

The electronic switch is closed at the time t_1. The ramp function of the current is described at the time $t > t_1$ and $t < t_2$ as follows:

$$I_A(t) = \frac{U_S - E}{R_A} + \left(I_{\min} - \frac{U_S - E}{R_A}\right)e^{-\frac{t-t_0}{\tau}} \tag{4}$$

If $t - t_0 = T - T_e = (1 - a)\,T$ is substituted in (3) and $t - t_1 = T_e = a\,T$ in (4), then the current I_{max} and I_{min} can be described as follows:

$$I_{\min} = \frac{U_S}{R_A}\,\frac{e^{-\frac{(1-a)T}{\tau}} - e^{-\frac{aT}{\tau}} + e^{-\frac{T}{\tau}}}{1-e^{-\frac{T}{\tau}}} \qquad (5)$$

and

$$I_{\min} = \frac{U_S}{R_A}\,\frac{1-e^{-\frac{aT}{\tau}}}{1-e^{-\frac{T}{\tau}}} - \frac{E}{R_A} \qquad (6)$$

The difference between I_{max} and I_{min} can be described as ΔI, so from (5) and (6) it follows:

$$\Delta I = \frac{U_S}{R_A}\,\frac{1-e^{-\frac{(1-a)T}{\tau}} - e^{-\frac{aT}{\tau}} + e^{-\frac{T}{\tau}}}{1-e^{-\frac{T}{\tau}}} \qquad (7)$$

Equation (7) is a function of the duty cycle 'a'. Here, the value 'a' is the range of variation of the load current ΔI. The function is illustrated in Fig. 5 with the constant τ/T = 10 and in continuous mode. The current ΔI describes the ripple of the load current at continuous mode [5].

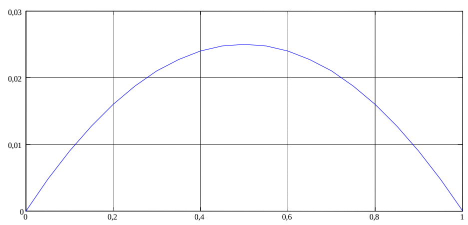

Fig. 5. ΔI as Function of Duty Cycle a with the Constant τ/T = 10

The average of the load current and the output voltage are overlapped of alternating values. If the resistance, the inductance and the duty cycle are constant, thens the overlapped alternating values are also constant, the continuous mode. The one-quadrant chopper has many advantages which allows the control of the rolling rotor switched reluctance motor. These advantages include:

- Simple regulation
- Few electronic devices
- Low ripple of load current
- Discontinuous mode only at small values of the duty cycle 'a'

The power electronics of a rolling rotor switched reluctance motor must allow a fast reduction of the current in each phase [2]. However, the one-quadrant chopper does not conform to this requirement.

B. *Two-Quadrant Chopper*

The movement of the rotor needs a fast decreasing load current. The two-quadrant chopper has the possibility to reduce the current with a negative voltage [5], [6]. In the load circuit the load current flows only in one direction. The voltage can have reverse polarity and consequently, the direct current chopper may work in two quadrants.

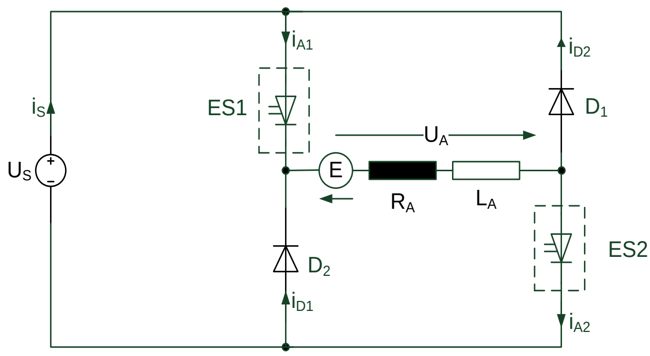

Fig. 6. Two-Quadrant Chopper

The basic circuit is highlighted in Fig. 6. The two-quadrant chopper can be operated in simultaneous and in alternating modes. Fig. 7 shows the simultaneous clock cycle of a two-quadrant chopper.

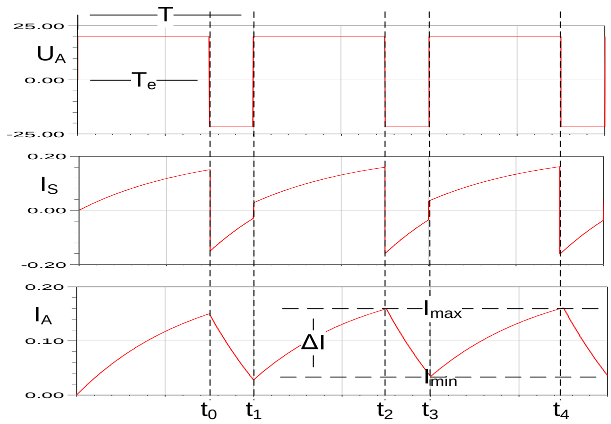

Fig. 7. Elapsed Time of Two-Quadrant Chopper at Continuous Mode

The first chart shows the supply voltage which can have a negative value. This effect arises if both ES's are opened. The current flow back to the source can be seen in the second diagram. The load current is illustrated in the third chart [7].

C. *Simultaneous Clock Cycle*

The operation of a two-quadrant chopper is indicated by the simultaneous control of ES1 and ES2. Discontinuous and continuous modes are also possible. In addition, the range of variation of the load current $\Delta I = I_{max} - I_{min}$ is twice the number of the one-quadrant chopper. This means, that the ripple of current and voltage is higher in comparison to the one-quadrant chopper [8].

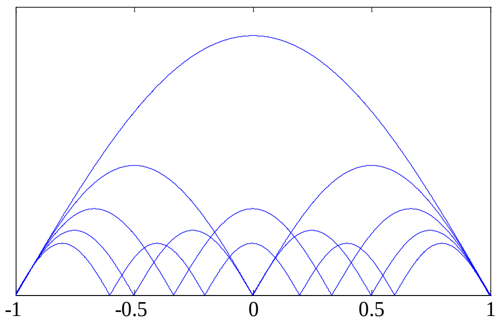

Fig. 8. Harmonic Oscillation of duty cycle *a* with the constant τ/T = 10

The simultaneous clock cycle of electronic switches affects the mode of operation and the source of the two-quadrant chopper. In Fig. 8 the Fourier analysis shows that the harmonic oscillations are a function of the duty cycle parameter '*a*'. These harmonic oscillations have influences on the input current I_S and the output voltage U_A. Furthermore, the simultaneous clock cycle shows a considerable variation of the current and voltage. This yields with utmost probability to discontinuous mode and a high consumption of reactive power. These disadvantages have influence on the mode of operation of the RRSRM [2] [3].

D. Alternating Clock Cycle

The alternating clock cycle uses a different control of ES1 and ES2. The principle function is illustrated in Fig 9.

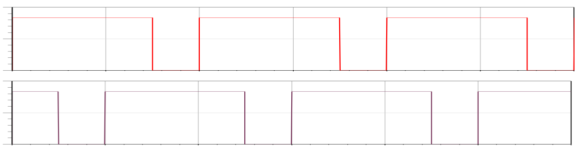

Fig. 9. Alternating Clock Cycle

This mode combines the advantage a two-quadrant chopper with the advantage of the one-quadrant chopper. The control conforms to all requirements. Using this power electronics a correct mode of operation of a rolling rotor switched reluctance motor is possible.

IV. Conclusion

This paper has presented the investigation and the development of the power electronics of a rolling rotor switched reluctance motor. The architecture of this motor needs power electronics that meet particular requirements. Therefore, multiple direct current choppers have been analysed, and these investigations have also clarified the advantages and disadvantages of both one- and two-quadrant choppers. Furthermore, the fundamental function of a buck converter has been illustrated. On the basis of these investigations further properties of a two-quadrant chopper have been described in the paper. In conclusion, all these expertise are used for better mode of operation of a rolling rotor switched reluctance motor.

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