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Characterization of Dual Stator Induction Machines

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Abstract

This paper presents a method to characterize a dual stator induction machine (DSIM). It combines a new method of parameter identification for DSIMs with the known characterization method used for three phase machines. Classical characterization of three phase machines can also be applied to DSIMs but requires assumption of leakage distribution between stator and rotor. Usually it is assumed, that rotor and stator leakage inductances are equal. The method described here requires no such assumption. It is possible to measure stator and rotor parameters individually and not just the sum of stator and rotor parameters as for three phase machines. To achieve this, an uneven current share is used between both stator systems and the machine is operated in idle or blocking mode. In idle mode the main inductance can be measured, wheras in blocking mode rotor leakage inductance and rotor resistor are identified. Stator resistor and stator leakage inductance can be identified in any operating point. A DC measurement is not required anymore. The result of this approach is a more accurate model for DSIMs with precise parameters. This is shown by a complete characterization of a prototype machine. It shows that leakage inductances differ by a large factor between stator and rotor. It also turns out that the stator leakage inductance depends on the operating point.

Keywords: AC-motor, asynchronous (induction) motor, control system, electric drive, EV (electric vehicle)

1 Introduction

Power of an electric machine is set by both supplied voltage and maximum current. Typically those are limited by the inverter. For certain voltage levels there are only semiconductors available with a certain maximum current. When the desired power exceeds both levels, a multi phase system can be an option because power is also scaled with the number of phases. There are mutlti phase topologies with common or separated star connections. Here a so called dual stator induction machine (DSIM) is used. A DSIM needs two three phase inverters and a more complex control structure, but it also has some advantages besides a higher power compared to a three phase system. If one stator systems is broken, a fail-safe operation might be possible with the remaing three phase system [1]. Due to the separated star connections, only four current sensors are required instead of five for a common star connection. The DC ripple can be reduced if both stator systems are switched interleaved, which leads to a smaller DC capacitor [1],[2]. DSIMSs with 30° between both stator system have a smaller torque ripple compared to three phase machines [2],[3],[4]. Another advantage is the improved parameter identification which is presented in this paper.

Prior to this paper, the system equations of a DSIM and an approach for parameter identification in a random operating point were presented by the author [5]. It was shown, that stator values could be identified by applying a different amount of current to both stator systems. Different approaches were presented to identify the rotor values with assumptions of the rotor leakage inductance. Those assumptions were based on experience from three phase machines. Since it is not obvious, that those assumptions are also valid for dual three phase machines, a more accurate measurement procedure is presented here. Idle and blocking measurements are used as known from characterization of three phase machines [6].

2 Dual Stator Induction Machine System Equations

The system equations of a DSIM in a fixed reference frame are [5]:

$$\underline{u}_{\mathrm{SI}} = R_{\mathrm{S}}\underline{i}_{\mathrm{SI}} + j\omega_{\mathrm{S}}L_{\mathrm{S}\sigma}\underline{i}_{\mathrm{SI}} + j\omega_{\mathrm{S}}L_{\mathrm{H}}\underline{i}_{\mathrm{M}} \tag{1}$$

$$\underline{u}_{\mathrm{SII}} = R_{\mathrm{S}}\underline{i}_{\mathrm{SII}} + j\omega_{\mathrm{S}}L_{\mathrm{S}\sigma}\underline{i}_{\mathrm{SII}} + j\omega_{\mathrm{S}}L_{\mathrm{H}}\underline{i}_{\mathrm{M}} \tag{2}$$

$$0 = \frac{R_{\mathrm{R}}}{s}\underline{i}_{\mathrm{R}} + j\omega_{\mathrm{S}}L_{\mathrm{R}\sigma}\underline{i}_{\mathrm{R}} + j\omega_{\mathrm{S}}L_{\mathrm{H}}\underline{i}_{\mathrm{M}} \tag{3}$$

$$s = \frac{\omega_{\mathrm{S}} - p\omega_{\mathrm{M}}}{\omega_{\mathrm{S}}} \tag{4}$$

It is assumed, that both three phase systems and all phases are equal. Iron losses are not considered. Windings shall be sinusoidally distributed. Equations (1) - (3) can be visualized in an equivalent circuit diagram as seen in fig. 1. The stator and rotor parameters can be combined to complex values $\underline{Z}_{\mathrm{S}}$ and $\underline{Z}_{\mathrm{R}}$.

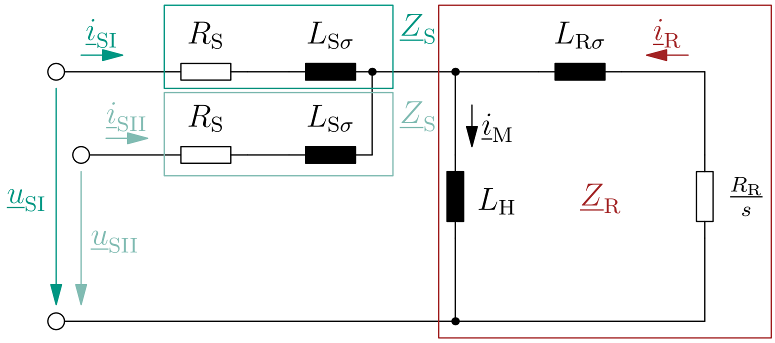

Figure 1: DSIM equivalent circuit diagram

3 Characterization

The parameter identification method described here uses an uneven current share between both three phase systems. This is done by setting a different set value for the current controller of both three phase systems. The resulting difference in stator voltages and currents can be used to identify the parameters.

3.1 Stator Parameters

The equation for the stator parameters is derived by subtracting both stator equations (1) and (2) from each other, solving for the impedance and dividing it into real and imaginary part:

$$\underline{Z}_{\mathrm{S}} = \frac{\underline{u}_{\mathrm{SI}} - \underline{u}_{\mathrm{SII}}}{\underline{i}_{\mathrm{SI}} - \underline{i}_{\mathrm{SII}}} = (R_S + j\omega_S L_{\mathrm{S}\sigma}) \tag{5}$$

$$R_{\mathrm{S}} = \mathrm{Re}\{\underline{Z}_{\mathrm{S}}\} \tag{6}$$

$$L_{\mathrm{S}\sigma} = \frac{1}{\omega_{\mathrm{S}}}\,\mathrm{Im}\{\underline{Z}_{\mathrm{S}}\} \tag{7}$$

Stator resistor and stator leakage inductance can be identified in any operating point and indipendently from the rotor parameters. This is only possible for DSIMs with two identical stator systems. If they are different, there are different leakage inductances and a mutual stator leakage inductance so that additional tests are required [7].

3.2 Rotor Parameters

In a similar way the rotor parameters can be identified by building a closed loop over one stator and the rotor and solving for the rotor impedance:

$$\underline{Z}_{\mathrm{R}} = \frac{\underline{u}_{\mathrm{SI}} - \underline{Z}_{\mathrm{S}}\underline{i}_{\mathrm{SI}}}{\underline{i}_{\mathrm{SI}} + \underline{i}_{\mathrm{SII}}} = \frac{j\omega_{\mathrm{S}}L_{\mathrm{H}}(\frac{R_{\mathrm{R}}}{s} + j\omega_{\mathrm{S}}L_{\mathrm{R}\sigma})}{\frac{R_{\mathrm{R}}}{s} + j\omega_{\mathrm{S}}L_{\mathrm{H}} + j\omega_{\mathrm{S}}L_{\mathrm{LR}\sigma}} \tag{8}$$

One issue is, that there are three parameters to be identified. Therefore it is not possible to identify them accurately in a random operating point. Here idle and blocking measurements are used to identify all three rotor parameters without any prior assumption. Those operating points can be reached by either blocking the machine or spinning it at idle speed on a test bench.

3.2.1 Idle Measurement

In idle mode the slip becomes zero and eq. (8) can be simplified so that the main inductance $\mathrm{L_H}$ can be measured in this operating point:

$$s := 0 \tag{9}$$

$$\underline{Z}_{\mathrm{R,IDL}} = j\omega_{\mathrm{S}}L_{\mathrm{H}} \tag{10}$$

$$L_{\mathrm{H}} = \frac{1}{\omega_{\mathrm{S}}}\,\mathrm{Im}\{\underline{Z}_{\mathrm{R,IDL}}\} \tag{11}$$

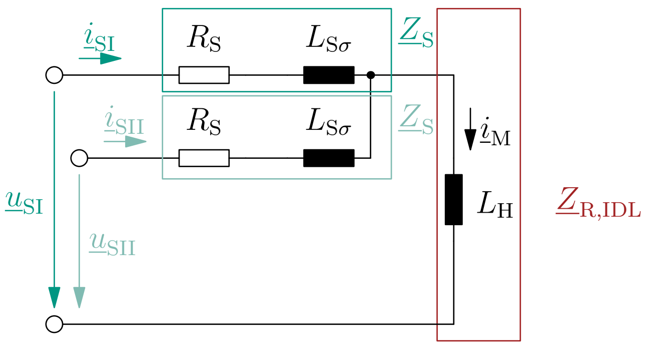

Figure 2: DSIM equivalent circuit diagram idle measurement

3.2.2 Blocking Measurement

When blocking the rotor, approximately all current flows through the rotor because the main inductance is considerably larger than the leakage inductance. The rotor resistor $\mathrm{R_R}$ and rotor leakage inductance $\mathrm{L}_{\mathrm{R}\sigma}$ can then be measured:

$$s := 1 \tag{12}$$

$$j\omega_{\mathrm{S}}L_{\mathrm{H}} >> j\omega_{\mathrm{S}}L_{\mathrm{R}\sigma} + R_{\mathrm{R}} \tag{13}$$

$$\underline{Z}_{\mathrm{R,BLK}} = R_{\mathrm{R}} + j\omega_{\mathrm{S}}L_{\mathrm{R}\sigma} \tag{14}$$

$$R_{\mathrm{R}} = \mathrm{Re}\{\underline{Z}_{\mathrm{R,BLK}}\} \tag{15}$$

$$L_{\mathrm{R}\sigma} = \frac{1}{\omega_{\mathrm{S}}}\,\mathrm{Im}\{\underline{Z}_{\mathrm{R,BLK}}\} \tag{16}$$

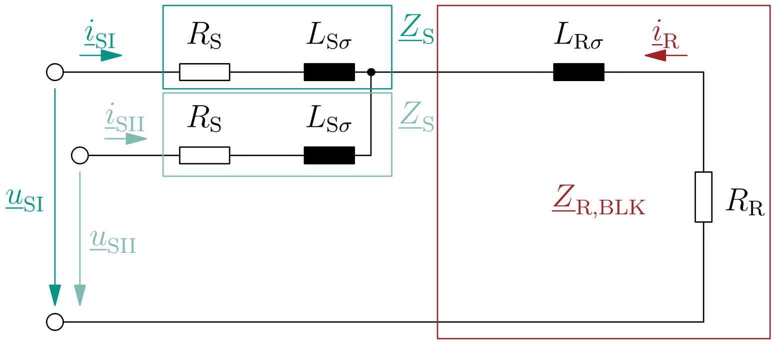

Figure 3: DSIM equivalent circuit diagram blocking measurement

4 Measurement Results

A prototype machine was built and its parameters were identified over a range of current and for various frequencies using the method descriped before.

4.1 Measurement Setup

In order to verify the parameter identification, an excisting design of a three phase machine was equipped with a dual stator winding. The key data of the machine can be found in table 1. All measurements were performed on a test bench for electrical machines. The setup is displayed in fig. 4.

Table 1: Machine data

Design voltage	325 V
Maximum current (rms)	250 A
Maximum speed	12000 rpm
Number of pole pairs	2
Active length	160 mm
Active diameter	220 mm

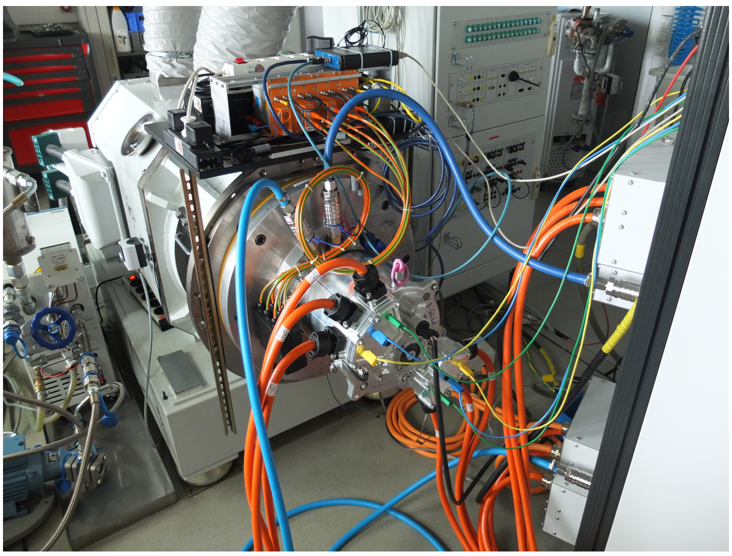

Figure 4: Measurement setup

4.2 Identified Parameters

For a first characterization of the machine, the current share was set so that only one three phase system was supplied and the other one was just used to measure the voltage across the main inductance. The identified parameters are shown in fig. 5-9. The resistors are in the expected range and the stator resistor is close to the control value (47mΩ) which was determined by a DC measurement. There are some variations in the resistance measurement, which can be traced back to temperature effects. At high currents, the measurement had to be interrupted and started again once the machine had cooled down. The resistors were referred to 25°C, however the measured temperature might not be accurate. Due to thermal reasons, the measurement can only be done for a short period of time. During this time the temperature is not the same across the machine. It can be noticed, that the leakage inductance on rotor and stator side are not equal as typically assumed when characterizing three phase machines. In fact they differ by a factor of up to 4. It is also interesting, that the stator leakage inductance is different depending on the operating point. The curves of the stator leakage inductance measured in idle mode look similar to the curves of the main inductance which saturates with higher currents. This indicates that the leakage inductance is also depending on saturation. For the blocking measurement the stator leakage inductance saturates less where as the rotor leakage inductance increases with increasing current. There is a single measurement point at around 230A at 30Hz which seems to be an outlier and can be considered invalid.

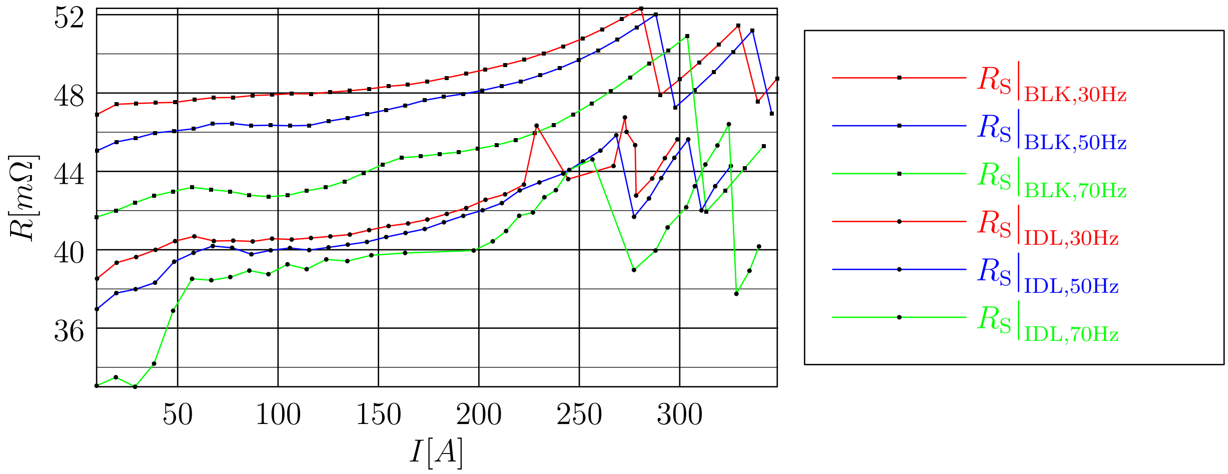

Figure 5: Stator resistor

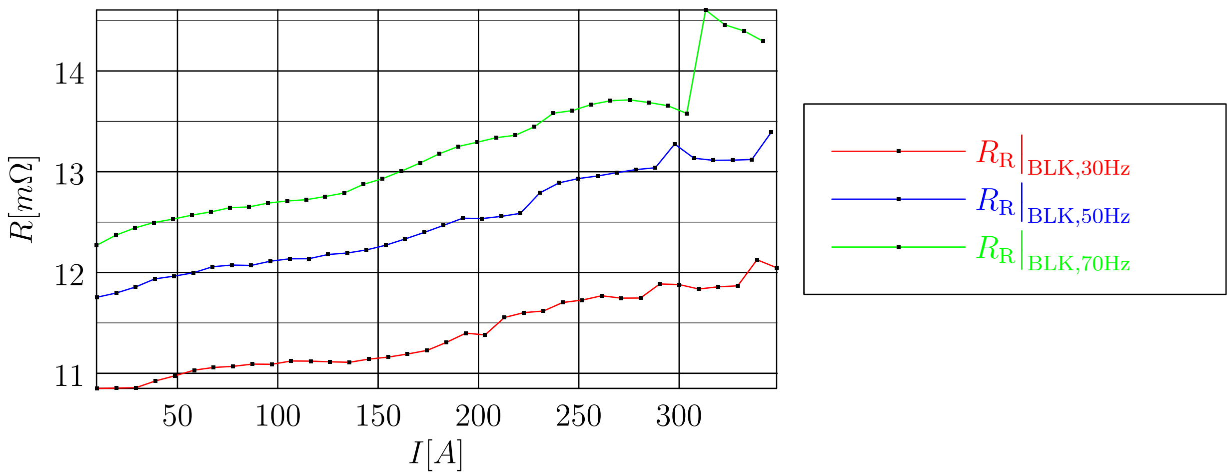

Figure 6: Rotor resistor

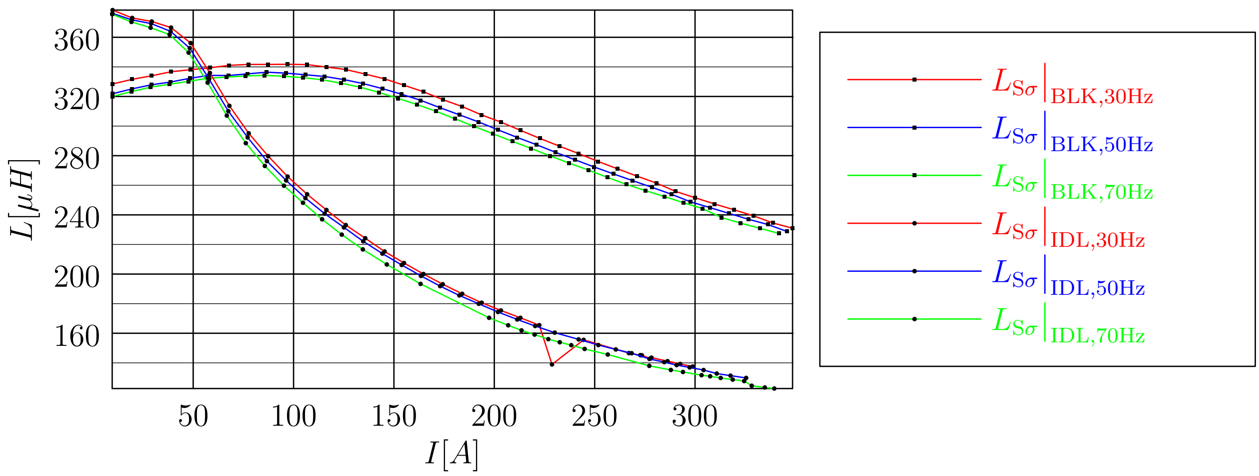

Figure 7: Stator leakage inductance

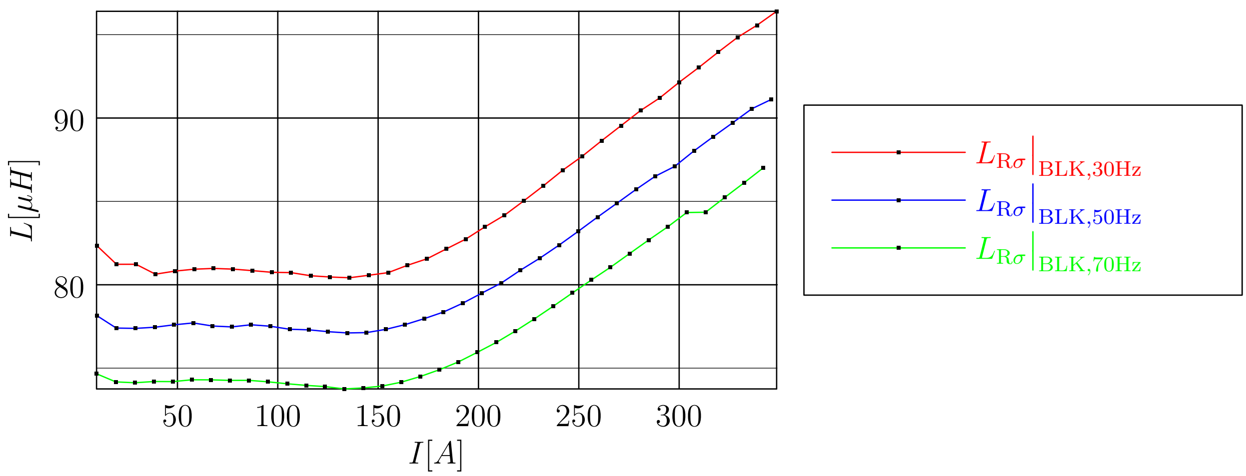

Figure 8: Rotor leakage inductance

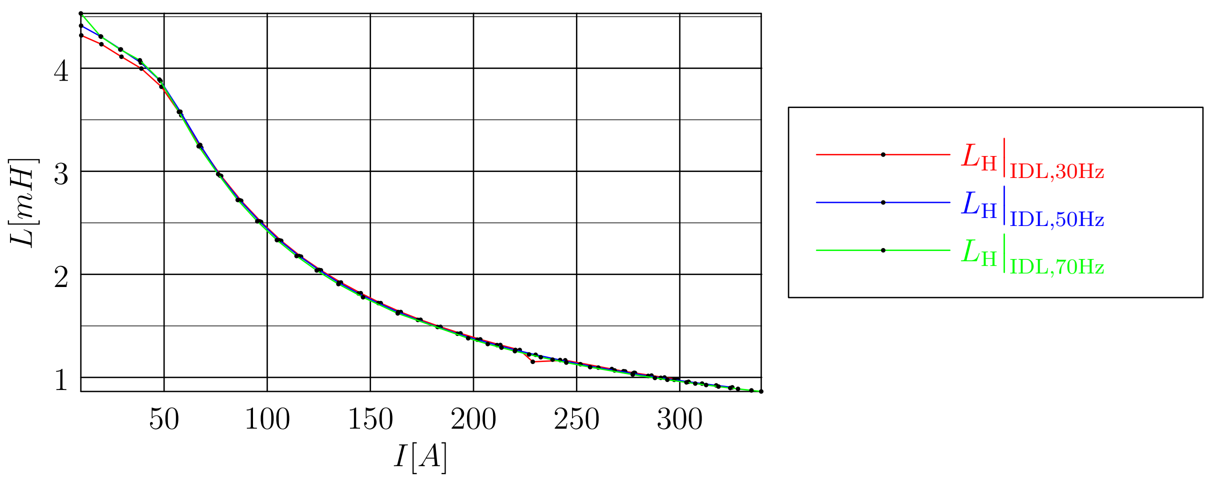

Figure 9: Main inductance

5 Conclusion

It was shown that the assumptions made for characterization of three phase machines seem not to match DSIMs. Since parameters can be identified more precisely than compared to a three phase machine and stator values can be measured in any operating point, this might lead to an advantage in torque accuracy and dynamic in a future control system.

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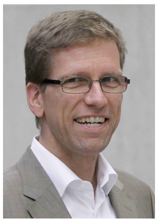

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