Frequency Domain Identification of Synchronous Machines by Multisine Excitation

Thomas J. Vyncke*, Frederik M.L.L. De Belie*, René K. Boel*,
Jan A.A. Melkebeek*, Yonghua Cheng† and Philippe Lataire†

*Department of Electrical Energy, Systems and Automation (EESA), Ghent University (UGent)
Sint-Pietersnieuwstraat 41, B-9000 Gent, Belgium
e-mail: Thomas.Vyncke@UGent.be   phone: +32 (0)9 264 3442   fax: +32 (0)9 264 3582

†Dept. Electric Engineering and Energy Technology (ETEC), Vrije Universiteit Brussel (VUB)
Pleinlaan 2, B-1050 Brussels, Belgium

Abstract—**Modelling and identification of synchronous machines has attracted much attention during the past decades. Although the standstill frequency response (SSFR) method has become standardized (IEEE Std. 115) it has some disadvantages (e.g. it is a time consuming method). To overcome these, the use of multisine excitation has been proposed in the literature.**

In this paper the use of multisine excitation for the frequency domain identification of synchronous machines is discussed. The selection of the applied excitation signal and the measurement set-up are dealt with. The obtained frequency domain data can be used in different applications, examples are given in this paper. Furthermore the extraction of a parametric model from the nonparametric frequency domain data is discussed. Measurement results and their processing are discussed for different types of synchronous machines to demonstrate that multisine frequency domain identification can be applied to extract the parameters (inductances) of permanent magnet synchronous machines.

These parameters can then be used to study the influence of saturation or can be applied in the simulation and control of permanent magnet synchronous machines.

I. Introduction

Modelling and identification of synchronous machines has been an interesting field of research for decades and the importance of the subject is reflected by the vast number of publications on these subjects. Almost every synchronous machine model for simulation and control is based on the two-axis theory by Blondel and Park and most identification procedures are aimed at estimating the parameters defined by these models. The standstill frequency response (SSFR) method [1] for estimating the synchronous machine parameters was standardized (IEEE Std. 115), focussing mainly on wound-rotor synchronous machines and large generators.

Standstill frequency response methods compare favourably to time domain methods (such as short-circuit and standstill time-domain tests) as they allow for an accurate determination of high order synchronous machine models with low risk for the machine under test and with a relatively simple measurement set-up. However, some drawbacks are associated with the SSFR test. Most notable are the limited excitation power and the time consuming nature of the SSFR. To overcome these problems the use of a switching converter and a broadband excitation signal are proposed in [2]. The broadband excitation, e.g. a multisine, allows a considerable reduction in measurement time as all desired frequencies are simultaneously excited.

The thus obtained frequency domain identification and the derived parameters are often used (in case of a large wound-rotor generator) for power system stability simulations. The same frequency domain data can be used for the simulation and control of a synchronous machine in a power electronics drive, though a different representation might be desirable.

Although permanent magnet synchronous machines (PMSMs) have had a growing market share for years, the use of these methods for PMSMs and especially smaller machines has not received as much attention. In this paper the multisine excitation and frequency domain identification of PMSMs at different levels of saturation are discussed.

The paper is organized as follows: in II the nonparametric identification procedure is discussed, different applications and possibilities to extract parametric information are given in III, measurement results are discussed in IV.

II. Frequency Domain Identification

A. Measurement set-up

The three terminals of the synchronous machine are connected to a three-phase linear amplifier. The amplifier is a PAS 15000 mains simulator from Spitzenberger-Spies with a rating of 15kVA (5kVA per phase). The three terminal voltages and two line currents are acquired with an Agilent VXI measurement system. Either the d- or q-axis is aligned with one of the three stator phases and the rotor is mechanically locked in this position. An identification voltage signal is impressed at the aligned phase, the voltages of the other two phases are used to apply a DC voltage bias along the aligned or perpendicular axis and thus to control the DC current along these axes. The applied identification voltage signal is a user-defined voltage waveform that can be stored in the oscillator memory of the linear amplifier. At this moment the lowest achievable frequency with the oscillator is 10 Hz, with a separate function generator this limit can be reduced. The highest achievable harmonic frequency for a given fundamental frequency is determined by the size of the oscillator memory.

B. Excitation Signal

1) Type of Signal: The use of a broadband excitation signal allows a faster frequency domain identification compared to a stepped frequency sine, as discussed in [2], [3]. Within this class of signals the multisine signal is an excitation of choice
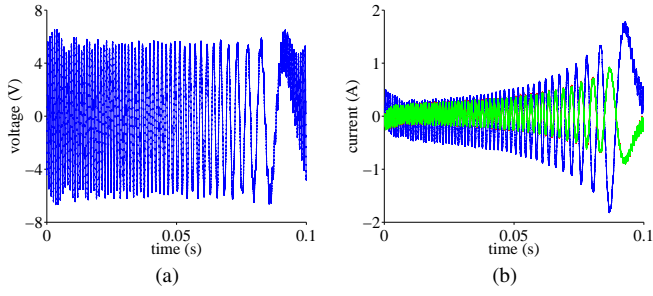
Fig. 1. Measured excitation voltage (a) and measured current response (b) in the time domain
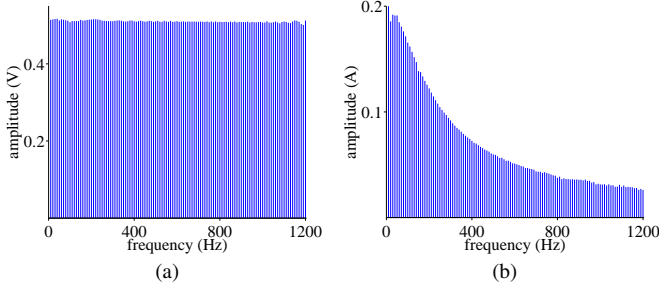

Fig. 2. FFT: excitation voltage (a), current response (b) (10 Hz resolution)

Fig. 3. Bode plot: Nonparametric form of the impedance along the d-axis of a synchronous machine (blue cross). Fitting the Bode plot with a linear RL circuit gives a parametric model (red line).

in the identification of the frequency response function of linear systems [3]. Multisine signals are linear combinations of sinusoids,

$$u(t) = \sum_{k=1}^{F} A_k \cos(2\pi f_k t + \phi_k) \qquad (1)$$

where F is the number of harmonics in the signal $u(t)$ and A_k, f_k and ϕ_k are the amplitude, frequency, and phase respectively of the kth harmonic. The phases ϕ_k of the sinusoids in the multisine $u(t)$ are usually chosen to yield the lowest crest factor ($CF(u) = \frac{u_{peak}}{u_{RMS}}$), maximizing the signal-to-noise ratio of the measurement for a given peak value of the signal.

Multisines are, unlike the often used swept sine identification signals, band-limited which is advantageous as aliasing during sampling is avoided. Furthermore the constrained frequency range offers a possibility to check for nonlinear effects. As multisines are also deterministic and periodical their use offers substantial advantages (e.g. avoiding leakage in the frequency domain data) compared with a random noise identification signal. Finally the user is free to define the frequency spectrum and the frequency grid and has the possibility to choose the amplitudes of the sinusoids in the multisine.

2) Multisine Phases: Three options are available for the phases: random, Schroeder phases or determined by an optimization procedure [3]. The Schroeder phases are not optimal but give good results for flat amplitude spectra of multisines which are band-limited and have a successive set of excited frequencies. Under these conditions the CF for Schroeder phases typically is about 1.7 and thus below typical values for random phases but slightly higher than typical values for the optimization, where an CF of 1.4 can be achieved (or even lower with certain optimization techniques which add spectral 'snow' lines to further compress the signal). The randomness of the first option makes it less suited for automation of the
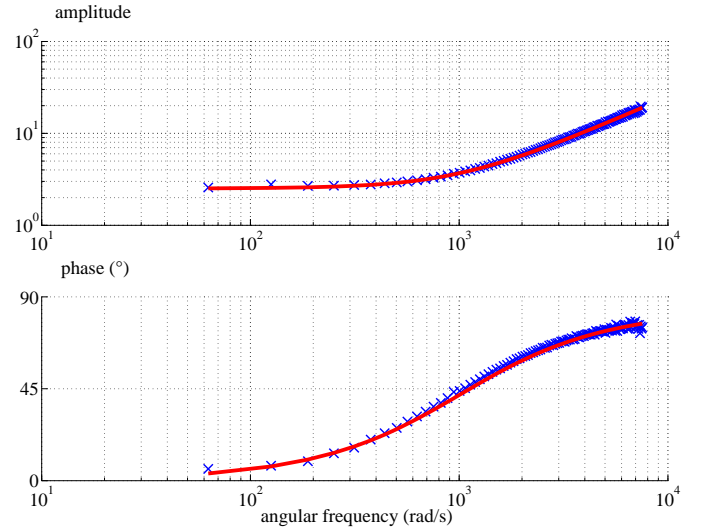
entire identification process. The iterative nature and large computational burden of the last option make it less attractive in terms of time reduction and automation of the process. As such we chose to use a Schroeder multisine where the phases are deterministic and given by an analytical formula,

$$\phi_k = \frac{-k(k-1)\pi}{F} \qquad (2)$$

where $f_k = l_k f$ and $l_k \in \mathbb{N}$.

One period of a voltage signal used in measurements, with 120 frequencies ($F = 120$) from 10 to 1200 Hz ($f = 10$ Hz, $l_k \in [1, 120]$) and a flat amplitude spectrum ($A_k = A$), is shown in Figure 1(a). As is clear from the figure, it is a well-compacted waveform. The fact that it is well-compacted is clear from the low $CF = 1.68$ as well.

In the case of a flat spectrum and randomly chosen phases the CF would be higher with typical values in the range of 2.45 to 5.3 (10000 realisations of the random-phase multisine gave an average CF of 3.32 with standard deviation 0.35). To ensure that the current response is measured with a sufficient accuracy, the selected voltage amplitude spectrum could be chosen logaritmic instead of flat to achieve a more flat current amplitude spectrum. In this case the CF for Schroeder phases is 1.92 whereas the characteristic values for the CF of random-phase multisine remain virtually unchanged. Clearly the relative advantage of using Schroeder phases declines when deviating from flat amplitude spectra.

C. Data processing

The excitation voltage supplied with the amplifier and the current response from the machine (shown in Figure 1) are measured and digitized. The data is transformed to the frequency domain by a fast fourier transform (FFT). The frequency domain amplitude image of the measured voltage and current are shown in Figure 2. From the frequency domain representation of the voltage and current a nonparametric model of the synchronous machine impedance in the d- or q-axis is derived directly. This frequency response function is shown in Figure 3 as a Bode plot.

III. APPLICATIONS FOR THE FREQUENCY DOMAIN DATA

As mentioned earlier, the typical application for SSFR data has been the determination of the transient and sub-transient reactances and time constants of large wound-rotor synchronous generators for power system stability studies. The information provided by the frequency response function can however be used in other applications as well. Some of the applications are discussed in the next section, with a focus on PMSMs. The list of given applications is not exhaustive, the use of frequency domain identification (though not by using a broadband signal) to identify the equivalent circuit parameters of induction machines for example is discussed in [4].

A. Study of impedances at higher frequencies

With sensorless control of PMSMs at standstill or low speeds, a high frequency voltage or current is injected. The rotor position is then determined from the measured response. To obtain the rotor position, some of these methods require the knowledge of the impedance of the machine. The multisine frequency domain identification can be used to determine the impedance of the machine at these higher frequencies in a nonparametric form or if necessary in a parametric form as elaborated upon further.

B. Identification of transfer functions for d- and q- axis

The 'classical' SSFR tests (as well as other identification methods) are aimed at identifying a two-port model for the d-axis (with one port for the armature variables and one port for the field variables) and a one-port for the q-axis. The synchronous machine is then represented by the following equations [1]

$$\Delta\Psi_d(s) = G(s)\Delta e_{fd}(s) - L_d(s)\Delta i_d(s) \quad (3)$$

$$\Delta\Psi_q(s) = -L_q(s)\Delta i_q(s) \quad (4)$$

with Ψ_d and Ψ_q the direct and quadrature axis stator flux linkages, i_d and i_q the corresponding stator currents, e_{fd} the field voltage and Δ a perturbation about some operating point. Estimators are then used to determine the parameters of three transfers functions $G(s)$, $L_d(s)$ and $L_q(s)$. As the identification of permanent magnet synchronous machines is the primary aim of this paper, the estimation of the armature to field transfer function $G(s)$ is not considered.

In [2], [5] a MIMO multisine frequency domain test is used to estimate individual d- and q-axis models for a wound-rotor synchronous machine at several magnetization levels which allows to detect the variation of the different parameters as a function of saturation. The idea that different parameter sets are estimated at different levels of excitation with the SSFR is recognized as well in [6].

In this paper, the nonparametric multisine frequency domain identification method described in the previous section is applied to PMSMs. With the frequency domain information the parameters of the transfer functions for the d- and q-axis at different levels of saturation are estimated.

1) Order of the model: The simplest parametric model to describe the direct axis operational inductance $L_d(s)$ or the quadrature axis operational inductance $L_q(s)$ is a first order model consisting of an inductance in series with a resistance. By fitting this model to the Bode plot for different values of DC bias we can obtain the inductance as a function of the

stator current. As discussed in [1], [2] higher order models with equivalent damper windings can be used to fit the data.

2) Method of fitting: The inductances in the measurement results are estimated from the nonparametric frequency domain data by a least squares method (part of the Matlab Optimization Toolbox) where the resistive part has been determined from a DC-measurement. Several other possibilities, including the maximum likelihood (ML) estimation as described in [2], exist for the estimation of the parameters. For the first order model used at the moment and by providing the resistance measurement, the least squares method is sufficiently accurate. The influence of the starting values for the estimation has been evaluated and was satisfying. However, other estimators should be explored in further research.

A global estimator of all the parameters in one global model including saturation could be desirable, but this is not the focus of this paper (for a discussion on this topic see [2], [5]).

C. Study of cross-saturation

The cross-saturation between d- and q-axis is often neglected in identification procedures. It is however of interest for (sensorless) control of PMSMs, especially in interior permanent magnet synchronous machines (IPMSM) [7]. With the measurement set-up previously described it is possible to add a DC bias current in the magnetic axis orthogonal to the aligned axis, thus obtaining the frequency domain identification of the impedance as a function of the two current components. The data can be used for simulation and control of PMSMs or for the verification of research results on cross-saturation.

IV. MEASUREMENT RESULTS

The method described in the previous sections of this paper has been applied on different machines: a surface PMSM and two types of interior PMSM. The frequency response functions for d- and q-axes have been fitted on the first order model and the measurement results show the variation of the inductance with saturation (application *B*). Furthermore some results on the study of cross-saturation for one machine are given as well (application *C*).

A. Surface permanent magnet synchronous machine

A surface permanent magnet synchronous machine (SPMSM) from Siemens (type: 1FT6084 8AC71, optimum speed = 2000 rpm, rated current = 8.3 A, N_p = 4) was tested. The identified inductances for both axes are shown in Figure 4 for different levels of saturation. As is clear from the figure, the influence of saturation is rather small. Variations of the q-axis inductance are less than 10% for a q-axis current equal to the rated current and variations of the d-axis inductance are less than 10% for a d-axis current of half the rated current.

The inductance variations along both axes correspond to what is expected on a physical basis: for the d-axis a negative bias $I_{DC} < 0$ will weaken the field of the permanent magnets and as such reduce the saturation and result in a higher inductance. A positive value of DC bias ($I_{DC} > 0$) will have the opposite effect. For a q-axis current the field due to the current is perpendicular to the permanent magnet field and the saturation effect is symmetric. The estimated inductances show that the machine has a low saliency effect. The measured values agree with the rotating field inductance according to the manufacturer, corresponding with a value of 15.6 mH.
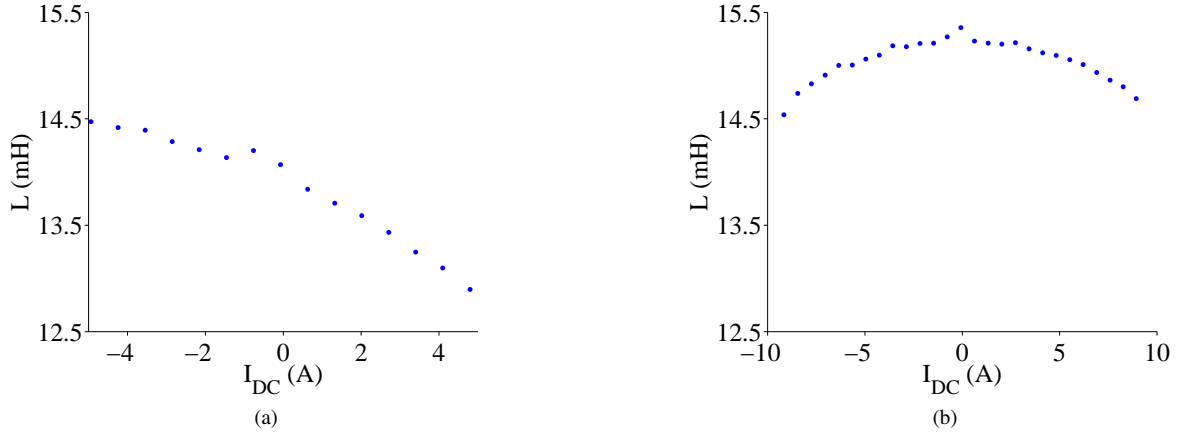
Fig. 4. SPMSM, inductance variation with saturation: d-axis (a), q-axis (b)

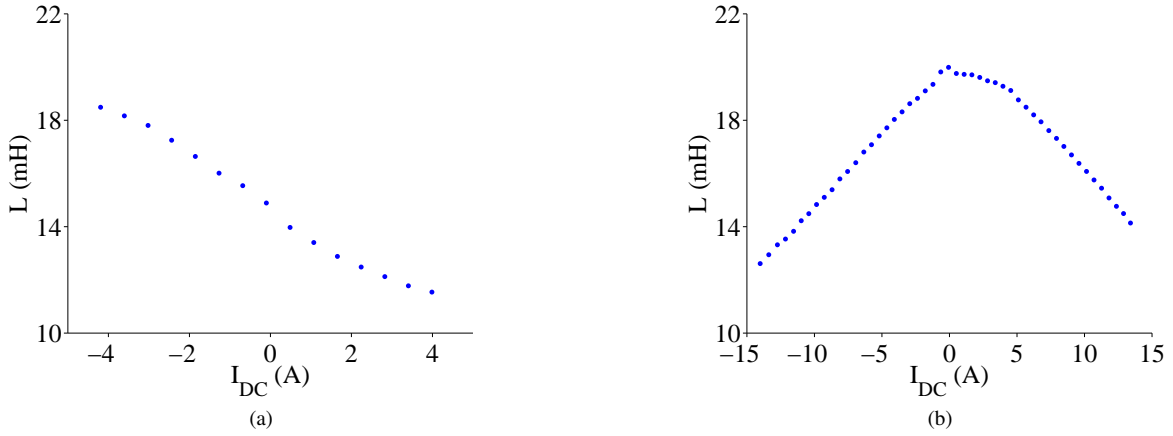

Fig. 5. Parvex IPMSM, inductance variation with saturation: d-axis (a), q-axis (b)

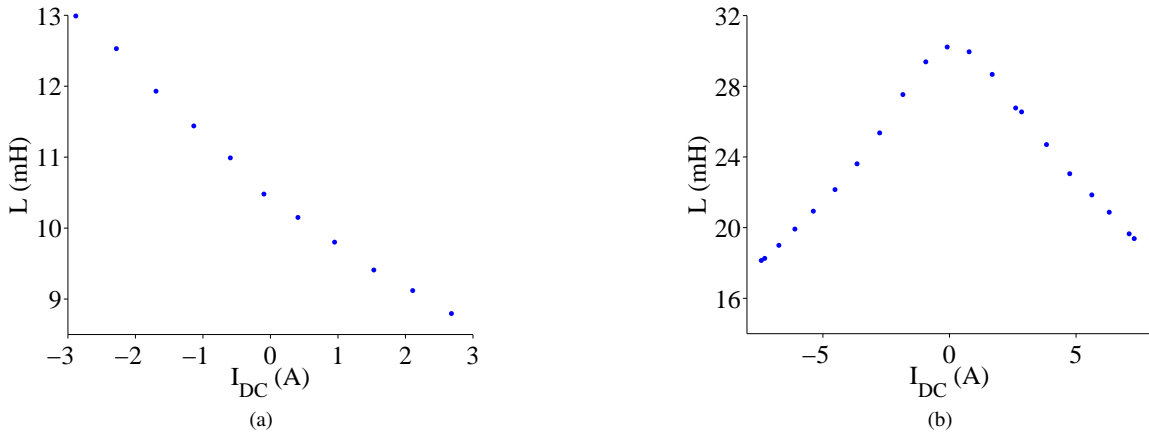

Fig. 6. Kollmorgen IPMSM, inductance variation with saturation: d-axis (a), q-axis (b)

B. Interior PMSM

The identified inductances for both axes of a Parvex IPMSM (type: HV820EZR9000, base speed= 2390 rpm, $I_{OS1} = 12.3$ A, $N_p = 5$) are shown in Figure 5. Noticeable saliency and a large influence of saturation (variations of the order of 30%) can be seen in the figure.

The identified inductances for both axes of a Kollmorgen IPMSM (type: BH-622-B-43 Goldline, speed = 4000 rpm, stall current cont. = 8.4 A RMS, N_p=3) are shown in Figure 6. Here a high saliency and a large influence of saturation are notable (variations of the order of 25% to 50%).

This machine was used in a study on cross-saturation, Figure 7 and 8 show the importance of the phenomenon. The variation of the d-axis inductance with both the d- and q-axis currents is given in Figure 7 where isolines for constant values of the inductance are drawn. It is clear that the magnitude of the q-axis current component influences the saturation of the d-axis inductance as a function of the d-axis current component, as discussed in [7]. In Figure 8 it is also clear that the value of the inductance depends on both current components.

For the IPMSMs as well as the SPMSM the measurement results are in line with the expectations, however verification
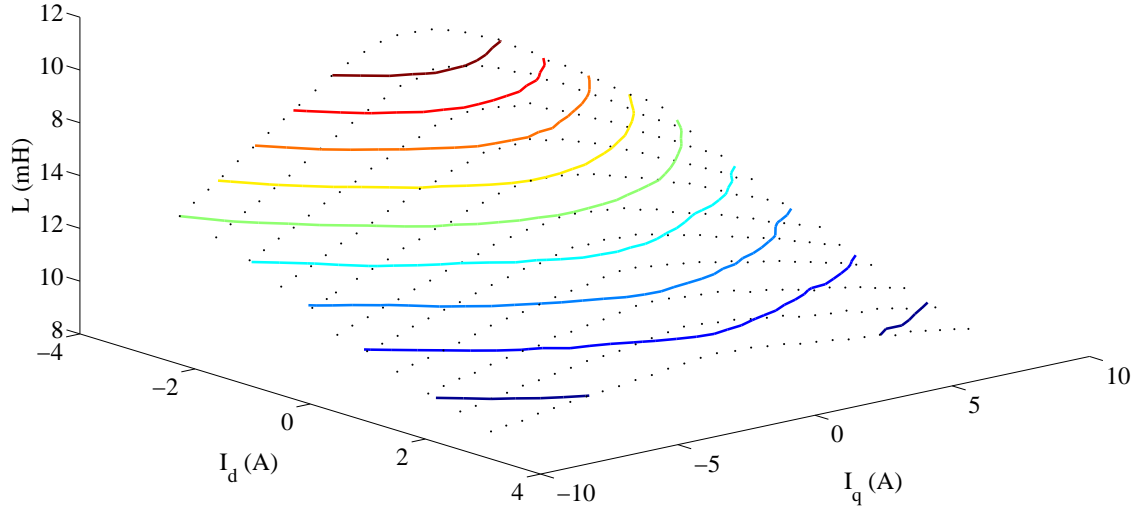
Fig. 7. A three-dimensional representation of the d-axis inductance of the Kollmorgen IPMSM as a function of d-axis and q-axis current. A measuring point is depicted by a dot, the lines of equal inductance (isolines) are drawn in colour.
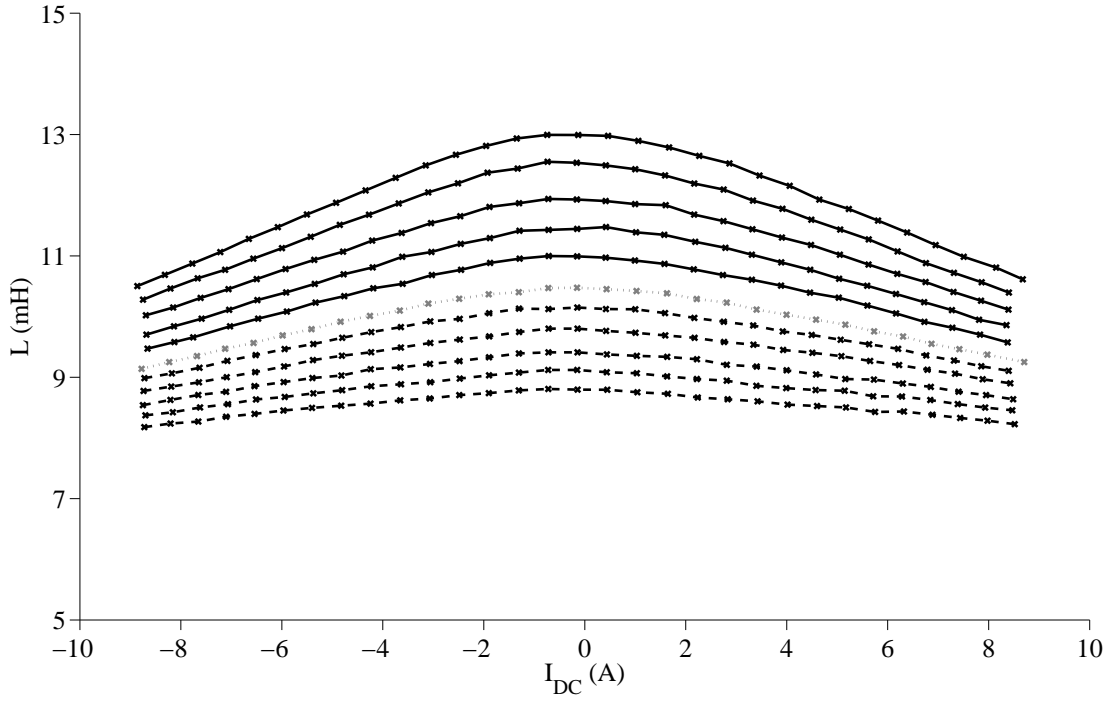

Fig. 8. Cross-saturation in the Kollmorgen IPMSM: the d-axis inductance is given as a function of the q-axis current I_q. The gray line is for a d-axis current $I_d = 0$, the full black lines for increasing negative values of I_d and the dashed lines for increasing positive values of I_d

by other (more classical) tests is desired.

V. Conclusions

A method to perform a frequency domain identification of synchronous machines has been discussed and applied to several PMSMs. By using a linear power amplifier we were able to obtain frequency domain data for several main types of synchronous motors. The frequency response functions were fitted to a first order model to obtain the variation of the inductances with saturation. It is shown that the effect of cross-saturation can be studied by the method discussed in this paper as well. Further research is conducted on more machines and a higher order of the models.

Acknowledgment

References

[1] *IEEE Standard 115-1995, IEEE Guide: Test Procedures for Synchronous Machines*, IEEE Std. 115 ISBN 1-55 937-710-0, 1995.

[2] J. Verbeeck, "Standstill frequency response measurement and identification methods for synchronous machines," Ph.D. dissertation, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels, Belgium, Jan. 2000.

[3] R. Pintelon and J. Schoukens, *System Identification a Frequency Domain Approach.* Piscataway, NJ: IEEE Press, ISBN 0-7803-6000-1, 2001.

[4] M. Sonnaillon, G. Bisheimer, C. De Angelo, and G. Garcia, "Automatic induction machine parameters measurement using standstill frequency-domain tests," *IET Electr. Power Appl.*, vol. 1, no. 5, pp. 833–838, Sept. 2007.

[5] N. Dedene, R. Pintelon, and P. Lataire, "Estimation of a global synchronous machine model using a multiple-input multiple-output estimator," *IEEE Trans. Energy Conversion*, vol. 18, no. 1, pp. 11–16, Feb. 2003.

[6] F. Sellschopp and M. Arjona, "Determination of synchronous machine parameters using standstill frequency response tests at different excitation levels," in *Proceedings of the IEEE International Electric Machines and Drives Conference (IEMDC 2007)*, Antalya, Turkey, May 2007, pp. 1014–1019.

[7] F. M. De Belie, T. J. Vyncke, J. A. Melkebeek, K. R. Geldhof, L. Vandevelde, and R. K. Boel, "On the influence of saturation and mutual coupling of both orthogonal magnetic axes on a MTPA controlled interior PMSM drive." in *Proceedings of the International Conference on Electrical Machines (ICEM)*, Chania, Crete Island, Greece, 2006, pp. OTM2–5.