Direct instantaneous torque control for switched reluctance machines considering mutual coupling

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Abstract: Torque ripple reduction is the main goal of direct instantaneous torque control (DITC). However, the quality of the switched reluctance machine control is only as good as its machine model. Depending on the saturation characteristics and the number of machine phases, as well as the coil orientation of the individual phases, different mutual coupling effects between the phases occur. This study discusses the influence mutual coupling has and how the coupling effects can be incorporated into the DITC machine model. Thus, effectively reducing the influence the coil arrangement has on the resulting output torque. Furthermore, the amount of harmonic content in the torque ripple is reduced considerably.

1 Introduction

Commonly switched reluctance machine (SRM) models are used which do not consider mutual phase coupling due to ease of use and the limited influence coupling has on the normally available three-phase SRM. The effect of mutual coupling increases as the number of phases available increases due to increasing overlap between active phases. Additionally, high-torque SRMs with a high amount of saturation show extensive mutual coupling effects [1].

As has been discussed previously in the literature [2], mutual phase coupling strongly depends on the orientation of neighbouring coils. The orientation of the coils affects the flux distribution within the machine and, therefore, the torque production.

In this paper, a 1 kW-SRM is discussed with respect to the amount of mutual coupling present and its influence on the implemented DITC algorithm. The investigated motor is a four-phase 16/12 SRM. The machine data and cross-section is shown in Table 1 and Fig. 1, respectively.

Table 1 Machine data of the investigated 16/12 SRM

<table>
<thead>
<tr>
<th>no. of phases</th>
<th>max. power</th>
<th>max. speed</th>
<th>max. MMF per tooth</th>
<th>switching frequency</th>
<th>DC-link voltage</th>
<th>outer radius</th>
<th>air-gap length</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1 kW</td>
<td>1500 rpm</td>
<td>3500 AT</td>
<td>20 kHz</td>
<td>60 V</td>
<td>62.5 mm</td>
<td>0.25 mm</td>
</tr>
</tbody>
</table>

Fig. 1 Cross section of the investigated SRM with both possible coil arrangements

(a) Non-alternating phases, (b) Alternating phases

First, the different excitation possibilities due to coil winding orientation in SRMs are discussed. Thereafter, the machine model for direct instantaneous torque control (DITC) considering phase coupling is presented. In Section 3 the predictive pulse-width modulation (PWM)-DITC algorithm for two-phase excitation is discussed, followed by simulation results in Section 4 showing the benefit of using a torque control algorithm with mutual coupling in regard to harmonic content in the output torque.

2 Modelling mutual coupling

2.1 Parallel and antiparallel coil coupling

Two neighbouring coils in an SRM can either be wound such that the magnetic flux direction of both coils are non-alternating (parallel), shown in Fig. 1a or alternating (antiparallel) shown in Fig. 1b. In literature, the two resulting flux paths are normally referred to as the long-flux path and short-flux path, respectively [2]. Phases are classified as active when excited by a current, i.e. the phase is carrying a current. During phase commutation (overlap) adjacent phases are active simultaneously. The more number of phases a machine has, the larger this overlapping period may become.

In alternating overlapping phases, the magnetic flux normally acts additive to each other, increasing overall phase flux and output torque of the coupled phase. On the other hand, non-alternating phase coupling mainly causes flux subtraction between the phases, reducing the output torque [3]. However, this is only true if the coupling flux does not cause excessive material saturation. Therefore, the geometry design of the SRM, especially stator and rotor yoke, and the material used determines how strongly phase coupling affects the overall output torque. SRMs with an odd number of phases can either be wound in alternating manner or block-wise in non-alternating and alternating manner. Even-numbered SRMs will inevitably always have both types of coil arrangements. This can be seen in Fig. 1, even though both different coil arrangements are shown, there is always a pair of phases containing the other coil arrangement, e.g. pole numbers 1.1 and 4.16.

Fig. 2 displays the phase coupling influence in the investigated SRM. The coupled non-alternating magnetic phase flux, thereby, is constantly lower than the self-flux demonstrating its subtractive nature. The self-flux is defined as the flux linkage generated by only the respective phase, i.e. without neighbouring phase coupling. On the other hand, the alternating coupled flux is higher than the self-flux at low phase currents, i.e. additive. The thin stator yoke of the investigated SRM causes early yoke saturation when
phase coupling effect always influences both active phases. Phase-based models, i.e. each phase of the SRM is represented by a self-flux at current values higher than 2.5 A visible in Fig. 2 depending on the rotation direction. Furthermore, the influence of neighbouring active phases. The general modelling approach is comparable to previously presented work, where switched reluctance machine models for simulation have effectively been applied using look-up tables [4, 5]. An overview of the used LUT model is shown in Fig. 4. Thereby, the active phases are defined as incoming phase (phase 1) and outgoing phase (phase 2) depending on the rotation direction. Furthermore, the phase coupling effect always influences both active phases.

The necessary LUTs to represent the SRM are constructed from FEM simulations. The FEM is calculated for a combination of two neighbouring phase currents and a number of rotor positions between 0°el and 360°el. The result is a table representing mutual torque $T(\psi_1, \psi_2, R_{ph})$ depending on the flux linkage of both active phases $\psi_1$ and $\psi_2$ and electrical rotor position $\theta_{el}$. Furthermore, to create a flux-linkage-based SRM model, the respective current LUT $i_1(\psi_1, \theta_{el})$ and $i_2(\psi_2, \theta_{el})$ and coupled flux-linkage LUT $\psi_2(i_1, i_2, \theta_{el})$ and $\psi_1(i_1, i_2, \theta_{el})$ tables for the active phases are necessary. The tables $i_1(\psi_1, \theta_{el})$ and $i_2(\psi_2, \theta_{el})$ are generated by inversion and iterative look-up from the flux-linkage LUT. The radial force acting on the rotor is determined from the $F_{rad}(\psi_1, \psi_2, \theta_{el})$ table. The LUT resolution, especially in regard to rotor position has a determinate effect on the quality of the torque control. It has been determined that a resolution of at least 3°el or less is necessary to minimise torque spikes due to mismatch of the LUT model and the later used coupled FEM model.

In contrast to previously presented work, this paper focuses on the torque control aspect considering mutual coupling and not on modelling the machine.

### 3 DITC considering mutual coupling

The number of simultaneously active phases can increase with increasing number of machine phases. For the investigated SRM, the coupling effect for two active phases is considered because in a four-phase machine mainly two phases are active during phase commutation.

The coupled model (Fig. 4) is used in MATLAB Simulink to implement the DITC control. This Simulink model is verified by using a coupled FEM analysis between MATLAB Simulink and Flux2D. Thereby, the SRM's geometry is modeled in Flux2D, the coupled model is computationally intensive, which is not the case for the LUT-based Simulink model. Therefore, a time effective control algorithm development, implementation and verification are only possible with a LUT-based model. The two machine models match very well as is visible in the results discussed in Section 4.

Fig. 5 shows a schematical overview of the used DITC control structure. In contrast to the common PWM-DITC approach [6], the flux linkage and torque estimation, torque sharing algorithm and flux linkage allocation are evaluated simultaneously. Similar as in [7] the flux-linkage estimations for both active phases are divided into an arbitrary number of $k$ equidistant values (states) between minimum and maximum flux linkage. In Fig. 5, the flux linkage equations are shown, whereby $\psi$ represents the phase being integrated and $v_{ph}$ is the effective phase voltage resulting from the dc-link voltage reduced by the voltage drop across the inverter switches and diodes, $R_{ph}$ and $i_{ph}$ are the phase resistance and phase current, respectively, at time step $n$.

To estimate the torque range for the time step $n + 2$, the flux linkage values $\psi_{1,n+2}$ and $\psi_{2,n+2}$ and $T(\psi_1, \psi_2, \theta_{el})$-LUT are used. For a fixed rotor position $\theta_{el}$, the torque and flux-linkage tuples $(T_k | \psi_{1,2})$ span a matrix of possible torque values which can be

![Fig. 2 Influence of coil-arrangement direction and phase coupling on flux linkage](image)

(a) Influence of pole current on flux linkage, (b) Influence of rotor position on flux linkage

![Fig. 3 Influence of coil-arrangement direction and phase coupling on static torque production versus rotor position](image)

![Fig. 4 Overview of LUT-based SRM model considering mutual coupling](image)
chosen by the controller. The torque area \((T_k | \psi_{1,k} | \psi_{2,k})\) with its boundary values \(\psi_{1/2, \min}\) and \(\psi_{1/2, \max}\) is shown in Fig. 5.

Similar to the common torque sharing algorithm from [7, 8], an algorithm is implemented where the reference torque \(T_{\text{ref}}\) is divided among the torque producing phases. Thereby, a priority list is used to ensure the incoming phase is magnetised to produce enough torque during phase commutation. The torque from \(T(\psi_{1}, \psi_{2}, \theta_{\text{el}})\) corresponds to the mutual torque produced by both active phases. The torque sharing algorithm uses this LUT to find the closest matching value to the reference torque \(T_{\text{ref}}\). From the selected reference torque \(T_{\text{ref}}\) the respective two reference flux linkage values \(\psi_{1, \text{ref}, n+2}\) and \(\psi_{2, \text{ref}, n+2}\) are selected from the previously determined tuples. The duty cycles for each phase which is set by the inverter is calculated from the reference flux linkages.

4 Simulation results and discussion

The simulations for this work have been performed in a MATLAB Simulink environment. The control algorithm, inverter, as well as the SRM model have been simulated. The machine model has been simulated as presented in Section 2.2 and Fig. 4 as a LUT-based model with phase coupling (Simulink SRM model) and to verify the results a coupled finite element simulation with Flux2D (FEM SRM model) has been performed.

Figs. 6 and 7 show simulation results when using DITC without and with a phase-coupled machine model for the investigated SRM at 400 rpm and 4.9 Nm torque reference. The SRM is simulated with a non-alternating coil arrangement as shown in Fig. 1a.

In Fig. 6a, the controller sets a reference torque of 4.9 Nm, while the other two torque waveforms represent the torque from either the Simulink SRM model as discussed previously and from the FEM, respectively. It is clearly visible that even though the control tries to control a constant torque that the resulting torque from Simulink and FEM are not constant. However, the torque waveforms from the LUT-based Simulink model and the FEM model match very well visible in Fig. 6b showing the spatial harmonics from the fast Fourier transform (FFT) of the torque waveforms. The high harmonic content results from phase coupling. Especially, the 4th, 8th and 12th harmonic considerably increased. The 16th harmonic is expected from a switched reluctance machine with 16 stator teeth.

The singular high peak-to-peak torque ripple at around 5 ms is specifically of the non-alternating coil arrangement. This high torque ripple is due to the phase commutation between the two neighbouring phases with alternating flux direction, i.e. between phases 1 and 2. This alternating flux direction causes an additive flux coupling effect resulting in a higher instantaneous torque. The subsequent next three-phase commutations all have a lower peak-to-peak torque ripple because of non-alternating neighbouring phases. Thus, during an entire mechanical rotor revolution there are four high peak-to-peak phase torque commutations, always followed by three low ones. These peaks are clearly visible in the spatial harmonics, corresponding to the 8th and 12th, respectively.

In contrast, with an alternating coil arrangement of a four-phase SRM, there would always be three-phase commutations with a high peak-to-peak waveform followed by one single low torque commutation.
In the small investigated SRM, a torque ripple due to mutual coupling is observed similar to the discussion in [9], where too a torque ripple of 5% is accounted for by mutual coupling. In an odd-phase SRM a coil arrangement with only alternating flux directions is possible. This would only increase the spatial harmonic already present due to the number of stator teeth it would not add additional harmonics. In contrast, in a machine where both coil arrangements are used additional lower order harmonic content is introduced.

The corresponding current and flux linkage waveforms for the non-mutual coupled simulations are shown in Fig. 6c and d, respectively.

Fig. 7 shows the simulation results at 400 rpm and 4.9 Nm when DITC considering mutual coupling is used. In comparison to Fig. 6, a smoother torque waveform is visible. Again, the waveforms of the Simulink LUT-based model and the FEM model match very well. This is also visible in the FFT of the torque in Fig. 7b. The FFT shows that only the 16th spatial harmonic (and its multiples) is still strongly visible due to the 16 stator teeth. In Fig. 7d, the phase flux linkage is plotted. The flux linkage of the FEM and the LUT-model match well. Furthermore, the negative flux linkage (reversal of flux direction) in the stator teeth resembles induced flux linkage from neighbouring teeth is visible and corresponds to the FEM.

Table 2 gives an overview, in percentage, of the change in total torque ripple and the spatial harmonic content. The absolute values and change in torque ripple is minor, however, the change in harmonic content when using a control algorithm which considers phase coupling is much more prominent.

5 Conclusions

Switched reluctance machines experience phase overlap during phase commutation leading to electric and electromagnetic mutual coupling. The higher the phase number, the higher the expected influence of the actual coupling. This paper has confirmed previously discussed findings that the coil arrangement and resulting additive or subtractive coupled phase flux have a direct influence on the resulting torque waveform. Furthermore, a method to include mutual phase coupling in the PWM-based direct instantaneous torque control algorithm is introduced. The control is verified by using a coupled finite element simulation. The results show that the implemented look-up-table-based model in the control is sufficient to incorporate all coupling effects visible in the finite element simulation. Furthermore, a noticeable reduction in the harmonic content of the output torque waveform is observed.

6 References