Parameter Identification and Self-Commissioning in AC Motor Drives: A Technology Status Review

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***Abstract*—In high-performance control of ac machines through variable frequency drives, the knowledge of machine parameters plays a decisive role. The accuracy with which machine parameters can be known is directly related to the time and effort put during the testing and commissioning process. In the ever-demanding industrial environments, the time spent on parameter identification translates into loss of production. To reduce commissioning times, research in this direction has focused on automatizing the identification procedure without loss of accuracy. This paper reviews different lines of research adopted over the past few decades for machine parameter identification. Parameter estimation of ac machines is considered because of their widespread applications from servomechanisms to traction to aviation. The surveyed works include self-commissioning schemes that have become an integral part and a salient feature of modern electric drives. This feature enables the drives to automatically identify machine parameters and tune the control loops.**

***Index Terms*—Control, induction motor drives, parameter estimation, permanent magnet machines, synchronous motor drives, variable speed drives.**

I. Introduction

HIGH-PERFORMANCE control of an electrical machine demands fast response, null steady state error and accurate tracking of controlled variables (such as speed, position, or torque) in an electromechanical energy conversion system. The quality of mechanical torque produced by an ac electrical machine, supplied by a power electronic converter, depends on how well the machine state variables, such as current and flux, are controlled. The precise control of these variables, in turn, is governed by the accuracy with which the electrical parameters and magnetic characteristics, of the connected machine, are known.

Manuscript received March 2, 2018; revised May 21, 2018; accepted June 29, 2018. Date of publication July 15, 2018; date of current version February 20, 2019. Recommended for publication by Associate Editor Dr. A. M. Trzynadlowski. *(Corresponding author: Shafiq Ahmed Odhano.)*

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TABLE I
SUMMARY OF THE IDENTIFICATION METHODS (S.C. DENOTES SELF-COMMISSIONING)

	Numerical	Dyno		Standstill/Blocked Rotor		Free shaft
		Flux mapping	*Phasor*	*Frequency response*	*Time response*	
IM	[18]–[21]		[22]			[23]–[25]
IM s.c.				[26]–[36]	[25], [37]–[43]	[44]
PMSM	[45]–[51]	[52]–[56]	[57]–[59]	[60]–[64]	[65]–[68]	[69]–[72]
PMSM s.c.				[73]–[76]	[50], [77]–[79]	[80]–[83]
SyRM	[84]–[87]					
SyRM s.c.				[88]	[89]–[94]	

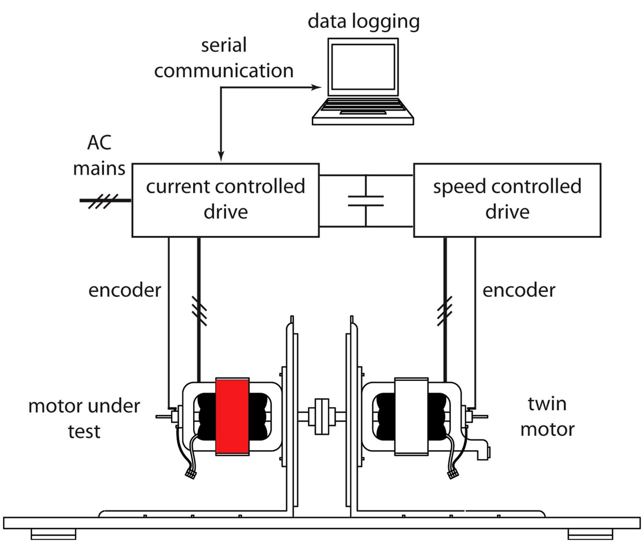

Fig. 1. Dedicated test rig with prime mover. Left: motor under test. Right: twin motor used as prime mover.

and have the limitations of being applicable only by the motor's designer. Any other user does not have enough data to build a numerical or finite element model of the machine.

Methods requiring a prime mover (dynamo) need dedicated setup including a speed-controlled prime mover (see Fig. 1), with dedicated instrumentation. These are further classified into those mapping the flux of the machine and those using phasor interpretation to get equivalent circuit parameters.

Standstill identification methods are of simpler application and often require rotor locking. They can be subdivided into frequency response and time response categories based on the principle of parameter estimation used. In both cases, the machine under test is supplied in single-phase with different signal patterns to estimate its parameters based on the response. These methods come under the heading of offline identification and can be best applied in a dedicated testing facility such as a laboratory. In a laboratory setting, the availability of specialized equipment, such as signal generators, high-precision measuring equipment, and data acquisition tools, enables accurate characterization of electrical machines. Some offline identification techniques can also be used with basic drive hardware and are, therefore, suitable for field application where high-precision instrumentation is unavailable.

The general idea is to excite the machine with different signals and observe the response through the measurement of electrical variables, such as current, voltage, power factor, etc. The recorded data is postprocessed to obtain the parameters of interest along with their dependence on physical variables, such as temperature or electromagnetic phenomenon, e.g., magnetic saturation.

In the offline identification techniques, self-commissioning is an important subcategory. The methods falling in this subcategory use a power converter for identification, but they must also satisfy an additional set of requirements imposed by the definition of self-commissioning. It is defined as the ability of an electric drive to identify accurately the parameters of the machine connected to it under the following conditions: at standstill; without requiring rotor locking; using the available sensors; employing computation algorithms executable on low-cost microcontrollers; with least operator intervention; without supplying torque to the load; with practically no available information about the machine; and in as short a time as possible. The aforementioned items are the "additional requirements" imposed by self-commissioning. Due to the importance of self-commissioning in the modern drive systems, the parameter estimation techniques that satisfy the requirements of self-commissioning are identified in Table I on a separate line (where s.c. stands for self-commissioning) for each machine type to guide the reader to specific references.

Finally, the parameter identification techniques that require the rotor shaft to be free to rotate are grouped separately under the heading of free shaft.

Most modern commercial drives, in their start-up routines, include algorithms for parameter identification. The methods adopted for parameter estimation may vary between different drive manufacturers, but the basic idea remains largely the same: identification through the inverter using only the available feedbacks. The speed and accuracy depend on the particular method of identification chosen from Table I and the available computational resources onboard the drive system.

The parameters of interest depend on the control strategy implemented for a given machine. We will consider identification techniques that estimate some or all of the machine parameters. For IM, these parameters include the following: stator resistance, stator leakage inductance, magnetizing inductance, core-loss equivalent resistance, rotor leakage inductance, and rotor resistance. The magnetizing characteristic of the IM is also considered as an unknown of interest as the knowledge of this characteristic is of particular importance in variable flux control schemes.

With regard to PMSMs and SyRMs, the stator resistance can be considered as a constant parameter (apart from thermal drifts). For the magnetic part, the unknowns can be described in the following three ways: as constant inductances; as inductances that are a function of current; and as current-to-flux-linkage characteristics. The first is a quick and easy way of giving preliminary information about the machine, for instance, for initial control tuning. Evidently, this constant inductances model is of a little value for machines that demonstrate highly nonlinear behavior in their magnetic characteristics. For such machines, either current-dependent inductances or current-to-flux-linkage characteristics are more reliable in describing the nonlinear magnetics. Differently from the IM and the PMSM, the SyRM is hardly described with constant inductances. More than elsewhere, the SyRM model is quite universally described in terms of flux-linkage curves or flux maps.

It should be noted that the parameter identification methods found in the literature are not classified based on their accuracy or convergence speed in this paper. A comparison based on these figures of merit would be more qualitative and less objective. Besides, it is not possible to generate a number that gives the overall accuracy of a method. For instance, the work presented in [22] identifies all the IM parameters with less than 5% error except rotor resistance, which has 25% error, and equivalent core loss conductance, which is estimated with 70% error. As far as the convergence speed and computational cost are concerned, these again depend on the depth of detail of each method and the resources available with the authors of each work.

Most of the parameter identification methods of Table I need information about the actual voltage applied to the machine terminals. When a power electronic converter is used for identification, it becomes imperative that the voltage errors introduced by the power converter are excluded in order not to corrupt the estimation of parameters [95]. The inverter voltage error consists of a nonlinear part and a linear part. The nonlinear part is due to the threshold voltage of power semiconductor devices and dead-time (also called blanking time, lockout time, or interlock delay time), which is a delay introduced deliberately to avoid a shoot-through fault across the dc-link. The voltage error caused by inverter dead-time depends on the setting of dead-time for inverter gate drivers, the switching frequency, the dc-link voltage, and the sign of current. The linear part instead is proportional to current and is caused by the ON-state resistance of the inverter switches. The literature reports a number of works that model the voltage error caused by the inverter and procedures to identify it [96]. The reader may find the works [96]–[102] useful in understanding this phenomenon and how to get rid of the error introduced by it.

III. IM Parameter Identification

The IEEE standard [103] outlines the guidelines for obtaining different IM parameters through standard no-load and locked-rotor tests. Clearly, these tests are fit only for a laboratory environment under stable ambient conditions as well as precise measuring instruments and data acquisition systems. The modern electric drives with powerful on-board computational facilities can easily eliminate the need for these standard tests.

Identification of machine parameters, through excitation signals generated by the power converter, prior to normal operation is known as offline identification as opposed to online estimation that tracks parameter variations during routine operation. In this paper, we will survey only the offline identification methods that propose tests through the inverter only; methods requiring sinusoidal power supplies, such as [104]–[108], will not be commented upon.

Offline parameter identification techniques can be classified in three broad categories, namely, using numerical analysis tools, excitation tests requiring shaft movement, and tests performed at standstill.

A. Parameter Identification With Numerical Analysis Tools

From geometric and/or nameplate data of the machine, its electrical parameters can be obtained by solving analytical equations. The methods that fall in this category do not require any power supply and measurement tools except numerical analysis software. Parameter estimates are obtained from manufacturer data using a least-squares algorithm in [18] and using genetic algorithms in [19]. Equivalent circuit parameters are computed from the geometric data of the machine as discussed in [20] and [21]. Although the parameters obtained through numerical tools give useful initial information about the machine, their accuracy may not always be guaranteed due to manufacturing tolerances and material imperfections.

B. Parameter Estimation Requiring Shaft Rotation

If shaft rotation is permitted, the parameters of an IM can be obtained from no-load tests conducted through the inverter and recording the available measurements (currents, speed, and dc-link voltage). For instance, data produced by a start-up transient, from rest to different no-load speeds, are used with genetic algorithms to identify machine parameters in [23]. Again, with shaft rotation permitted, the values of machine parameters are obtained in [24] by using total least-squares error minimization algorithm on voltage, current, and speed samples acquired during offline tests. Offline identification of machine parameters, along with the estimation of core-loss conductance, is presented in [22]; the machine is driven by a prime mover that controls the shaft speed.

Automatic parameter identification is proposed in [25] in which the electrical parameters are estimated at standstill and rotor rotation is inevitable for mechanical parameters estimation. A neural network based self-commissioning for sensorless drives is presented in [44], where the stator resistance and leakage inductance are the only identified parameters needed for the sensorless control implemented.

These identification techniques are useful to get information about the machine in its actual operating condition (i.e., rotation); their use may not always be possible due to application limitations.

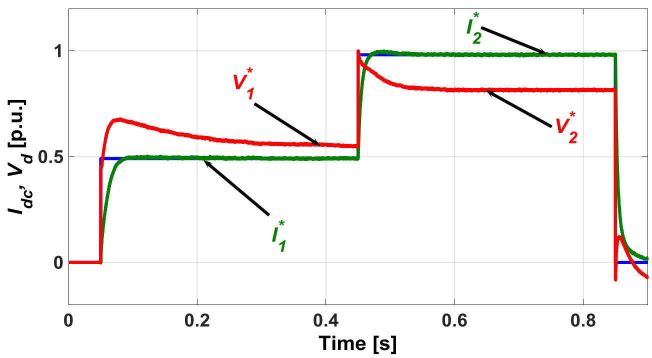

Fig. 2. Experimentally observed current and voltage for stator resistance identification of an IM.

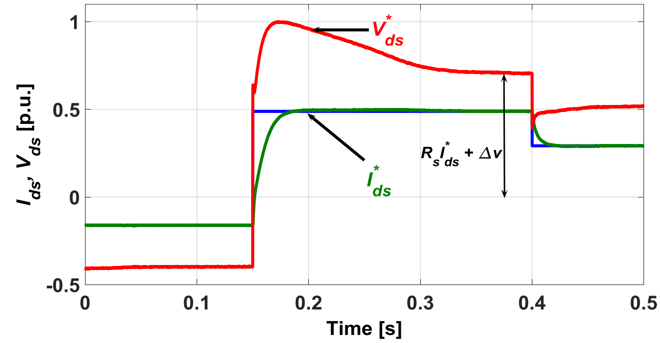

Fig. 4. Rapid current reversal test for identifying rotor resistance referred to stator (experimental results).

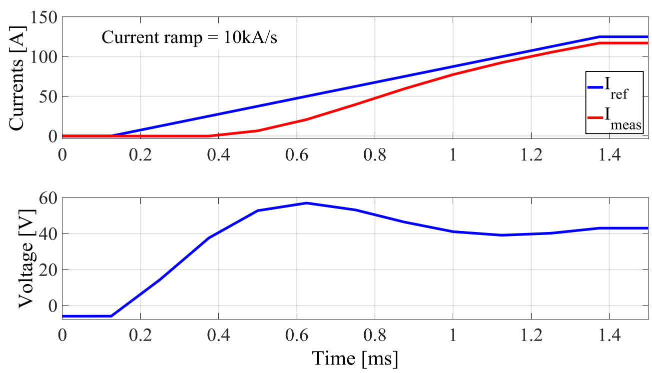

Fig. 3. Experimental results for fast current ramp (top) and resultant controller voltage (bottom) for an IM's transient inductance estimation.

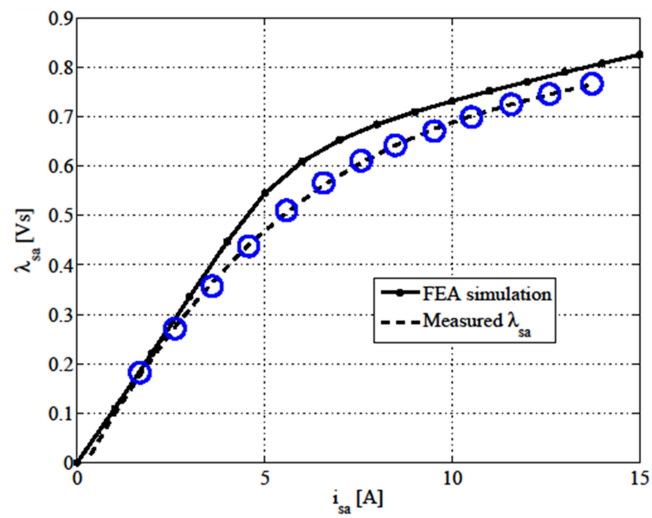

Fig. 5. Induction motor magnetizing characteristic using the procedure of [27]—figure reproduced with permission.

C. Identification at Standstill (Self-Commissioning)

The equivalent circuit parameters of an IM can be estimated by applying different excitation signals through the inverter. The power electronic converter, with apposite control circuitry, allows us to generate signals across a wide frequency spectrum, i.e., from dc to high frequency ac. This feature of the power converter is exploited in parameter identification techniques that do not require shaft rotation or rotor mechanical blocking. For instance, dc current or voltage can be used to estimate stator resistance (see Fig. 2) [37], [38]. A fast current ramp is applied to estimate the total leakage inductance of high-power low-reactance machines, as shown in Fig. 3 [39]. Similarly, the rotor resistance referred to the stator is obtained through a rapid current reversal test of Fig. 4 [37]. Finally, single-phase ac at varying amplitudes allows us to characterize the machine's saturation characteristic [26] at standstill. Another method for identifying this characteristic is based on dc decay tests from which the main flux of the machine is computed through voltage integration in steady state [27]. In Fig. 5, the current-to-flux-linkage characteristic of an IM is shown, which is obtained in [27]. Machine parameters, including magnetic saturation effects, are identified through offline tests in [29]; rotor rotation is excluded by the choice of applied test signals for identification. All these tests can be programmed into a drive's start-up routine as self-commissioning algorithm.

The literature reports a number of methods that allow us to identify one or more IM parameters at standstill, i.e., suitable for embedding in self-commissioning routines. For instance, estimation of induction motor parameters at standstill, suitable for self-commissioning, is presented in [27] and [40]. In [28], parameters of an alternate *dq* model of an IM are estimated from steady-state measurements and standstill frequency response through genetic algorithm optimization; however, the additional equipment such as a power analyzer and an *LCR* meter is needed. Tests involving the injection of single-phase ac voltage through the inverter are proposed in [30], where voltage vector reconstruction is used to estimate machine parameters. Single-phase excitation is also used in [41] for parameter identification through prediction error minimization. Due to the single-phase nature of these tests, the rotor remains stationary and mechanical means of rotor blocking are not required. A parallel adaptive observer was designed to identify induction motor parameters at standstill considering magnetic saturation effects in [42]. The magnetizing curve of the induction motor was identified at standstill in [38].

Standstill variable frequency response tests are used for induction motor parameter estimation in [31]; the authors have used single-phase ac supply for validation, but it has been shown elsewhere that the same tests can be carried out through the inverter [32]. High-frequency injection is used in [32] for standstill identification of induction motor model. Standstill identification is also proposed in [43] based on integral calculation; the stator resistance and leakage inductance are treated as known parameters. Adaptive linear neural networks are employed for standstill parameter estimation in [33]. Another method for standstill frequency domain tests is described in [34], where very low frequency is used. A parameter estimation method at standstill is proposed in [35], where a sequence of voltage pulses is applied to the machine and the resulting currents are acquired. A linear regression model is constructed to minimize the error between measured and predicted currents to obtain parameter values. A standstill method is proposed in [36], where sinusoidal current injection and current decay tests are used for rotor resistance and rotor time constant estimation, respectively. The frequency of the injected sinusoid is in the range of a few tens of hertz.

While the details of each injection method can be found in the respective works cited above, some considerations about the impact of different test signals on the accuracy of identified parameters must be made here. In order to estimate the rotor resistance in a reliable manner, an ac component is needed in the excitation, but its frequency content should not be too high (much below 50 Hz, otherwise the deep-bar effect makes the estimate much too high). Similarly, to estimate the stator/magnetizing inductance, a very low-frequency AC current, e.g., [29], [34], or the dc current step together with flux integration [38] could be used. Therefore, the voltage magnitude in these tests has to be comparatively low, which is a fundamental limitation coming from the induction motor model.

It must be mentioned here that offline parameter identification or self-commissioning is not only needed for optimal control performance but can also be used as a diagnosis tool for a machine. For example, self-commissioning is used to assess the health of induction motor drive by identifying asymmetries caused by fault conditions [109].

IV. PMSM and SyRM Identification

Before discussing the identification of synchronous PM and SyRMs, let us first see the structural variants in which they can be constructed. A number of designs in which the PMSMs can be made are given in [17]. The rotor can be designed in a host of different geometric shapes, some enhancing the PM contribution to torque and some offering a significant reluctance torque. Dealing with the stator side, distributed and concentrated windings can be found. Of course, Odhano *et al.* [17] do not give an exhaustive list of PMSM designs and there can be many more variants that can be found in the literature and applications. SyRMs are a special case of synchronous machines in which there are no permanent magnets on the rotor and the torque is entirely generated by reluctance.

The design variants of PMSMs and SyRMs can be arranged on a saliency versus PM-flux plane (ξ–$\lambda_{\rm PM}$ plane) as done in [110], where ξ is the ratio of the two quadrature axes inductances (L_d and L_q), commonly known as the saliency ratio, and $\lambda_{\rm PM}$ is the per-unit flux-linkage of permanent magnets. Every synchronous machine can be located at a precise position of this plane, for instance, the surface-mounted PMSM with distributed windings will find its place on the horizontal axis ($\xi = 1$), around $\lambda_{\rm PM} = 1.0$ p.u. All the PMSMs have $\lambda_{\rm PM} > 0.0$ p.u., whereas the machines along the vertical axis ($\lambda_{\rm PM} = 0.0$ p.u) are an exception with no PM flux and $\xi > 1.0$: these are SyRMs.

The ξ–$\lambda_{\rm PM}$ plane also gives a concise picture of the trend in the magnetic model nonlinearity of these machines. As we approach the bottom-right corner of the plane ($\lambda_{\rm PM} \approx 1.0$ p.u. and $\xi \approx 1.0$), the machines tend to exhibit *less* nonlinearity. Both the *anisotropic* machines ($\xi > 1.0$, i.e., with reluctance torque) and the machines with a *significant armature flux linkage* ($\lambda_{\rm PM} \approx 1.0$ p.u., e.g., PMSMs with concentrated windings) demonstrate a marked nonlinearity in their magnetic models. All such PMSMs tend to need the identification of their flux or current-dependent inductance maps, progressively with their distance from the $\lambda_{\rm PM} = 1.0$ p.u., $\xi = 1.0$ corner of the plane. The SyRMs included in this category, having $\lambda_{\rm PM} = 0.0$ p.u. and $\xi >> 1.0$, are at the opposite corner of the plane and their magnetic model is markedly nonlinear.

The vast diversity in synchronous machine designs points to the fact that a universal parameter identification method to describe the nonlinear magnetics of these machines is no less than an uphill task. A variation of such magnitude in the design of these machines has prevented the defining of an IEEE standard practice similar to [103] for them except for a trial-use guide [111], which has recently been approved. This paper, therefore, surveys the literature for different identification techniques used for obtaining as much accurate information about the machine's parameters as possible. The parameter identification methods reported here include those techniques that require sinusoidal power supplies or signal generators, such as [57], [60], and [61]. Parameter estimation schemes that use the power converter as sole test supply are also reviewed.

A. *Identification Through Analytical Equations, Nameplate Data, and/or Finite Element Analysis (FEA)*

During the electromagnetic design of a machine, it is always possible to get an initial estimate of its parameters by using analytical equations or FEA software. Similarly, the machine's nameplate data can also serve as a preliminary source of information that can be used to have an idea of machine parameters. Although the parameters thus obtained are grossly approximate, they serve as a valuable initial input for defining the characteristics of a machine.

The estimation of an IPMSM's parameters through a magnetic circuit model is presented in [45]. A general method for the computation of synchronous inductances of multiphase PM machines is developed in [46], which requires FEA simulations along with analytical expressions. In [47], the synchronous reactances of a PM machine are obtained from analytical computations and the FEA method, which are then compared with measurements. Analytical equations in conjunction with FEA simulations or measurements are used for inductance and PM flux estimation in [48]; a similar approach is followed in [49], which considers skew as well. Initial estimates for machine parameters are obtained from its nameplate data in [50] for rough tuning of current controllers.

The SyRM inductances are calculated using winding function theory in [84] and [85]; the latter includes the computation of electromagnetic torque as well. The analytically computed inductances and torque are compared with FEA results in [86]. A combination of analytical equations and FEA is used for inductance identification for a machine model in terms of stator quantities in [87].

The numerical analysis tools give valuable initial information about machine parameters, but the deviations from actual parameter values cannot be predicted and prevented as they depend on manufacturing tolerances and final material properties.

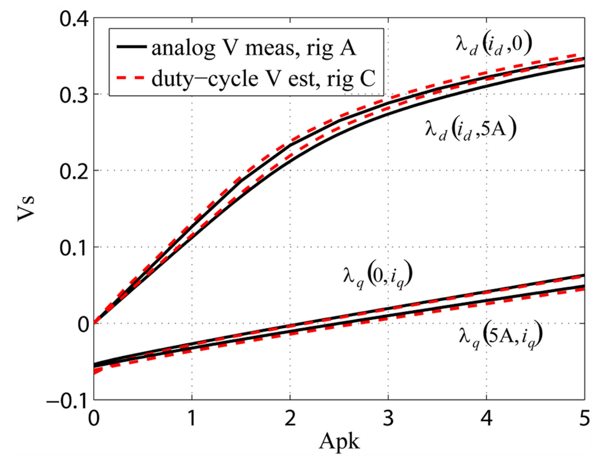

Fig. 6. Magnetic model identification of [52]: *d* and *q* axes current-to-flux-linkage relationships (experimentally observed).

B. *Offline Identification Using Specialized Signal Injection and Data Acquisition Equipment*

The identification methods that fall in this category excite the machine with different signals and observe their response for parameter estimation. The use of sinusoidal signal generators allows the injection of only the fundamental frequency signals as opposed to the case when pulsewidth-modulated inverters are used that inject signals with a rich harmonic content. Since the PM machines are almost always operated through a power electronic converter (line-start PM machines are rare), the influence of space and time harmonics on machine parameters must always be considered, as presented in the modeling and identification carried out in [51].

The works presented in [57], [58], [60], [62], [63], [65], and [69] belong to this category of parameter identification. The analysis of how the parameters obtained through sinusoidal supplies compared to those estimated through a vector-controlled drive (i.e., a power converter) is presented in [112]. The authors compared the results with other known methods of identification to draw their conclusions.

Other methods falling in this category include [59] and [66]. In [66], the estimates for the PM machine's synchronous inductances are obtained through dc decay tests. The machine's starting performance is predicted based on these estimates. In [59], the authors proposed load tests of the machine. The data acquired through these load tests were used in conjunction with linear regression and neural network solution techniques to obtain reliable estimates of the machine parameters. A detailed review of the identification methods for synchronous reactances of PMSMs is presented in [113].

The above-mentioned methods defined for PMSMs are also valid for SyRM identification especially the ones that work at standstill, such as dc decay tests.

As the heading suggests, these methods can exclusively be applied in laboratory environment where the equipment needed for testing is available.

C. *Offline Identification Through a Power Converter*

A current-controlled power electronic converter offers a plethora of possibilities when it comes to identifying the parameters of a PMSM and a SyRM. The availability of rotor position through an encoder adds to the ease with which tests can be conducted as well as the accuracy of the obtained results. Parameter identification methods that make use of a power converter include [52]–[56], [64], [67], [68], [70]–[72], and [80].

The basic idea of these identification methods is to apply a current vector of varying magnitude along a predetermined direction with respect to rotor permanent magnets and observe the machine response. With a PM machine at hand, the application of a current vector is bound to produce torque; thus, the rotor should either be free to rotate [54], [55], [70], [80] or it must be locked by mechanical means [68] to properly estimate parameters. For SyRMs, the current vector along the axis boundaries (i.e., along the *d*-axis or the *q*-axis only) does not produce any torque, so the identification along these axes can be carried out without necessarily locking the rotor. However, as the cross-saturation effects are the most significant in SyRMs, the identification must also be carried out with the current vector having both the *d*- and *q*-axis components. In this case, rotor locking or shaft rotation at controlled speed becomes necessary also for SyRMs.

If a prime mover is available that maintains a constant shaft speed, the experimental characterization methods similar to [52], whose test setup is shown in Fig. 1, can very well be used. The authors have characterized the test machines throughout the entire *dq*-current plane (up to rated current) to highlight saturation and cross-saturation phenomena. The current-to-flux linkage characteristic curves given in Fig. 6 are obtained as function of self-axis current and the cross-axis current as parameter. For instance, the curve labeled $\lambda_d(i_d, 0)$ represents the *d*-axis flux-linkage as a function of the *d*-axis current when the *q*-axis current is zero; similarly, $\lambda_d(i_d, 5)$ gives λ_d as a function of i_d with $i_q = 5$ A. Positive and negative current along each axis is applied to emulate generating and motoring modes of operation to exclude the effect of thermal drift in stator resistance as well as the inverter nonlinearity. A test strategy similar to this is adopted in [53] to estimate the PM machine parameters. The results are verified by comparing the torque estimated using the obtained parameters with the measured torque as an indication of the accuracy of estimated machine parameters. The use of immune clonal quantum genetic algorithm is proposed in [56] for the identification of *d*- and *q*-axis flux-linkage maps of a PM machine. In this paper, two penalty functions are designed for the identification and surface fitting of flux-linkage maps and the minimization of these penalty functions is carried out through immune clonal quantum genetic algorithm. The method requires recording of data to be processed offline.

The same tests of [52] can also be performed with the rotor shaft rigidly clamped as presented in [68] with a slight difference that a voltage vector is applied in the latter. With the rotor blocked at a known position, a voltage vector with varying magnitude is applied by appropriately controlling the inverter switches. The measured current and known voltage are used to estimate the flux, after removing stator resistance and inverter drops. The procedure is repeated for different current values along the cross axis (as discussed above for [52]) to obtain complete magnetic model. While the strategy of [68] requires a blocked rotor, the one adopted in [80] applies a similar procedure with a free-to-rotate shaft. The magnetic model self-identification method of [80] recommends a series of acceleration tests by imposing different current vector magnitudes. Once the machine accelerates to a speed at which the back electromotive force is sufficiently above the stator resistance and inverter voltage drops, the equations of [52] are used to compute *d*- and *q*-axis flux-linkages. The procedure is repeated for a number of different current vectors to define the entire magnetic model of the machine. However, this method needs to be applied with care when the rotor inertia is too low to prevent runaway condition at high current magnitudes.

The application of these methods of identification requires machine detachment from mechanical load and, in some cases, rotor blocking. This can be a bottleneck, but the identified parameters/characteristics are sufficiently accurate [52].

D. Self-Commissioning

The literature reports very few works that satisfy all of the requirements imposed by the definition of self-commissioning (listed in Section II); therefore, the research in this area is intense and the number of publications has grown steadily over the past decade or so. Nowadays, as the demand for very high bandwidth current control is on the rise in PM servomotor drives, the same is pushing for the use of model-based control strategies, such as deadbeat and predictive control [114], and the need for accurate machine model is felt more than ever. So, self-commissioning has become an all the more important feature of modern electric drives used in servo applications.

Identification methods appearing in [50], [73]–[79], and [81]–[83] satisfy some of the prerequisites of self-commissioning. However, the universal applicability of these methods is yet to be demonstrated, and the accuracy of identified parameters widely varies across different test methods.

In [81] and [82], both electrical and mechanical parameters of the drive system are estimated, but the procedures necessitate shaft rotation and ignore the saturation effects on machine inductances. The self-commissioning technique presented in [50], on the other hand, takes into account the effects of magnetic saturation as well as voltage errors introduced by inverter dead-time. However, this technique is based on open-loop voltage injection that may trigger overcurrent protection in case of low-impedance machines. The *d*-axis inductance identification strategy of [75] satisfies the constraints of self-commissioning, but it does not define the complete magnetic model of the machine.

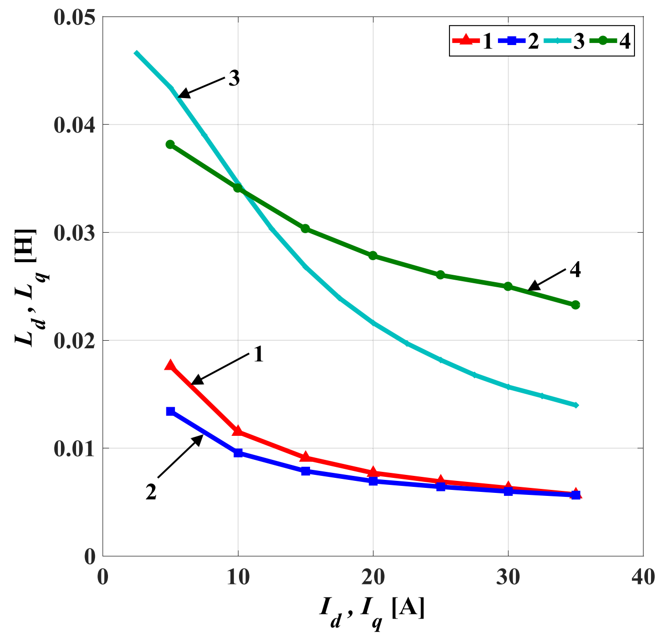

Fig. 7. L_d and L_q variation as a function of the self-axis current—comparison between high-frequency (HF) test and magnetic characterization. (1) L_d (magnetic characterization). (2) L_d (HF test). (3) L_q (magnetic characterization). (4) L_q (HF test) (experimental results).

Closed-loop controlled high-frequency current injection is used in [73] to identify machine inductances as a function of current. With the rotor position known, a high-frequency sinusoidal current is injected along the *d*- and *q*-axis of the machine and the controller output voltage is observed. The saturation of the self-axis (i.e., the axis whose inductance is being identified) is taken into account by varying the amplitude of injected current, whereas the cross-saturation effect is analyzed by maintaining a constant current along the cross axis (i.e., the axis perpendicular to the self-axis). Fig. 7 shows *d*- and *q*-axis inductances as functions of respective currents, as presented in [73]. The estimation of PM flux-linkage is also addressed in this paper.

Another self-commissioning method similar to [73] is proposed in [74], wherein the authors have used dc-biased small-signal ac injection to define the complete magnetic model of IPM and SPM synchronous machines. The dc-bias point decides the magnetic operating point, whereas the ac injected current identifies differential inductance at the operating point. In this way, by simply shifting the dc-bias points up and down the current scale, the entire magnetic operating region is explored and a model is defined. As in [73], the cross-saturation effects are taken into account by applying a constant current in the cross axis while identification is underway in the self-axis. Results from [74] are given in Figs. 8–10. Fig. 8 shows the variation of the *q*-axis incremental inductance ΔL_q as a function of the *q*-axis current with the *d*-axis current as a parameter. Fig. 9 shows the current-

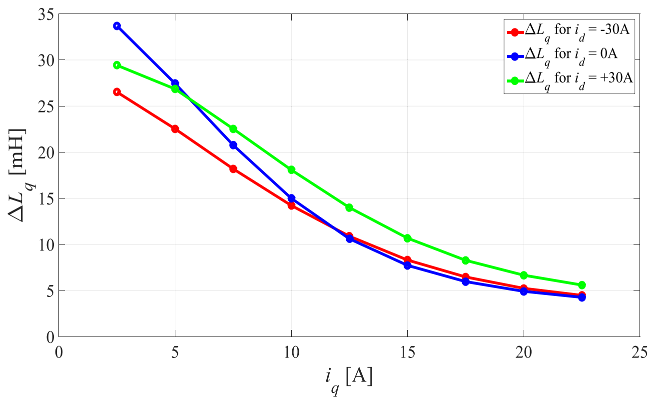

Fig. 8. ΔL_q as a function of i_q at $i_d = -30$ A (red), $i_d = 0$ A (blue), and $i_d = +30$ A (green) (experimentally observed).

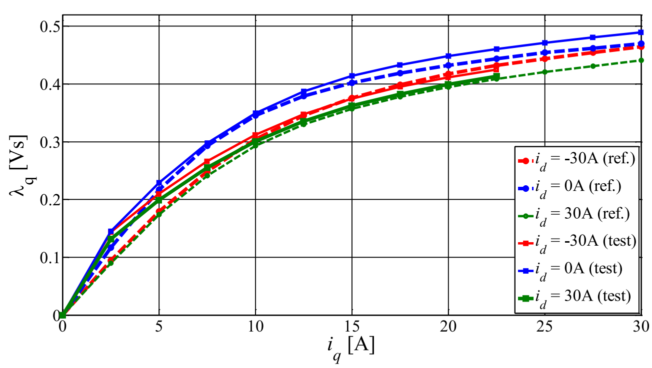

Fig. 9. q-axis current-to-flux linkage characteristic at different d-axis current levels compared with a known model (experimental results).

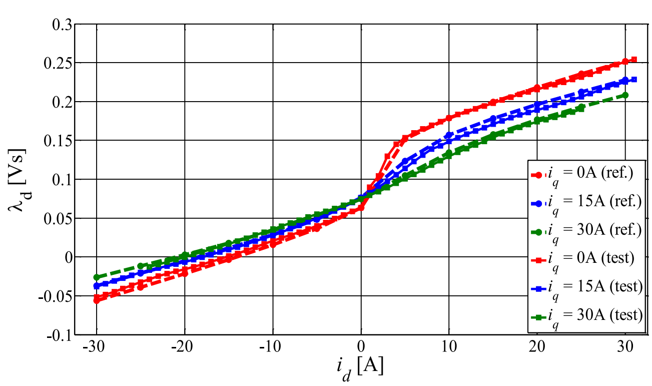

Fig. 10. d-axis magnetic characteristic at three different q-axis current levels compared against a known model (experimentally observed).

to-flux linkage characteristic for the q-axis, and Fig. 10 gives that for the d-axis. It must be noted that a constant current along the q-axis would give rise to a torque, thus resulting in a rotor movement; the authors have applied a special q-axis current waveform to avoid any sustained shaft rotation.

A number of self-commissioning methods are available for SyRMs. Several methods use bipolar voltage steps as excitation signals. The stator flux linkage is estimated from the measured currents and the reference (or measured) voltage. In [68], [89], and [90], the applied voltage steps are selected so low that the steady state is reached, making the flux computation highly sensitive to the stator resistance and inverter voltage.

The higher is the test voltage, the lower is the effect of the stator resistance and offset errors on the estimated flux. The method proposed in [91] uses bipolar voltage steps with a larger magnitude (up to the rated voltage), compared with the ones used in [68], [89], and [90]. The whole range of currents is scanned during a single voltage step, and unlike in [68], [89], and [90], the steady state is not reached. A piecewise mathematical function is fit to the measured samples. Overall, the method in [91] works well for self-axis identification, but the cross-saturation model is impractical due to its high number of parameters and moderate accuracy.

The identification method proposed in [92] combines the test sequence of [91] and the algebraic magnetic model of [93], taking into account also the cross-saturation effect. Only one parameter is needed to model the cross-saturation effect in [92], while tens of parameters as well as separate postprocessing and interpolation algorithms would be needed in the method of [90]. During the cross-saturation test, the variation in the rotor speed and angle is small due to the high test voltage. Fig. 11 shows the identified flux characteristics. It can be seen that the results obtained using [92] are comparable to the ones obtained from the constant-speed identification [52].

For the method of [92], the effects of the variation of stator resistance, inverter voltage distortion, iron losses, and unwanted rotor movements were studied recently in [94]. The method was also combined with the high-frequency signal injection in order to further increase the range of inspected currents in [88]. Even though the inspection area for the self- and cross-saturation tests was increased, it was observed that there was no significant change in the obtained flux characteristics.

Although the self-commissioning methods are rapidly growing in number, their application in practical/industrial systems is still very limited, partially due to scarce computational power available on-board an industrial drive system. However, the increasing use of fast digital signal processors in modern variable speed drives will be an enabling factor for the application of these methods on a larger scale.

For PMSMs and SyRMs parameter identification, it is necessary to know the position of the rotor dq frame with respect to stator windings to be able to identify d- and q-axis inductances or flux-linkage curves. Usually, a rotor position sensor provides this information. However, whether the absolute rotor position is available at drive start-up depends on the type of sensor used. With an absolute encoder, the position of the rotor dq axes can be known at drive start-up, but if an incremental encoder is used, the absolute position information is lost every time the drive restarts. The literature reports a number of methods that deal with this problem and provide solutions for initial rotor position identification. The readers may find the methods presented in [115]–[119] useful for initial rotor position identification for PMSMs. In sensorless applications where the rotor position sensor is not installed, the methods for initial rotor position detection are numerous [120], [121].

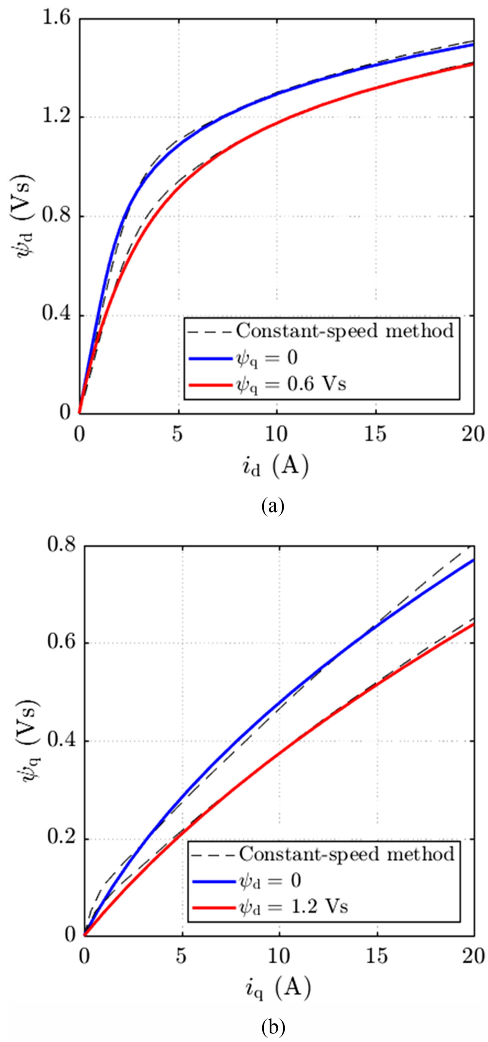

Fig. 11. Currents as functions of fluxes. (a) ψ_d as a function of i_d for $\psi_q = 0$ and $\psi_q = 0.6\,\mathrm{V\cdot s}$. (b) ψ_q as a function of i_q for $\psi_d = 0$ and $\psi_d = 1.2\,\mathrm{V\cdot s}$. Dashed lines show the reference data, measured using the constant-speed method [52]. Solid lines show the results from the standstill identification method of [92].

V. Conclusion

This paper presented an up-to-date review of parameter identification methods for ac motor drives. The surveyed methods were arranged for different machine types and implementation techniques, such as methods using nameplate data and numerical tools, methods using offline precommissioning procedures, etc. This paper particularly highlighted those offline identification schemes that satisfy the requirements of self-commissioning.

The parameter estimation strategies of induction motor drives listed in this paper included those appearing after the last review was performed [16]. The methods that identify machine parameters at standstill with no rotor movement were particularly emphasized as they can be embedded into drive start-up routines for self-commissioning.

For PMSMs, the survey included most of the works appearing in the literature and categorized them into different subgroups. The identification schemes that define the complete nonlinear magnetic model of anisotropic machines were highlighted.

The parameter estimation of SyRMs is an area of active research, and the authors included those works that were published at the time of compiling this review.

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