Influence of power electronics on design of Switched Reluctance Machines

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Keywords

Abstract
An adjustable speed drive using a doubly salient Switched Reluctance Machine (SRM), because of its ability to operate efficiently from unidirectional winding currents, enables the number of main switching devices in the inverter to be halved, yielding a very economical brushless drive. In general, the SRM is a robust, reliable and almost maintenance free electric drive. The high level performance expected from an adjustable speed drive is not easy to meet, as it is required to accommodate a large number of system nonlinearities in the case of a SRM.
Approaches using machine construction aspects making influence on the machine performance becoming more equivalently to efforts at torque control. In this context modern design methods - analytical design by a self-prepared design program and simulation of the whole drive system - are presented which allow the examination of essential machine parameters in advance. Target is to find optimal construction parameters of the machine by investigation of single appearances like saturation effects which considerable influence the inverter voltampere requirement. The calculation results show that the SRM can be an attractive alternative to a.c. and d.c. variable speed drives under the condition that the entire drive system is optimally designed and coordinated.

Introduction
The functionality of Switched Reluctance Machines is already known for more than 150 years, but only the huge improvements of the power electronics and their integration in drive technologies have made the enormous progress of adjustable speed drives with SRMs possible. Today the designing engineer can select from a number of different converter configurations adapted to the specific application. For current and torque control high efficient micro-controllers and digital signal processors are available.
A SRM has salient poles on both stator and rotor. Each stator pole has a simple concentrated winding and there are no conductors of any kind on the rotor. Diometrically opposite windings are connected together either as a pair or in groups to form motor phases. For each phase a circuit with a single controlled switch (power transistor) is necessary and sufficient to supply an unidirectional current during appropriate intervals of rotor rotation. Fig. 1 shows the typical cross sectional arrangement for a 4-phase SRM having 8 stator and 6 rotor poles (8/6-SRM).
The specific advantages of SRM have made it a serious alternative to converter/inverter fed a.c. and d.c. drives. The high level performance expected from an adjustable speed drive includes minimum torque ripple, low steady state error, low starting time, reduced speed oscillation and the ability to operate over a wide speed range at constant power. Such a performance is not easy to meet, as it is required to accommodate a large number of system nonlinearities. The electromagnetic torque developed by the SRM is a nonlinear function of stator current $i$ and rotor position $\Theta$.

![Fig. 1: Arrangement of a 4-phase 8/6-SRM with switching circuit for one phase](image)

For forward motoring, the appropriate stator phase winding must remain excited only during the period when rate of change of phase inductance is positive. Else, the motor would develop braking torque or no torque at all. The inductance of a stator phase is maximal when its pole is directly opposite the rotor pole (‘aligned position’) and is minimal when the inter-polar rotor region is opposite to it (‘unaligned position’) due to the maximal air gap. For motoring operation the stator phase must be excited when its inductance starts rising and must be de-excited when the phase inductance ceases to increase. The switching function thus must ensure that current in phase winding reaches its reference value at the desired instant of inductance rise and is again brought to zero when inductance reaches its maximum and does not increase further. Due to delay in current rise and fall on account of winding inductance, the switch must be closed at a turn-on angle (also called advance angle) $\Theta_{\text{on}}$ and must similarly be opened at a turn-off angle $\Theta_{\text{off}}$. These switching angles must be variable for adjustable speed drives and depend mainly on speed and desired current in phase windings of the SRM (see also Fig. 2).

In recent times, approaches using machine design to influence the machine performance becoming more and more equivalently to efforts at current and hence torque control. The design of SRMs by numeric methods with FEM-programs (Finite Elements Method) provides the most precise and proof results. However, calculations by FEM are time consuming and require special software knowledge. For a complete design of new type series of machines respectively other dimensioning variants the exclusive way of using the FEM is at present not feasible. Therefore software is necessary that can abbreviate the preparation time for the following FEM-calculation considerable. Often the dynamic operational behaviour and the combination of the electric machine with other components like energy storage, converter or mechanic elements must be considered. In that case parameters calculated during the design stage have to be involved in a simulation model.

A new simulation model with SIMPLORER® and a special analytical program for designing and computation SRMs of various constructions are shown in this paper. This software is the basis of which a rapid design of the machine and the estimation of its parameters are possible without special software knowledge. Saturation effects, losses of the machine and the converter are regarded as well as the torque control strategy. Additionally, the progress of the developed analytical program EntwurfGRM [7] in relation to the commercial software package PC-SRD [5] will be pointed out.
Basic System Operation

This section describes the general control requirements for the example of a typical 8/6 pole SRM shown in Fig. 1. It is a 4-phase machine excited by an asymmetric bridge converter. The ideal inductance profile \( L \) of the four phase windings of motor versus rotor position \( \Theta \) is shown in Fig. 2(a) where the different zones of inductance, namely minimum inductance zone, rising inductance zone, maximum inductance zone and falling inductance zone of different phases are seen. The inductance profile of a Switched Reluctance Motor depends upon its configuration and pole geometry and therefore the profile of say a 6/4 pole configuration SRM will be different from that of an 8/6 pole configuration motor. In motoring, the current is established for the positive slope region (rising inductance zone), as the developed torque is positive when \( dL/d\Theta \) is positive. The four phase windings should ideally become excited with reference current at instants \( \Theta_1, \Theta_2, \Theta_3 \) and \( \Theta_4 \) respectively [see Fig. 2(a)].

![Fig. 2: (a) Ideal inductance profile of SRM. (b) Turn-on and turn-off angles of any phase of SRM.](image)

The respective semiconductor switches therefore are closed at a turn-on angle, so that current in the particular phase rises to the reference current at the start of its rising inductance. Similarly, the respective switches are opened at a turn-off angle to ensure that the current in the particular phase decays to zero by the end of the end of the positive slope region. Zero turn-on angle corresponds to the instant when a rotor pole just enters the stator pole to be excited and hence is the instant when the inductance of the excited winding starts rising. Zero turn-off angle corresponds to the instant when a leading pole of the rotor just leaves the trailing pole of the excited stator phase. This is the instant when the inductance of the excited phase has attained its maximum value and remains at this value for some time depending on the overlap of stator and rotor pole widths. Later the inductance begins to fall as the rotor pole moves away from the stator pole. Fig. 2(b) presents the concept of turn-on and turn-off angles for any phase winding of Switched Reluctance Motor. The practical range of turn-on angle and turn-off angle depends on the inductance profile and therefore on the configuration and pole geometry of the particular SRM.

Analytical Design and Calculation Method

General design procedure

The magnetic properties of the iron, the number of phases, and the number of poles per phase all have a nonlinear effect on an SRM’s performance. These effects, along with the sizing of the machine envelope and internal dimensions, make the machine design an insight-intensive effort. Maximization of torque density, power output, efficiency, speed range, and first critical speed and minimization of torque ripple, temperature rise, acoustic noise, and overall cost are among the many design objectives and critical issues that must be addressed during the design process. Fig. 3 gives an impression about the complexity of designing a high performance adjustable speed drive with Switched Reluctance Machines.
Note that only under the condition that all components of the electric drive consisting of SR Motor, converter and control strategy are optimally designed and coordinated, the SRM can be an attractive alternative to conventional a.c. and d.c. machines.

In order to fulfill the requirements in an effective machine design the analytical design program *EntwurfGRM* was developed by the authors [7]. This is a special software tool for designing SRMs of various constructions, based on analytical calculation methods.

Starting from a performance requirement (torque, speed, etc., depending on the application) or after loading a machine dataset the computation of all results follows in seconds. A control window shows the program progress and guides the user through the design. The general calculating procedure shows Fig. 4:

**Choice of the number of phases and poles**

The choice of phase number $q$ is influenced in a mayor way by the required starting torque and hence the effective value of $dL/d\Theta$. To ensure adequate starting torque at all rotor angles there must be adequate overlap between the $L(\Theta)$ variations of adjacent phases. Beside the starting capability the number of phases is usually determined by the following factors:
**Directional capability:** Whether the SRM needs to run in one or two directions dictates the minimum number of stator phases.

**Reliability:** A higher phase number leads to a higher reliability because a failure of one or more phases will still allow the running of the SRM with the remaining healthy phases.

**Cost:** A higher phase number requires a corresponding number of converter phase units.

**Power density:** A higher phase number tends to give higher power density in many applications.

**Efficient high speed operation:** Efficiency is enhanced by reducing the core losses at high speed by decreasing the number of stator phases and lowering the number of phase switchings per revolution. Three phases is preferred over four phases for high-speed operation.

![Fig. 5: Torque waveforms of a 3 and 4-phase motor](image)

The comparison of torque characteristics between a 3- and a 4-phase machine in Fig. 5 shows: The angle of overlap in which two phases can produce positive torque is 60° for $q=3$ and 90° for $q=4$ (electrical angle). During rotor rotation the phase current must commutate from one phase to the next inside this overlap zone. The waveform for the higher phase motor shows that the torque dips can be reduced and uniform torque is achievable without boosting the current in regions of low torque per ampere. Of course there is still the question of the optimum current waveform. The price paid for a smoother torque is a higher commutation frequency leading to higher core- and converter losses. If the mechanical speed of the machine is $\omega$ in rad/sec, then the voltage switching frequency per phase $f_{ph}$ is

$$f_{ph} = \frac{N_r \cdot \omega}{2\pi}$$  \hspace{1cm} (1)

Attention is turned now to the number of rotor and stator poles $N_r$ and $N_s$. It is preferred to have the ratio between them be a noninteger even though some at integer values have been attempted. Based on this guideline, the stator and rotor pole combinations common in industrial designs are given below:

**Table I: Typical stator and rotor pole combinations**

<table>
<thead>
<tr>
<th>Poles</th>
<th>Stator $N_s$</th>
<th>6</th>
<th>12</th>
<th>8</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor $N_r$</td>
<td>4</td>
<td>8</td>
<td>6</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

The limiting factors in the poles selection are the number of converter switches and their associated cost of gate drives and logic power supplies and control requirement in terms of small rise and fall times of the phase currents. The stator frequency for a phase is defined by (1). Therefore, increasing the rotor poles increases the stator frequency in proportion, resulting in higher core losses and more importantly greater conduction time to provide the rise and fall of the current compared to that of an SRM drive with a smaller number of rotor poles. The latter one leads to higher copper losses and larger phase conduction overlaps. On the other hand, due to increased switching frequency, the commutation torque ripple frequency is also increased, thus making its filtering easier. Furthermore, the overlapping phase conductions and their effective control lead to a quiet operation. Note that this comes at the expense of efficiency and simplicity in control. The cost of motor production rises with higher pole numbers because of the increased winding insertion costs and terminal costs and most of all due to the increased inverter costs.
Influence of constructional parameter on electromagnetic torque

To investigate the influence of constructional parameters on the electromagnetic torque with EntwurfGRM for the example of an 18.5 kW SRM, the values of the rotor and stator pole width were changed. During changing one of these parameters, the other one remains constant. Increasing the rotor pole arc causes only changing of maximum torque with rotor position and influences the width of the torque impulse. The maximum value of torque is practical constant in the examined range (see Fig. 6). There is an optimum value of rotor pole width when the torque integral (area under curve shown in Fig. 8) has its maximum. Increasing the stator pole arc leads to a smaller slot area and limits the maximum magnetomotive force (mmf) and therefore the maximum torque. On the other hand it has to be considered from the mechanical aspect that a narrower stator pole can be easier stimulated to oscillate, what influences noise negatively.

![Fig. 6: Influence of rotor pole and stator pole arc on the electromagnetic torque](image)

The optimum stator and rotor pole arc is a compromise between various conflicting requirements, and there is no single value that is appropriate for all applications. The choice depends on two main conditions: self-starting requirement and the shape of electromagnetic torque characteristics. These requirements can be included into the machine design by computing the minimum rotor and stator pole arcs to achieve self starting [3]:

\[ \min(\beta_s, \beta_r) \geq \frac{2\pi}{q \cdot N_r} \]  

(2)

with the number of rotor poles \(N_r\) and the phase number \(q\). An upper limit is placed on the overlap of stator and rotor teeth [3]:

\[ \beta_s + \beta_r \leq \frac{2\pi}{N_r} \]  

(3)

This ensures that in the unaligned position there is a clearance between rotor and stator poles. In practice is \(\beta_r \geq \beta_s\) providing a slightly larger slot area without sacrificing aligned inductance. To maintain balanced phase currents and minimize acoustic noise, the SRM needs a uniform air gap. It also requires a small air gap to maximize specific torque and minimize the volt-ampere requirement in the converter. However, the bending of the shaft and the expansion of the material with increasing temperature must be considered during design in addition to manufacturing tolerances, so the air gap should...
be chosen in such a way that the machine works reliable under default operating conditions in every operating point. A typical air gap length $\delta$ is usually in the range of $0.2 \leq \delta \leq 0.6 \text{mm}$. The air gap value influences the maximum torque value and also the flat torque range on the characteristic, as Fig. 7 shows for the example of a 4-phase -SRM with $P=18.5\text{kW}$.

**The effect of saturation**

Actually, Switched Reluctance Machines can perform well only when they work in saturated regime. The flux density in the area where the stator and rotor teeth overlap commonly approaches two teslas. Under conditions of heavy saturation, a well-designed motor can develop quite high torque values and be effective in various industrial applications. To understand the electromagnetical energy conversion properly, a nonlinear analysis is needed that takes account of the saturation of the magnetic circuit. One such analysis is based on magnetization curves, shown in Fig. 8. These curves describe the relationships between the flux linkages $\psi$ vs. current $i$ as a function of the rotor position angle $\Theta$.

In the unaligned position the air gap and therefore the reluctance is maximal. Since no saturation occurs, the flux linkage is a linear function of the current. Saturation of a typical magnetization curve occurs in two stages. When the overlap between the rotor and stator pole corners is quiet small, the concentration of flux saturates the pole corners, even at low current. This leads to an enlargement of the effective air gap and the linear relationship is lost between current and flux-linkage. When the overlapping poles are closer to the aligned position, the yokes saturate at high current, tending to limit the maximum flux-linkage. The energy supplied by the inverter can be divided into two parts: the stored field energy $W_F$ which is returned except hysteresis losses to the supply after commutation, and the coenergy $W_C$ that is available to be converted into mechanical work in each working stroke. An "energy ratio" relates the coenergy to the entire absorbed energy $W$ and tells how much energy conversion is obtained for a given input energy [3]. The ratio of the coenergy increases for the field energy due to increasing saturation of the iron. As a result the energy ratio $\lambda$, comparable with the power factor of ac machines, increases.

$$\lambda = \frac{\Delta W'}{\Delta W_F + \Delta W'}$$  \hspace{1cm} (4)

$$W_F = \int id\psi$$ \hspace{1cm} (5)

$$W_C = \int \psi di$$ \hspace{1cm} (6)

Furthermore it can be analytically shown that the effect of saturation is to reduce the energy conversion capability of a motor of given dimensions, but at the same time it reduces the inverter voltampere-requirement for a given torque and speed by a greater factor. The degree of saturation will influence the balance between motor and inverter size. Saturation is desirable from this point of view, but must be localized on the tooth tips, for instance by a tapered shape of the teeth, since the electromagnetic energy conversion occurs in the air gap. Consequently, the demand to operate the SRM partially in the range of saturation is not in the contradiction to the generally usual procedure to avoid the non-linear operation at electrical machines. Fig. 9 shows the computation results for an 18.5kW SRM. The voltampere requirement decreases for a given motor in case of saturation. At the same time the energy ratio increases.
with increasing load torque. That considerably influences the dimensioning of the inverter, which can be smaller. To minimize the sizes of both the motor and the inverter, $W_c$ should be maximized and $W_F$ minimized. This requires a small air gap and iron with very high permeability.

Fig 9: Voltampere requirement and power factor vs. torque of an 18.5kW saturated and unsaturated SRM

**Progress of new analytical program vs. PC-SRD**

The analytical program *EntwurfGRM*, presented in this paper, shall be compared with the commercial program *PC-SRD* from the SPEED-software package, developed at the University of Glasgow.

The motivation for developing a new, own software tool for designing and calculating electrical machines is not only a question of cost for the commercial software, but also the challenge to improve these traditional programs by new, own calculation conceptions. Furthermore, self-made software offers the invaluable advantage to upgrade the actual software because source code is available. From this point of view *EntwurfGRM* is not a finished program but it is still in a steady developing process.

The design process can be started in two ways with *PC-SRD*. The first one is as follows: Sizing the SRM begins with the determination of the main dimensions by the output equation, which relates the bore diameter $D$, rotor length $L$, speed $n$, and magnetic and electric loadings to the output $P$:

$$ P = C \cdot D^2 \cdot L \cdot n $$

(7)

This procedure is similarly to *EntwurfGRM*. The output coefficient $C$ essentially depends on the machine dimensions and the cooling system. Additionally the user has to define the number of stator and rotor teeth. During this first design step *PC-SRD* has the problem that the user has no influence on the standard design criteria for the internal dimensions, e.g. air gap length or yoke thickness, leading to a machine which possibly cannot fulfill the mechanical and electromagnetical requirements. *EntwurfGRM* offers the option to modify such design criteria by variable design ratios, e.g. stator/rotor diameter, air gap/pole pitch, yoke wideness/tooth wideness, etc.

The second way of designing a new SRM with *PC-SRD* starts with the choice of a standard machine, for example a small 6/4 or 8/6-SRM. In this case useful geometric values are suggested which can be modified by the user in the outline-editor. A serious mistake occurs if the user changes the number of teeth leading to a new phase number. In that case the resulting geometry will be calculated correctly, but the performance calculation, for example the electromagnetic torque, bases on the old phase number! This problem is solved in *EntwurfGRM* by checking and updating the number of phases and poles after a design modification. During various tests with *PC-SRD* the following disadvantages

- basic design criteria like dimensioning of the air gap or high and wideness of the teeth cannot be modified by the user before the first automatic design step,
- different units are mixed what makes it difficult to interpret calculation results correctly,
- many error messages are not helpful and insufficient to find the mistake,
- the abbreviations are confusing in many cases,
and advantages were detected:
  - many degrees of freedom offer the possibility for designing also unconventional machine geometries, e.g. multiple teeth per pole structures for high-torque applications,
  - beside analytical design and calculation methods PC-SRD offers an additional FEM module,
  - static and dynamic calculations in motoring and generating mode are possible,
  - distinction between different control modes (current regulation, single pulse mode),
  - PC-SRD offers thermal computations and
  - a scripting language can be used to automate many processes.

Of course, the presented program cannot reach the enormous range of functions offered by PC-SRD, the goal was to develop a design and calculation program for SRMs which assists the user during the design procedure. By relatively small efforts a first well working machine construction can be achieved which can be optimized by the combination of three main design parts: analytical calculation by EntwurfGRM, numerical calculation by FEM and simulation of the electromechanical system. However, both programs don’t synthesize optimized machine designs by themselves. The user produces them, the software just improves the productivity of the engineer, but it does not do his job.

**SRM model with SIMPLORER**

In order to investigate the operational behaviour as well as special operating states of the entire drive system, a simulation model of the SRM has been developed with the program SIMPLORER [7]. The simulation model contains the inverter with power supply, a current regulation and the motor model, consisting of an electrical and a mechanical part (Fig. 10). The electrical part represents the voltage equation assuming that there is no mutual coupling to other phases:

\[
  u = Ri + \frac{\partial \psi(i, \Theta)}{\partial i} \frac{di}{dt} + \frac{\partial \psi(i, \Theta)}{\partial \Theta} \frac{d\Theta}{dt},
\]

where \( u \) is the supply voltage and \( R \) is the winding resistance. The dependence of the inductance \( L \) of the current and the rotor position angle can be considered by including the \( L(i, \Theta) \) characteristic from a preceding analytical computation or a FEM calculation. The mechanical part of the motor model corresponds to the mechanical equations with the load torque \( T_L \), the friction torque \( T_F \), the moment of inertia \( J \), the number of rotor poles \( N_r \) and the angular frequency \( \omega \):

\[
  T - T_L - T_F - J \frac{d\omega}{dt} = 0, \quad \omega = \frac{d\Theta}{dt}
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\]

\[\text{Fig. 10: Simulation model of a 4-phase SRM in SIMPLORER}\]
The inverter model is an asymmetric bridge converter. It offers the maximum flexibility during the current regulation, caused by a tolerance band procedure. Fig. 11 shows the phase currents and the resulting torque of a 4-phase motor as a function of time. The turn-on and turn-off angle of current can be adjusted. With it two essential parameters are available for torque control. The 3rd control parameter, the width of the current band, has influence on the inverter losses as well as the vibrations and the resulting acoustic noise in the SRM. The simulation of various control schemes is possible. Note that the simulation can not consider the real saturation conditions, but it gives acceptable results multiple faster then the FEM.

Fig. 11: Current and torque control of a SRM (q=4)

Conclusion

Switched Reluctance Machines are one of the least expensive and most reliable electrical machines to produce. The inverter is only required to supply a unidirectional current to each motor phase, thereby halving the number of main switches required. As such, the SRM and variable speed drive systems using SRMs are receiving considerable attention from industry during the last decade. However, successful realization of an SRM drive system demands an optimized design and coordination of both machine and converter.

The design and some fundamental optimization approaches have been described for SRMs in this paper. The problem is to determine which design would yield the best machine performance to fulfil the requirements of the later application. Particular attention has been paid to various highly nonlinear features due to saturation of the iron, which do not occur in conventional a.c. or d.c. machines. Furthermore important questions as how to choose the number of phases, poles, rotor and stator teeth etc. are discussed. The machine design consists of the specification of all dimensions and the stepwise optimization of geometry, winding and material. In general the developed design procedure can reduce the developmental period by the combination of design and detail computation. Moreover the precision of the calculation increases and expensive prototype-tests can be saved particularly by extended simulations.

An optimized machine design is always a compromise between various conflicting effects resulting from geometrical modifications. The application of the developed SRM drive system must be the guide which specifies the optimization criteria. Under the condition that motor and converter are optimally designed and coordinated, adjustable speed drives using SR Motors offer an attractive alternative to inverter fed induction motors.

References

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