Stator flux oriented control of a cascaded doubly-fed induction machine

B. Hopfensperger, D.J. Atkinson and R.A. Lakin

Abstract: A cascaded doubly-fed induction machine (CDFM) is a connection of two wound rotor induction machines. In comparison to a single doubly-fed induction machine (SDFM) brushes are obsolete. Due to recent developments in brushless doubly-fed machine design, there is a renewed interest in associated control. Theoretical and experimental studies of a stator flux oriented control method for a CDFM are presented. The use of vector control principles to control torque, speed, active and reactive power is investigated. It is found that the additional closed rotor circuit of the CDFM introduces a cross coupling between the d-axis and the q-axis. Nevertheless, the cross coupling effect remains small in relation to the overall control concept so that the control of the CDFM resembles that of the SDFM.

List of symbols

Abbreviations:

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>SDFM</td>
<td>single doubly-fed induction machine</td>
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<tr>
<td>CDFM</td>
<td>cascaded doubly-fed induction machine</td>
</tr>
<tr>
<td>SF-CDFM</td>
<td>single frame cascaded doubly-fed induction machine</td>
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<tr>
<td>BDFM</td>
<td>brushless doubly-fed induction machine</td>
</tr>
<tr>
<td>DFRM</td>
<td>doubly-fed reluctance machine</td>
</tr>
<tr>
<td>µC</td>
<td>microcontroller</td>
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<tr>
<td>PWM</td>
<td>pulse width modulation</td>
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Superscripts (for reference frames):

<table>
<thead>
<tr>
<th>Superscript</th>
<th>Description</th>
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<tbody>
<tr>
<td>a</td>
<td>side 1 of CDFM (stationary) reference frame</td>
</tr>
<tr>
<td>b</td>
<td>side 2 of CDFM reference frame</td>
</tr>
<tr>
<td>c</td>
<td>side 3 of CDFM reference frame</td>
</tr>
<tr>
<td>d</td>
<td>side 4 of CDFM reference frame</td>
</tr>
<tr>
<td>e</td>
<td>excitation reference frame for orientation</td>
</tr>
<tr>
<td>*</td>
<td>demand value</td>
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Other:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>V₁, V₂, V₃, V₄</td>
<td>voltage space vector of respective machine side</td>
</tr>
<tr>
<td>i₁, i₂, i₃, i₄</td>
<td>current space vector of respective machine side</td>
</tr>
<tr>
<td>Ψ₁, Ψ₂, Ψ₃, Ψ₄</td>
<td>flux linkage space vector of respective machine side</td>
</tr>
<tr>
<td>Ψₐ, Ψₐ*B</td>
<td>rotor circuit loop flux linkage space vector</td>
</tr>
<tr>
<td>TₑA, TₑB</td>
<td>electromagnetic torque of machine A and B of CDFM</td>
</tr>
<tr>
<td>TₑAB</td>
<td>total electromagnetic torque of CDFM</td>
</tr>
<tr>
<td>P₁, Q₁</td>
<td>side 1 active and reactive power</td>
</tr>
<tr>
<td>f₁, f₄</td>
<td>frequency of side 1 and side 4</td>
</tr>
<tr>
<td>fᵣ</td>
<td>mechanical rotor frequency</td>
</tr>
<tr>
<td>ωₐ</td>
<td>mechanical angular frequency of rotor (side 2)</td>
</tr>
<tr>
<td>ωₐ*₄</td>
<td>mechanical angular frequency of side 4 relative to side 1</td>
</tr>
<tr>
<td>ωₑ</td>
<td>angular frequency of the excitation reference frame in elec. rad/s</td>
</tr>
<tr>
<td>Θₑ</td>
<td>rotor angle in mech. rad</td>
</tr>
<tr>
<td>ΘₑA*, Θₑ*B</td>
<td>rotor angle of machine A and B in elec. rad</td>
</tr>
<tr>
<td>ΘₑAB</td>
<td>angle between frame a and d</td>
</tr>
<tr>
<td>Ω</td>
<td>angle between frame b and e</td>
</tr>
<tr>
<td>ε</td>
<td>angle between frame d and e</td>
</tr>
<tr>
<td>µ</td>
<td>angle between frame a and e</td>
</tr>
<tr>
<td>p₆, p₇</td>
<td>pole pair number of machine A and B</td>
</tr>
<tr>
<td>R₁, R₂, R₃, R₄</td>
<td>resistance of respective machine side</td>
</tr>
<tr>
<td>Rₑ</td>
<td>combined rotor resistance</td>
</tr>
<tr>
<td>L₁, L₂, L₃, L₄</td>
<td>self inductance of respective machine side</td>
</tr>
<tr>
<td>Lₑ</td>
<td>combined rotor inductance</td>
</tr>
<tr>
<td>LₑₐA, LₑₐB</td>
<td>mutual inductance of machine A and B</td>
</tr>
<tr>
<td>nₑ</td>
<td>mechanical rotor speed, rpm</td>
</tr>
<tr>
<td>k₁, k₂, k₃</td>
<td>constants</td>
</tr>
</tbody>
</table>

1 Introduction

Recent developments by Wallace, Spee et al. [1], in conjunction with Williamson [2] have resulted in improvements in the design of the so-called brushless doubly-fed induction machine (BDFM). Their work has shed new light and interest on the field of doubly-fed induction machines in...
Connecting the stator windings of a wound rotor induction machine to a stiff voltage supply and the rotor windings to a bi-directional power converter constitutes a doubly-fed machine arrangement. It is referred to as a single doubly-fed induction machine (SDFM) in this paper. The SDFM is the simplest type of doubly-fed machine [3]. A field oriented control method for the SDFM was introduced by Leonhard [4] nearly 20 years ago. The rotor current vector is oriented into a reference frame aligned with the stator flux, enabling the torque and the stator active power to be manipulated with the q-component of the rotor current vector. Since the flux in the machine is mainly determined by the stator voltage, this enables the stator reactive power to be controlled by the d-component of the rotor current vector. This stator flux oriented control principle is now well enstablished in research and industry. Due to the decoupled active and reactive control possibilities, the main area of application for the SDFM is in variable speed generating systems such as wind power [5] and hydro power [6].

Compared to a variable speed singly-fed machine arrangement with a cage induction machine, the SDFM has the advantage of a reduced power converter rating, which is related to the desired speed range. As a drawback, the SDFM has slip-rings and brushes on the rotor side, which are subject to maintenance and additional cost.

Fig. 1 CDFM machine arrangement

A machine arrangement consisting of two wound rotor induction machines, which avoids brushes, is shown in Fig. 1. The stator of machine A (side 1) is connected to the stiff voltage mains supply and the rotor slip-rings of machine A (side 2) are then directly connected to the slip-rings of machine B (side 3). The stator of machine B (side 4) is fed by a bi-directional power converter. Since the two rotors have a stiff mechanical coupling no brushes are needed for the slip-ring connection. This brushless machine arrangement leads to a so-called cascaded doubly-fed induction machine (CDFM). The idea of this machine connection has been known for more than a century [7, 8].

Several researchers investigated the stability and scalar control schemes [9-11]. In [11], it is pointed out that scalar control methods lead to either poor steady state control conditions or the control shows large dynamically unstable operational areas. Field orientation control principles for the CDFM were first applied by Bauer [11]. In his method the rotor (side 2) current vector is oriented into an artificial flux reference frame based on measurements of the two stator currents. A mathematical control extension allows the non-accessible rotor current to be manipulated by the side 4 current. Bauer’s scheme encounters stability problems at higher speeds and it is only applicable to a CDFM consisting of two identical machines. Krebs [12] continued the work of Bauer on a SF-CDFM and introduced an observer for the non-measurable rotor currents to stabilise the control method. Sathikumar and Koczara [13, 14] investigated a stator (side 1) flux oriented control scheme for the CDFM by simulation. It is claimed that the q-axis side 4 current component in the side 1 flux reference frame controls the active power flow in the CDFM and the d-axis component the reactive power flow. In that case, the CDFM would behave exactly like a SDFM. To date, there has been no comment on the influence of the closed rotor circuit upon the control algorithm.

This paper presents theoretical and experimental research results on the stator flux oriented control method for the CDFM. The extent to which the additional closed rotor circuit loop affects the control scheme has been investigated.

Other machine types, which can generally be classified as a brushless doubly-fed machine, are the single-frame-CDFM (SF-CDFM), the brushless doubly-fed machine (BDFM) and the doubly-fed reluctance machine (DFRM). The SF-CDFM is a more compact version of the CDFM. Both stator windings are fitted axially, aligned next to each other in a common frame. A cage rotor, with the rotor bars cross-over between the two machine halves, goes over the whole machine length [15]. The analysis in [12], for example, is carried out on this machine type.

Research into the BDFM is concentrated with Wallace and Spec at the Oregon State University [1], together with more recent work by Williamson [2]. The BDFM machine path was initiated by Hunt in 1907 [16]. He aimed to unite two machines into one. A special type of stator winding sets up two rotating fields, which interact with a special type of cage rotor. The latest control contribution to the BDFM is a rotor flux oriented control scheme [17].

Having the same stator as a BDFM, but a reluctance type rotor, leads to the doubly-fed reluctance machine (DFRM) [18]. The dynamic model of this machine type is identical to the SDFM and therefore the same stator flux oriented control method is applicable to the DFRM [19].

The analysis in this paper is applicable to the CDFM, the SF-CDFM, and is also relevant for the BDFM.

2 Experimental arrangements

The following investigation of the CDFM will be better understood if the experimental equipment is first described. The complete laboratory arrangement is illustrated in Fig. 2. The power circuit (thickened lines) consists of a bi-directional power converter and the CDFM. A 3.75kW DC machine (not shown in Fig. 2), acting as a prime mover to the system, has a through-shaft so that one wound rotor induction machine of the CDFM is connected on either side of the DC machine. Machine A of the CDFM is a 2.25kW, 4 pole pair and machine B a 2.25kW, 2 pole pair wound rotor induction machine. The CDFM is described in this paper as a brushless machine arrangement with directly interconnected rotor windings. However, due to the machine configuration with one wound rotor induction machine on either side of the DC machine, the slip-rings and brushes are still used in the laboratory set-up. It is therefore possible to monitor the rotor quantities, which assists in the understanding of the machine behaviour. Although set up in this way, the electrical behaviour of the CDFM remains unchanged.

The independently functioning front-end of the bi-directional power converter creates a unity power factor interface at the grid connection point and controls the DC-link voltage to 650V. The gate drive circuits of the machine-side inverter module are interfaced to the PWM signals coming from the external controller unit.
The control hardware comprises two paralleled 16-bit fixed point 80C167 microcontrollers, denoted as μC1 and μC2 in Fig. 2. Microcontroller μC1 performs most of the control functions, which include current control with PWM generation, position and speed calculation. The microcontroller’s PWM unit generated interrupt request sets the switching frequency of the machine-side inverter and also determines the available processing time. A switching frequency of 2.5kHz was chosen, which gives 400μs for software execution. Microcontroller μC2 performs the remaining functions such as angle calculation, power calculation and power control. A high speed serial link provides the communication link between both microcontrollers. The 10 bit A/D conversion for the measured quantities is shared between the microcontrollers depending on the respective control functions. The sensed quantities are the side 1 voltage and current, and the side 4 current.

Various interface circuits allow electrical isolation between power and control hardware. Incremental encoder signals are received at a timer-unit of μC1 for position and speed calculation. μC1 produces control variables for data storage and monitoring purposes on the PC and an oscilloscope.

3 Steady state operation of the laboratory CDFM

There are two possible ways to electrically connect the individual machines of the CDFM: either in positive phase sequence or in negative phase sequence. Positive phase sequence results by connecting the rotor windings (slip-rings) with same naming together. Owing to the back-to-back machine arrangement, the resulting rotor fields rotate in opposite directions relative to the rotor. For negative phase sequence connection, with a phase-swap on side 3, the rotor fields have the same rotational direction. The developed torques of machine A and machine B are co-acting for positive phase sequence rotor connection and are counter-acting for negative sequence connection [20]. Therefore, only the positive phase sequence connection is of any real importance and it is the only connection sequence considered in this paper.

Fig. 3 shows the frequency behaviour of the laboratory CDFM with a 4/2 pole pair relationship. Side 1 is connected to the 50Hz supply line. Side 2 and side 3 frequencies are identical due to the positive phase sequence connection. The CDFM reaches the synchronous point of machine A at 750 rpm \( f_3 = f_2 = 0\text{Hz} \). In the vicinity of machine A synchronous speed the individual machines lose their electromagnetic coupling so that the CDFM can no longer be regarded as one unit. It is not possible to drive the CDFM through that crucial interval in motoring mode. A practical speed range for the laboratory CDFM is up to 80% of machine A synchronous speed, which is up to 600 rpm. The so-called cascaded synchronous point, related to the sum of the individual pole pairs, is reached at 500 rpm with \( f_4 = 0\text{Hz} \).

The resulting frequency relationship of the CDFM between side 1 and side 4 follows as

\[
\frac{f_1}{f_2} = (p_A + p_B)f_m + f_4
\]  

with \( p_A \) and \( p_B \) as the pole pair numbers and \( f_m \) as the mechanical rotor frequency. Negative frequencies in Fig. 3 symbolise reversed phase sequence in comparison to positive frequency values.

It has to be mentioned that the laboratory machine set could also be arranged in a 2/4 pole pair relationship. The cascaded synchronous point would still be at 500 rpm, but the machine A synchronous speed would result at 1500 rpm. However, this machine arrangement is not favourable since at the maximum practicable speed range of 80% of machine A synchronous speed, the majority of machine power would flow via side 4. This counter affects the
advantage of a doubly-fed machine system with reduced inverter power rating. The power flow in the machine is affected by the machine pole pairs and it is preferable to choose $p_A$ greater than $p_B$ [21].

4 Stator flux oriented control of the CDFM

The expression ‘stator’ is ambiguous when used with the CDFM since there are two stators involved, but this term shall be used throughout this paper and it is solely related to the machine A stator (side 1).

4.1 Dynamic model and reference frames

The individual machine side quantities expressed at their respective machine sides as space vectors are

$$
\begin{align*}
v^a_1 &= R_1 i^a_1 + \frac{d\Psi^a_1}{dt} \\
v^b_2 &= R_2 i^b_2 + \frac{d\Psi^b_2}{dt} \\
v^c_3 &= R_3 i^c_3 + \frac{d\Psi^c_3}{dt} \\
v^d_4 &= R_4 i^d_4 + \frac{d\Psi^d_4}{dt}
\end{align*}
$$

The corresponding reference frame system for the CDFM is shown in Fig. 4. Frame a is attached to the stationary side 1. Frames b and c are identical and are attached to the rotor of the CDFM. Frame d for side 4 moves with the angular velocity of $\omega_{AB} = (p_A + p_B)\omega_m$ relative to frame a. Although this may not agree with the physical picture of the CDFM with both stators, side 1 and side 4, stationary, the reference frame of Fig. 4 is preferable for developing the control of the CDFM. The machine can be regarded only from one stationary reference frame and the view through the CDFM goes from side 1 onto side 2 and side 3. Side 4 is then seen relative to side 3. This view of the CDFM is adopted for all the following considerations.

Fig. 4 Reference frames and angles for the CDFM

Expressing the voltage equations of side 1 and side 4 in the excitation reference frame $e$, which is attached to the stator flux, leads to

$$
\begin{align*}
v^e_1 &= R_1 i^e_1 + \frac{d\Psi^e_1}{dt} + j\omega_e \Psi^e_1 \\
v^e_4 &= R_4 i^e_4 + \frac{d\Psi^e_4}{dt} + j(\omega_e - \omega_{AB}) \Psi^e_4
\end{align*}
$$

Since the rotor windings constitute a closed rotor circuit loop the voltage eqns. 3 and 4 can be combined with the connection constraints for the positive phase sequence connection of

$$
\begin{align*}
v_2 &= v_3 \\
i_2 &= -i_3
\end{align*}
$$

This creates the rotor loop voltage equation expressed in the $e$ frame as

$$
0 = R_R \Psi_R^e + \frac{d\Psi_R^e}{dt} + j(\omega_e - \omega_{AB}) \Psi_R^e
$$

with $R_R = R_2 + R_3$ as the combined rotor resistance and

$$
\Psi_R^e = \Psi^e_2 - \Psi^e_3 = L_m A_i^2 + \psi_L - L_m i_4^e
$$

as the rotor circuit loop flux linkage, which is an artificial quantity not physically existing in the CDFM. This is created by Kirchhoff’s Law being applied to the flux linkages in the rotor loop and is composed of the individual rotor flux linkages. $L_R = L_2 + L_3$ is the combined rotor circuit inductance value. It is useful for further analysis to derive the rotor loop flux linkage as a function of the stator flux. Resolving the side 1 flux eqn. 2, expressed in the $e$ frame, in terms of the side 1 current, and substituting it in eqn. 10 yields

$$
\psi_k = k_1 i_1^e + \frac{L_{mA}}{L_1} \Psi^e_1 - L_{MB} i_4^e
$$

In the same way, substituting the rotor current leads to

$$
\psi_k = k_2 i_1^e + \frac{L_{mA}}{L_1} \Psi^e_1 - L_{MB} i_4^e
$$

where $k_1$ and $k_2$ are constants with the values

$$
k_1 = L_R - \frac{L^2_{mA}}{L_1} \quad \text{and} \quad k_2 = L_{mA} - \frac{L_{RL}}{L_{mA}}
$$

The voltage eqns. 6, 7 and 9, together with the flux linkage eqns. 2 and 5 expressed in the $e$ frame, and eqn. 10 constitute the electrical model of the CDFM in the excitation reference frame.

4.2 General features of the control

4.2.1 Determination of the orientation angle $\varepsilon$: In order to orientate the side 4 current vector into the stator flux reference frame the position of the stator flux relative to the stationary reference frame has to be known. A common way to achieve this is by neglecting the stator resistance and measurement of the stator (side 1) voltage [22]. With the neglect of the side 1 resistance the stator flux vector lags $90^\circ$ behind the stator voltage vector. Therefore, measuring the side 1 voltage in the $a$ frame together with a cartesian to polar transformation delivers the position angle $\alpha_1$ of the stator voltage vector. A subsequent subtraction of $\pi/2$ gives the angle $\mu$.

Fig. 5 Angle construction method for the CDFM

The mechanical rotor position angle $\Theta_m$ is measured with an incremental encoder. Multiplying the angle $\Theta_m$ with the sum of the machine pole pairs $(p_A + p_B)$ delivers $\Theta_{AB}$ which is the angle between frames a and d. The angle $\varepsilon$ between the $e$ frame and the $d$ frame can be thus calculated as $\mu + \Theta_{AB}$. The angle construction method is displayed in Fig. 5. All angles, apart from $\Theta_m$ in Figs. 4 and 5 are in electrical rad/s.
4.2.2 Voltage and flux constraints on side 1: By neglecting the resistance on side 1 the voltage eqn. 2 reduces to

\[ v_1^a = \frac{d\Psi_1^a}{dt} \quad (14) \]

From this it can be seen that a reference frame attached to the stator flux has the same angular frequency as the stator voltage with

\[ \omega_c = \omega_1 = \frac{d\mu}{dt} = \text{const.} \quad (15) \]

By substituting \( \Psi_1^e = \Psi_1^a e^{j\mu} \) in eqn. 14 and applying the rules of differentiation, the magnitude of the stator flux expressed in the \( e \) frame is given by

\[ \Psi_{q1}^e = \Psi_1^e = \sqrt{2} V_1 = \text{const.} \quad \text{and} \quad \Psi_{d1}^e = 0 \quad (16) \]

where \( V_1 \) is the stator phase voltage in RMS. The individual components of the stator voltage space vector in the excitation reference frame take the value

\[ v_{q1}^e = 0 \quad \text{and} \quad v_{d1}^e = \omega_1 \Psi_1^e = \sqrt{2} V_1 = \text{const.} \quad (17) \]

4.2.3 Influence of the closed rotor circuit: The additional closed rotor circuit on side 2 (= side 3) is the distinct electrical difference between the CDFM and the SDFM. This rotor winding is not accessible and introduces another set of voltage and flux equations to the machine model as covered above. The influence of this rotor circuit upon the control algorithm is investigated in the following.

Consideration of the rotor loop voltage eqn. 9 in the \( e \) frame and splitting it into \( d-q \)-components, by regarding only steady state, yields

\[ \Psi_{qR}^e = \frac{R_R i_{q2}^e}{\omega_2} \quad (18) \]

\[ \Psi_{dR}^e = -\frac{R_R i_{d2}^e}{\omega_2} \quad (19) \]

where

\[ \omega_2 = \omega_0 - \omega_A = \frac{d\Theta}{dt} \quad \text{with} \quad \Theta = \mu - \Theta_A \quad \text{as the angle between the rotor reference frame \( b \) and the excitation reference frame \( e \).} \]

From eqns. 18 and 19 it can be seen that the rotor circuit introduces a cross coupling between the \( d \)-axis and the \( q \)-axis in the \( e \) frame. The degree of cross coupling depends on two parameters: the combined rotor resistance and the rotor angular speed relative to the angular speed of the excitation frame \( \omega_2 \).

From eqns. 18 and 19 it can be seen that the rotor circuit introduces a cross coupling between the \( d \)-axis and the \( q \)-axis in the \( e \) frame. The degree of cross coupling depends on two parameters: the combined rotor resistance and the rotor angular speed relative to the angular speed of the excitation frame \( \omega_2 \).

By ignoring the transient in the step response, the first set of simulations (middle graph), at a speed of 200 rpm, clearly shows the cross coupling effect in the \( q \)-component of \( \Psi_R^e \) (denoted as ‘flux R’ in the graphs) caused by a step in the \( d \)-component of \( i_4^e \), and the effect in the \( d \)-component of \( \Psi_R^e \) caused by the \( q \)-component of \( i_4^e \). The second set shows the case for 600 rpm (80% of speed range). Compared to the simulation results at 200 rpm, there is an increase in the magnitude of the rotor loop flux linkage and its cross coupling. The value of the combined rotor resistance has a linear effect on the cross coupling. With half the resistance value, only half the cross coupling effect would occur.

4.2.4 Side 1 to side 4 relationships: For the stator flux oriented control of a SDFM, the rotor current \( d-q \)-components are directly linked to the respective stator current \( d-q \)-component in the \( e \) frame. It is the case that the stator active power is directly linked to the rotor current \( q \)-component and the stator reactive power to the rotor current \( d \)-component. In the following, it is investigated whether such a direct relationship between side 4 and side 1 also exists for the stator flux oriented CDFM.

Relating the side 4 currents to the side 1 currents in the \( e \) frame for the CDFM with the help of eqn. 12, and splitting it into \( d-q \)-components with \( \Psi_4^e = 0 \), gives

\[ i_{q1}^e = \frac{1}{k_2} \Psi_{dR}^e - \frac{L_R}{k_2 L_m A} \Psi_{q1}^e + \frac{L_m B}{k_2} i_{q4}^e \quad (20) \]

\[ i_{q1}^e = \frac{1}{k_2} \Psi_{qR}^e + \frac{L_m B}{k_2} i_{q4}^e \quad (21) \]

By ignoring the transient in the step response, the first set of simulations (middle graph), at a speed of 200 rpm, clearly shows the cross coupling effect in the \( q \)-component of \( \Psi_R^e \) (denoted as ‘flux R’ in the graphs) caused by a step in the \( d \)-component of \( i_4^e \), and the effect in the \( d \)-component of \( \Psi_R^e \) caused by the \( q \)-component of \( i_4^e \). The second set shows the case for 600 rpm (80% of speed range). Compared to the simulation results at 200 rpm, there is an increase in the magnitude of the rotor loop flux linkage and its cross coupling. The value of the combined rotor resistance has a linear effect on the cross coupling. With half the resistance value, only half the cross coupling effect would occur.
From eqn. 20 it can be seen that the side 1 current d-component is manipulated by the side 4 current d-component, but there is also the rotor loop flux d-component present, which is subject to cross coupling. The stator flux component in eqn. 20 is constant as derived above. A similar relationship exists for the q-axis components in eqn. 21, where the q-component of the rotor loop flux is subject to cross coupling. It shows that the side 1 current components are manipulated by the respective side 4 current component, but not in a totally decoupled manner as it is the case for the SDFM.

Employing eqns. 20 and 21, together with the side 1 voltage constraints of eqn. 17, and substituting it in the side 1 active and reactive power eqns. 29 and 30, creates the stator active and reactive power equations of the CDFM in the e frame as

\[ P_1 = \frac{3}{2} \sqrt{2} V_1 \left( \frac{1}{k_2} \Psi_{dR}^e + \frac{L_{mB}}{k_2} \Psi_{qR}^e \right) \]  

\[ Q_1 = \frac{3}{2} \sqrt{2} V_1 \left( \frac{1}{k_2} \Psi_{dR}^e - \frac{L_{mB}}{k_2} \Psi_{qR}^e + \frac{L_{mB}}{k_2} \Psi_{qR}^e \right) \]  

The side 1 active power expressed in the e frame is dependent on the side 4 q-axis current component, but also on the q-axis component of the rotor loop flux, which is subject to cross coupling. The side 1 reactive power is influenced by the side 4 d-axis current component and also contains the d-component of the rotor loop flux. Compared to a SDFM, the CDFM does not yield a totally independent decoupled relationship between the side 4 current components and the side 1 power components.

### 4.3 Inner current control loop

The use of a voltage source inverter as a control unit requires the implementation of a fast current control loop on side 4. This current control loop ensures that the current values demanded by the outer control loops (power or speed) actually appear on side 4 of the CDFM. The effect of the current loop is analysed in the following.

Resolving eqn. 11 in terms of the rotor current and substituting it in the side 4 flux linkage equation in the e frame gives

\[ \Psi_{dR}^e = -\frac{L_{mB}}{k_1} \Psi_{dR}^e + \frac{L_{mA} L_{mB}}{k_1 L_1} \Psi_{qR}^e + k_3 i_{dR}^e \]  

with the constant

\[ k_3 = L_4 - \frac{L^2_{mB}}{k_1} \]

Replacing eqn. 24 in the side 4 voltage eqn. 7 and considering only the steady state yields

\[ v_{d4}^e = R_4 i_{d4}^e + (\omega_e - \omega_{rAB}) \left[ \frac{L_{mB}}{k_1} \Psi_{dR}^e - k_3 i_{dR}^e \right] \]  

\[ v_{q4}^e = R_4 i_{q4}^e - (\omega_e - \omega_{rAB}) \left[ \frac{L_{mB}}{k_1} \Psi_{dR}^e - k_3 i_{dR}^e \right] \]

\[ + (\omega_e - \omega_{rAB}) \frac{L_{mA} L_{mB}}{k_1 L_1} \Psi_{qR}^e \]

It is enough to consider only the steady state since all the control quantities are DC values in the excitation reference frame. The second terms of eqns. 25 and 26 constitute slight cross coupling effects in the voltage equations, and the third term of eqn. 26 is a slip proportional back EMF term related to the stator flux. The cross coupling terms in eqns. 25 and 26 are an order of magnitude smaller than the back EMF term. Their minor influence upon the control is compensated by the PI-controllers in each axis. However, the third term of eqn. 26 acts as a disturbance to the output of the PI-controller of the q-axis. It is possible to compensate the influence of this back EMF term by choosing high PI-controller gains, but a steady state tracking error will persist [23]. The tracking error can be eliminated by adding a feed forward term to the output of the q-axis controller with the value

\[ \text{feed forward} = (\omega_1 - \omega_{rAB}) \frac{L_{mA} L_{mB}}{k_1 L_1} \frac{\sqrt{2} V_1}{\omega_1} \]  

This also results in easier tuning. The complete current control structure for the CDFM in stator flux orientation is shown in Fig. 7. For clarity the CDFM is symbolised as a single machine.

It should be noted that the cross coupling within the current control loop is not to be confused with the cross coupling within the machine control structure, as covered in Section 4.2. The cross coupling within the current control loop is compensated by the PI-controllers in each axis, but the cross coupling due to the rotor circuit flux remains.

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**Fig. 7**  Stator flux control structure of the CDFM - inner current control loop
Experimental results obtained from the inner current control loop are presented in Figs. 8 and 9. Fig. 8 shows dynamics for a step change in the d-component of $i_d^e$ from 0A to 5A and back to 0A. The q-component is kept at 2A and the speed is approximately 400 rpm. It can be seen that the influence of the cross coupling caused by the rotor loop flux has only a marginal effect on the results. The side 4 current components manipulate the respective components of the side 1 currents in an almost completely direct manner. Since the side 1 active power is proportional to the q-component of $i_d^e$, and the reactive power is proportional to the d-component of $i_d^e$ (as a result of $v_d^e = 0$), a near decoupled step response would also appear in the active and reactive power of side 1.

Fig. 9 shows dynamics for a step change in the q-component of $i_q^e$ from 0A to 3A and back to 0A with the d-component held at 2A. The influence of the cross coupling caused by the rotor loop flux now has an increased effect on the results. The side 1 current components are still largely manipulated by the respective side 4 current components, but the cross coupling in the d-component of $i_d^e$ is clearly recognisable. Active and reactive side 1 power would be affected in the same way.

The reason for the unequal cross coupling effect on the d-axis and q-axis due to the rotor loop flux lies in the positioning of the rotor loop flux vector within the e frame. The d-component and the q-component of $\Psi_R$ do not necessarily need to have equal values, and their step response to a change in the side 4 current components can be different as the simulations in Fig. 6 show.

Despite the cross coupling effect it can still be said that the side 1 active and reactive power are largely controlled by the d-q-components of the side 4 current, as is the case in the SDFM control.

Fig. 9 also displays the speed changes caused by the torque manipulation via $i_d^e$. Depending on the torque balance between the DC machine (set at constant torque) and the CDFM, the machine set accelerates and decelerates.

4.4 Power control loop

When the SDFM is used as a variable speed generator, the inner current control loop is extended with an outer power control loop in a cascaded manner. The d-axis is extended with a reactive power loop and the q-axis with a active power loop. Taking the same approach with the CDFM leads to a control structure where the side 4 d-axis current demand is the output of the reactive power PI-controller, and the side 4 q-axis demand value is the output of the active power PI-controller. Active and reactive power components are calculated in the stationary frame a by measur-
ing side 1 current and voltage (see the power equations in the Appendix). The DC machine acts as a prime mover to the system.

Fig. 10 shows experimental dynamics for a step in the side 1 reactive power demand value from 1.7kVAR to 0.5kVAR and back to 1.7kVAR. It can be seen that with an outer power control loop side 1 active and reactive power can be controlled totally independently of each other. At the same time, the side 4 current component \( i_{d4} \) of the inner loop, shown in Fig. 10, changes accordingly to eqn. 23 and \( i_{q4} \) remains almost unaffected from the step change, confirming the minor influence of the cross coupling effect in this case. Regarding the reactive power flow in the CDFM, the reduced magnetising reactive power supplied via side 1 during the step is compensated by an increased magnetising reactive power supplied via side 4, expressed by the increased magnitude in \( i_{d4} \).

Fig. 11 displays the experimental results for a step in the side 1 active power demand value from -1kW to 4kW and back to -1kW (the generating, DC machine acts as prime mover). Again, active and reactive power show no sign of cross coupling. Now \( i_{q4} \) performs a step change to justify eqn. 22. As seen already in Fig. 9, the cross coupling effect due to the rotor circuit is more pronounced in the d-axis of the e frame. The d-component of \( i_{q4} \) shows a slight change at the step in Fig. 11.

With the implementation of an outer active and reactive power control loop, the side 1 active and reactive power can be controlled independently of each other. The current components of the inner loop are nearly proportional to the power components, with only a slight cross coupling influence compensated by the outer power control loop.

4.5 Speed control loop

This Section considers the behaviour of a speed control loop for the CDFM. To obtain the developed torque of the CDFM for stator flux orientation, the torque equation has to be developed as a function of the stator flux linkage and the side 4 current vector. Resolving eqn. 11 in terms of the rotor current and substituting it in eqn. 33 yields

\[
T_{eAB} = -\frac{3}{2} \left( p_A \frac{L_{mA}}{L_1} \Psi_{qR} + p_B L_{mB} i_{d4} \right)
\]

Carrying out the cross product and considering the constraint of \( \Psi_{qR} = 0 \) results in the following torque equation

\[
T_{eAB} = -\frac{3}{2} \left\{ \left( p_A \frac{L_{mA}}{L_1} \Psi_{e1} + p_B L_{mB} i_{d4} \right) \Psi_{qR} + \left( p_A + p_B \frac{L_{mA} L_{mB}}{k_1 k_1} \Psi_{d1} - p_B \frac{L_{mB}}{k_1} \Psi_{dR} \right) i_{q4} \right\}
\]

(28)

This equation looks rather complicated and does not give a straightforward relationship between \( i_{q4} \) and the torque at first sight. Both side 4 current components appear in eqn. 28, which indicates that the torque may be affected by either a change in \( i_{d4} \) or \( i_{q4} \). However, if \( \Psi_{qR} \) is kept at a constant value, then the term

\[
\left( p_A \frac{L_{mA}}{L_1} \Psi_{e1} + p_B L_{mB} i_{d4} \right) \Psi_{qR}
\]

remains constant. No cross coupling is involved since \( \Psi_{qR} \) would only be affected by a change in \( i_{d4} \).

The remaining term in eqn. 28 is governed by \( i_{q4} \), but the d-component of the rotor loop flux is present, which is subject to cross coupling caused by \( i_{d4} \). This cross coupling has no influence in this case because \( i_{d4} \) would take a certain value to give a set torque, despite the effect in \( \Psi_{qR} \).
Consequently, for a fixed value of $i_{dq}$, the torque developed by the CDFM in the stator flux reference frame is manipulated by the q-component of $i_q^*$, despite cross coupling caused by the rotor circuit. As long as saturation is avoided, the larger the set value for $i_{dq}$, the more reactive power is supplied by terminal 4 and the less via side 1. Additionally, the larger the magnitude of $i_{dq}$, the less magnitude of $i_{q}$ is necessary to develop a certain torque value. However, this effect is only minor.

Extending the q-axis of the inner current control loop with an outer speed loop, so that the output of the PI-speed controller gives the side 4 q-axis current demand value, and setting the side 4 d-axis current demand value to a constant value allows the CDFM to be applied to speed control applications. The speed is obtained from position measurements with an incremental encoder.

Experimental results of a speed control loop at no-load are shown in Fig. 12. It can be seen that the q-component of $i_q^*$ varies, depending on the torque demand value set by the outer speed loop controller to follow the desired speed ramp. The d-component remains unaffected.

The last graph in Fig. 12 displays the rotor voltage and shows clearly the change in frequency and magnitude of the rotor voltage for varying speed. The closer the speed approaches machine A synchronous speed, the more the rotor voltage magnitude and frequency reduces.

5 Conclusions

This paper presents theoretical and experimental results of a stator flux oriented control scheme. This scheme has not previously been applied to the CDFM. In particular, the influence of the closed rotor circuit loop on the control structure has been investigated. It is found that the presence of the closed rotor circuit loop introduces a cross coupling between the d-axis and the q-axis in the stator flux reference frame. However, the cross coupling has only a minor effect on the overall control concept. It is therefore possible to achieve decoupled control of active and reactive power in the CDFM in a manner similar to that established for the SDFM. In comparison to a previous field oriented control method for the CDFM, the scheme in this paper is independent of the CDFM machine combination.

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8 Appendix

Stator side 1 active and reactive powers are calculated in terms of space vector components (non-power invariant transformation) from the side 1 voltage and current as

\[ P_1 = \frac{3}{2} \left( v_{d1}^* i_{d1} + v_{q1}^* i_{q1} \right) \]

\[ = \frac{3}{2} \left( v_{d1}^* i_{d1} + v_{q1}^* i_{q1} \right) = \frac{3}{2} v_{q1}^* i_{q1} \]  

\[ Q_1 = \frac{3}{2} \left( v_{q1}^* i_{d1} - v_{d1}^* i_{q1} \right) \]

\[ = \frac{3}{2} \left( v_{q1}^* i_{d1} - v_{d1}^* i_{q1} \right) = \frac{3}{2} v_{q1}^* i_{d1} \]  

The torque of machine A expressed in the e frame, involving the stator flux linkage, can be written in space vector form as

\[ T_{eA} = \frac{3}{2} \frac{p A L_{mA}}{L_1} \left( \Psi_1^* \times i_2^* \right) \]

and the torque for machine B as

\[ T_{eB} = -\frac{3}{2} \frac{p B L_{mB}}{L_1} \left( i_1^* \times i_2^* \right) \]

Combining both torque equations gives for the CDFM torque

\[ T_{eAB} = T_{eA} + T_{eB} \]

\[ = -\frac{3}{2} \left( \frac{p A L_{mA}}{L_1} \Psi_1^* + p B L_{mB} i_1^* \right) \times i_2^* \]