Estimation of the Leakage and Magnetizing Inductances of Induction Motors

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ABSTRACT In addition to the IEEE Standard Test Procedure for Induction Motors (IM), several advanced methods have been presented to achieve higher accuracy on parameters estimation. Some of them allow to estimate with high precision only a specific parameter, while others improve the parameters estimation at the price of high computational efforts and time due to finite elements analysis or the use of recursive algorithms.

After a survey of the main typologies adopted to estimate the electrical parameters in IMs, that highlights the main advantages and drawbacks of each category, this paper presents a novel procedure that can be adopted as parameters estimation. According to the proposed method the motor parameters are calculated through locked-rotor tests performed as the motor is fed by a standard inverter, by exploiting simple relationships which do not increase the computation effort. Simulation and experimental results have been performed on different motors and, comparing the proposed approach to other methods, they have confirmed its validity.

I. INTRODUCTION

Electrical machines parameter estimation is an important issue to take into consideration for their performance prediction and correct control. Most of the efficiency optimization scalar control techniques as well as vector control strategies for IM machines require the knowledge of some or all model motor parameters. Moreover, even the back-emf based sensorless motor drive techniques allow rotor or flux position estimation by exploiting the model of the machine. In classic machine equivalent circuits, the effects of the iron losses, copper losses as well as the linkage and leakage magnetic fluxes into the machine are modeled by using constant parameters values.

Different techniques have been proposed to estimate the values of those parameters. The IEEE Standard 112-1996 Test Procedure for Polyphase Induction Motors and Generators (STP) suggests no load and rotor locked tests to calculate the parameters, by exploiting active and reactive power measurements. This procedure makes some assumptions regarding the leakage and magnetizing fluxes distribution during the tests; on this hypothesis the stator and rotor leakage inductances are calculated.

Through Finite Element Analysis, estimation of the electrical parameters of the machine is achieved without performing any experimental test as this approach uses numerical techniques to determine the distribution of the magnetic field paths inside the electrical machine. In addition to the nameplate, such a method requires the exact knowledge of the geometry of the machine and magnetic materials properties. In this way a more precise estimation of the parameters can be obtained at the price of higher computational efforts. The foregoing methods may also exploit recursive algorithms to increase the accuracy of the estimations.

Other approaches have been suggested to perform parameters estimation [1-15]; some methods need appropriate equipment and have been specifically designed to estimate specific parameters, while others exploit complicated algorithms to reach the goal of an accurate estimation of the machine parameters. In [11] the authors presented a new method for measuring the magnetizing inductance of an induction machine. The proposed technique makes use of a static dc excitation and requires the access to the neutral point of the stator windings. Since this method exploits a dc excitation, the iron losses in the motor are considerably reduced compared to standard no load tests.

Several authors have proposed techniques which perform estimation of the electrical parameters making use of an inverter as power source for the motor [10-12]. The use of a power converter to feed the motor provides more flexibility in the generation of the applied test signals. In particular, in [11] the stator leakage inductance and the stator resistance are obtained through injection of zero sequence voltages, while the other parameters are obtained from the dynamic q-d model by applying different signal tests. In [10], a sinusoidal current with DC bias is applied to the motor to determine the rotor resistance, while the other parameters are extracted through different tests in which the decaying stator current trajectory is measured. The main advantage of parameters estimation techniques using a voltage source inverter is given by the possibility to include an estimation algorithm of the machine parameters in an autotuning procedure. In that way it is possible to perform vector control or model based sensorless control of the electrical drive even if the motor parameters are unknown.

The approach proposed in this paper allows to measure most of the parameters of an induction motor only performing three rotor locked tests and exploiting analytical relationships which do not increase the computational effort demanded to the control unit.

II. PROPOSED ESTIMATION METHOD

The proposed method essentially exploits the q-d axis reference frame model of the induction machine and the field oriented control condition.

$$\begin{cases} v_{qs} = R_s i_{qs} + \dfrac{d\lambda_{qs}}{dt} + \omega\lambda_{ds} \\ v_{ds} = R_s i_{ds} + \dfrac{d\lambda_{ds}}{dt} - \omega\lambda_{qs} \\ v_{os} = R_s i_{os} + \dfrac{d\lambda_{os}}{dt} \end{cases} \qquad (1)$$

$$\begin{cases} v_{qr} = 0 = R_r i_{qr} + \dfrac{d\lambda_{qr}}{dt} + (\omega - \omega_r)\lambda_{dr} \\ v_{dr} = 0 = R_r i_{dr} + \dfrac{d\lambda_{dr}}{dt} - (\omega - \omega_r)\lambda_{qr} \\ v_{or} = 0 = R_r i_{or} + \dfrac{d\lambda_{or}}{dt} \end{cases} \qquad (2)$$

$$\begin{cases} \lambda_{qs} = (L_{ls} + M)i_{qs} + Mi_{qr} \\ \lambda_{ds} = (L_{ls} + M)i_{ds} + Mi_{dr} \\ \lambda_{os} = L_{ls} i_{os} \end{cases} \qquad (3)$$

$$\begin{cases} \lambda_{qr} = Mi_{qs} + (L_{lr} + M)i_{qr} \\ \lambda_{dr} = Mi_{ds} + (L_{lr} + M)i_{dr} \\ \lambda_{or} = L_{lr} i_{or} \end{cases} \qquad (4)$$

$$\begin{aligned} T_e &= \frac{3}{2}\overline{p}(\lambda_{qs} i_{dr} - \lambda_{ds} i_{qr}) \\ T_e - T_r &= \frac{J}{\overline{p}}\frac{d\omega_r}{dt} + \frac{F}{\overline{p}}\omega_r \end{aligned} \qquad (5)$$

Three different tests performed at locked rotor are required in order to estimate the parameters of the machine. In particular, the method makes use of the stator flux equations on q-d axis (6):

$$\begin{cases} \lambda_{qs} = (L_{ls} + M)i_{qs} + Mi_{qr} \\ \lambda_{ds} = (L_{ls} + M)i_{ds} + Mi_{dr} \end{cases} \qquad (6)$$

When the field-oriented regime is reached, the term i_{dr} is zero and:

$$i_{qr} = -\frac{M}{(L_{lr}+M)} \cdot i_{qs}$$

In these conditions (6) becomes:

$$\begin{cases} \lambda_{qs} = \left(L_{ls}+M\right) i_{qs} - \dfrac{M^2}{\left(L_{lr}+M\right)} i_{qs} \\ \lambda_{ds} = \left(L_{ls}+M\right) i_{ds} \end{cases} \tag{7}$$

The previous equations relate the machine parameters with the q-d stator axis flux measurements. Parameters can be estimated from (7) by assuming three separate working conditions at locked rotor. The first test is performed by setting i_{qs} equal to zero and i_{ds} at its rated value. In this situation no torque is produced and, the system (7) reduces to:

$$-(L_{ls}+M) = -\frac{\lambda_{ds}}{i_{ds}} = A \tag{8}$$

Such a test provides the total stator inductance by reconstructing the stator d axis flux, that in these conditions represents the total stator flux, and dividing it by the current i_{ds}.
The second test is carried out through the condition $i_{qs} = i_{ds}$, keeping the stator current to its rated value; in this case, from the system (7) one can obtain:

$$-\frac{M^2}{(L_{lr}+M)} = \frac{\lambda_{qs}-\lambda_{ds}}{i_{ds}} = B \tag{9}$$

In this case, the estimated flux λ_{qs} and λ_{ds} are required.

The two previous mentioned tests give two equations in three unknown variables L_{ls}, L_{lr} and M; hence, it is necessary to introduce a third equation. It can be demonstrated that in practice it is no possible to obtain such an equation still exploiting (7). The only mathematical but not physically applicable solution would be to fix to zero the stator current component i_{ds}, and of course, this condition cannot be imposed in field oriented conditions.

The third equation can be obtained from a conventional locked rotor test according to [1], with the only difference that the motor is supplied through the inverter at the required rated stator current amplitude I_{asn} and frequency ω_e. The locked rotor test allows to estimate the total leakage inductance, providing the following equation:

$$L_{ls} + L_{lr} = C \tag{10}$$

The inverter must provide the stator current components i_{qs} and i_{ds} according to the following constraints:

$$\sqrt{\left(i_{qs}^2 + i_{ds}^2\right)} = \sqrt{2} I_{asn} \qquad \omega_{s\lambda r} = \frac{1}{\tau_r}\frac{i_{qs}}{i_{ds}} = \omega_e \tag{11}$$

The previous three tests allow to achieve the following equation system, whose solutions are shown in (12).

$$\begin{cases} -(L_{ls}+M)=A \\ -\dfrac{M^2}{(L_{lr}+M)}=B \\ L_{ls}+L_{lr}=C \end{cases} \quad \Rightarrow \quad \begin{cases} M=-B\pm\sqrt{\left(B^2-B\left(A+C\right)\right)} \\ L_{ls}=-A-M \\ L_{lr}=C+A+M \end{cases} \tag{12}$$

Although the system solution gives two values for M, the experimental tests confirm that only one of them is physically consistent. It should be observed that in the proposed method the stator resistance has to be known a priori or calculated by exploiting one of the solutions already presented in [10-13]. In fact, the constants A, B, and C are calculated through the q-d axis stator flux and by numeric integration of the difference between the stator voltage and the resistive voltage drop. Also note that, as the proposed method is based on indirect field oriented control, a precise knowledge of the rotor time constant is a critical issue. However, in practice, in equation (10) field oriented control is not required, and in (8), as i_{qs} is zero, the slip angular pulsation is zero and a rotor time constant error does not affect the equation. Only (9) is affected by an error occurring in the rotor time constant. The rotor time constant can be estimated by exploiting standard approaches or more sophisticated techniques [16]÷[20]. The accuracy of the measured quantities is strongly affected by the nonlinearities introduced by the inverter such as the dead time and the forward voltage drop of the IGBT; such drawbacks can be minimized through implementation of a dead time compensation algorithm and including the voltage drop profile of the power devices in the phase voltage calculation.

III. COMPARISON BETWEEN DIFFERENT APPROACHES

The proposed method has been validated by means of simulations and experimental tests performed on two different motors whose nameplate and technical characteristics are reported in Tables I and II. The results obtained with the proposed method have been compared with those obtained with the IEEE Standard 112-1996 Test Procedure for Polyphase Induction Motors and Generators, and the Finite Element Analysis methods. Measurement of the stator leakage inductance has been also performed by applying a method based on the zero sequence voltage injection. In this case only the zero-axis circuit is involved in the calculation of the leakage inductance, since the q-d-axes voltages are equal to zero.

A. MODELING VALIDATION

Simulations of the different test procedures have been performed on standard q-d reference frame model of the induction machine including iron losses through the parameter R_{fe}, as shown in Fig. 1. The electrical parameters used for the machine model have been obtained by applying IEEE STP to the motor indicated in the following as Motor I. By applying to such a model each singular test procedure, a set of new parameters has been identified for each technique.

A comparison of the estimated parameters is shown in Table III. It can be noted that the different approaches allow to achieve an estimate of the electrical parameters very close to that adopted by the q-d model. The proposed method yields to accurate estimations with relative errors limited to 6%. Also, it is evident that the best method to measure the stator leakage inductance is provided by the use of a zero sequence voltage.

Tab. I: Motor I nameplate

Phase numbers	*3*
Rated power	*1,1 kW*
Rated voltage	*400 V*
frequency	*50 Hz*
Rated speed	*1400 rpm*
Rated current	*3 A*

Tab. II: Motor II nameplate

Phase numbers	*3*
Rated power	*3,7 kW*
Rated voltage	*400 V*
frequency	*50 Hz*
Rated speed	*1475 rpm*
Rated current	*8,6 A*

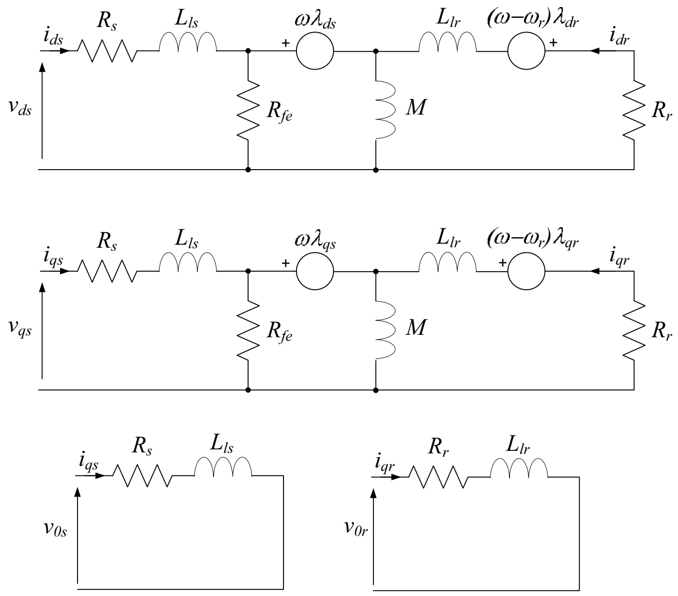

Fig. 1: Induction Machine Model used in the simulations.

Tab. III: Comparison of the simulation results obtained by exploiting different approaches

Parameters	q-d Model Parameters	IEEE STP	Zero Sequence	Proposed Method	Relative error IEEE STP %	Relative error proposed method %
R_s (Ω)	9,500	9,500	9,500	9,500	0	0
L_{ls} (H)	0,023000	0,02278	0,02305	0,02163	-0,95	-5,9
R_{fe} (Ω)	695,0000	702,3	----	----	1	----
M (H)	0,476000	0,48792	----	0,4772	2,5	-0,25
L_{lr} (H)	0,023000	0,02278	----	0,02253	-0,96	-2,04
R_r (Ω)	8,370	7,644	----	8,416	-8,6	0,55

B. EXPERIMENTAL VALIDATION

The proposed method was also experimentally tested and the results have been compared with the parameters estimation obtained through FEM analysis, IEEE Standard Test Procedure, and the method based on the zero sequence voltage injection.

The IEEE Standard Test Procedure has been executed by using a three phase variac and an electronic three phase power analyzer, while the proposed approach and the method based on the zero sequence voltage injection have been performed by exploiting a commercial three phase inverter which includes Hall effect current sensors and DC bus voltage measurement. Accuracy and linearity of the sensors are key elements of the parameters measurement, which heavily affect the estimation of the parameters. In particular, the overall accuracy of the Hall effect based current sensors is equal to ±

0.45% and linearity < 0.15%. Measurement of the DC bus voltage has been carried out through a Hall effect based voltage sensor, whose overall accuracy is equal to ± 0.9% and linearity < 0.2%.

As already mentioned, the rotor time constant can be calculated using different approaches [16]÷[20]; in particular, the technique reported in [19] has been performed to estimate τ_r in the locked rotor condition. Such a method exploits the injection of a small high frequency rotating field and the measurement of the corresponding high frequency component included in the zero sequence voltage to estimate the rotor flux angular position $\theta_{\lambda r}$ and the angular speed $\omega_{\lambda r}$; since the slip angular frequency can be also computed by the relationship (13), it is possible to estimate the rotor time constant through the measurement of the low frequency stator current components i_{qs} and i_{ds} and the estimation of $\omega_{\lambda r}$.

$$\omega_{s\lambda r} = \frac{1}{\tau_r} = \left[(\omega_{\lambda r} - \omega_r) \frac{i_{ds}}{i_{qs}} \right] = \omega_{\lambda r} \frac{i_{ds}}{i_{qs}} \tag{13}$$

Note that the stator current components can be calculated from the actual values of the stator currents by a reference frame transformation using the estimated rotor flux angular position.
In practice, the motor is fed by keeping a constant ratio between the reference values i_{qs}^* and i_{ds}^* and considering an arbitrary value $\tau_r^{'}$ for the rotor time constant. Upon application of the high frequency additional signals to the motor, the relationship (13) is exploited to calculate the correct value of τ_r.

The method based on the zero sequence voltage injection has been performed by connecting the neutral point of the motor to the mid point of the DC bus as shown in Fig. 2. A low pass filter has been connected between the inverter and the motor, in order to remove the high frequency harmonics due to PWM modulation. The motor was supplied by a zero sequence voltage at its rated current and frequency. The DC bus voltage measurement plays an important role in the compensation of the DC bus voltage variations. The stator leakage inductance is calculated by means of current and voltage phase measurement at the output of the low pass filter; in particular, the real and imaginary part of the impedance is calculated in order to estimate both stator resistance and stator leakage inductance.

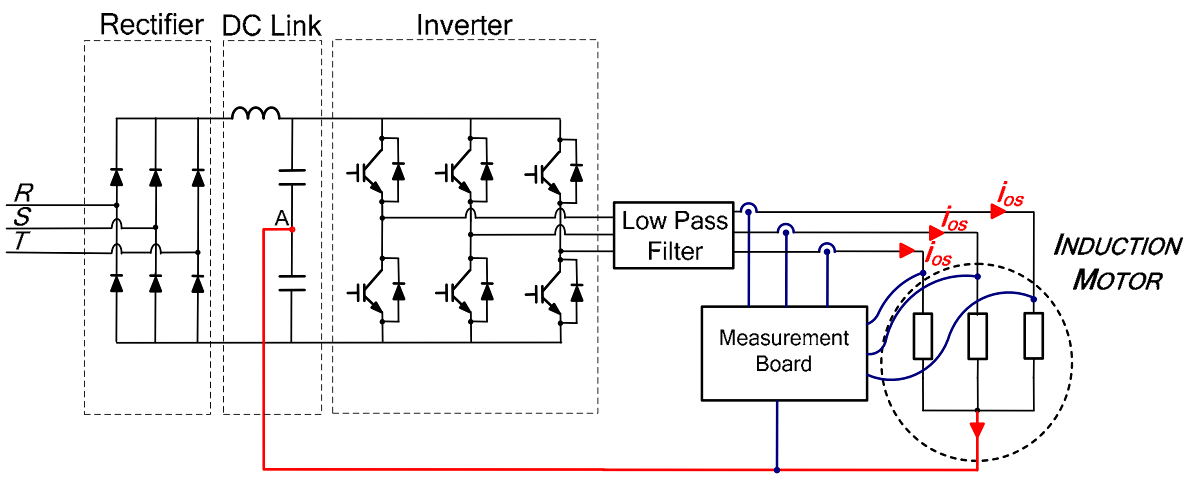

Fig. 2: Experimental setup related to the zero sequence injection.

In the approach proposed in this paper, the stator resistance is measured through volt-amperometric technique by using the inverter and the current sensors included into it, while the numeric integration is performed by using a compensation algorithm as indicated in Fig.3. This allows us to remove drift effects in the pure integration operation. As previously asserted, the proposed measurement technique exploits the indirect field oriented control algorithm; such a control scheme performs the decoupling between torque and flux control indirectly, by adding a slip contribution signal to the measured rotor position. It should be observed that, as the proposed parameters estimation is implemented by keeping the machine at locked rotor, the rotor position sensor is not required.

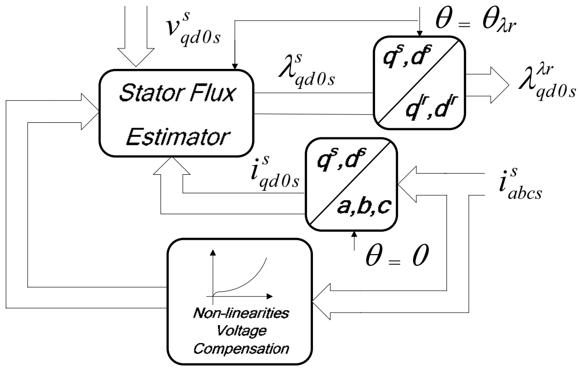

Fig. 3: Stator flux estimator with voltage compensation.

The block diagram control scheme of IFOC (Indirect Field Oriented Control) is displayed in Fig. 4. The slip signal is obtained by the q-d axes feedback current components, synchronous with the rotor flux reference frame. The current control loop imposes the appropriate amplitude and phase shift of the stator current vector in the three tests required by the proposed parameter estimation.

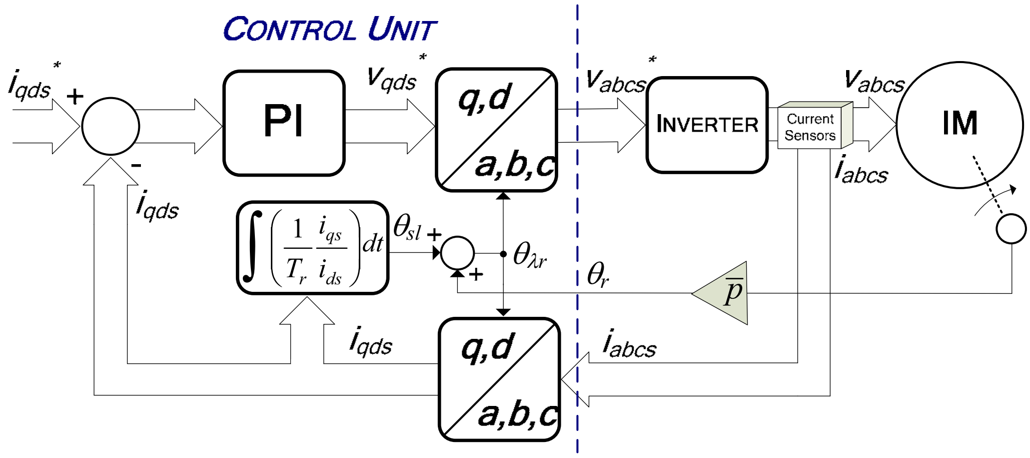

Fig. 4: Indirect Field Oriented Control Scheme

Experimental results obtained applying different methods to the measuring of the motor parameters are shown in Tab. IV and V, respectively for Motor I and Motor II. As one can see, the proposed measurement technique provides comparable results with those obtained by other approaches for Motor I, while a higher error in the estimation of some parameters can be observed for Motor II. The main reason of these errors are sensor accuracy and a non perfect compensation of the nonlinearities introduced by the use of the inverter. In fact, since in Motor II the values of the electrical parameters are small, the rotor locked tests at rated current require small phase voltages; hence, inaccuracy in the measurement or in the compensation algorithms can produce large errors.

Tab. IV: Comparison of the results obtained by performing different approaches on Motor I

Parameters	IEEE STP	Zero Sequence	FEA	Proposed Method
R_s (Ω)	9,500	9,500	9,500	9,500
L_{ls} (H)	0,023000	0,021189	0,019000	0,021795
R_{fe} (Ω)	695,0000	----	700,4914	----
M (H)	0,476000	----	0,500600	0,497786
L_{lr} (H)	0,023000	----	0,019000	0,022634
R_r (Ω)	8,370	----	8,201	8,729

Tab. IV: Comparison of the results obtained by performing different approaches on Motor II

Parameters	IEEE STP	Zero Sequence	Proposed Method
R_s (Ω)	0,7	0,7	0,7
L_{ls} (H)	0,00644	0,005926	0,006121
M (H)	0,1998	----	0,1796
L_{lr} (H)	0,00644	----	0,008073
R_r (Ω)	0,750	----	0,630

Figs. 5-10 show some experimental results obtained during the three rotor locked tests. It is possible to note, that with the exception of test 1, the phase stator currents of the motor have the same amplitudes and different frequencies, which are dependent on the slip angular frequency given by the field oriented condition. The q-d axes voltages used for parameters estimation are the output of the PI current regulator, after performing suitable correction of the voltage drop due to the power devices, of the DC bus variations, and dead time.

The variables calculated in the rotor flux reference frame as the q-d axes stator flux components are almost constants; in order to remove the ripple around their average value, further digital filtering has been adopted.

As mentioned in section II, the proposed method requires field oriented condition to be correctly performed; such a requirement is obtained by the exactly knowledge of the rotor time constant τ_r.

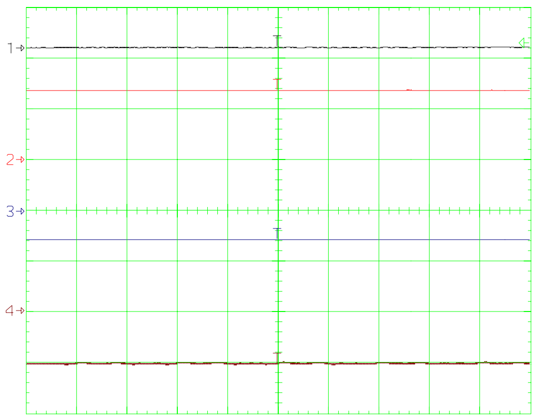

Fig. 5: Test 1 *CH1 – i_{qs} [1 A/div], CH2 – i_{ds} [1 A/div], CH3 – v_{as} [40 V/div], CH4 – i_{as} [1 A/div]; Time[10 ms/div]*

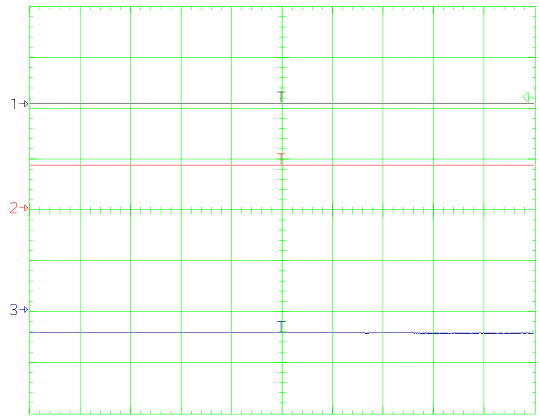

Fig. 6: Test 1 *CH1 – λ_{qs} [1 Wb/div], CH2 – λ_{ds} [1 Wb/div], CH3 – Constant A [1H/div]; Time[10 ms/div]*

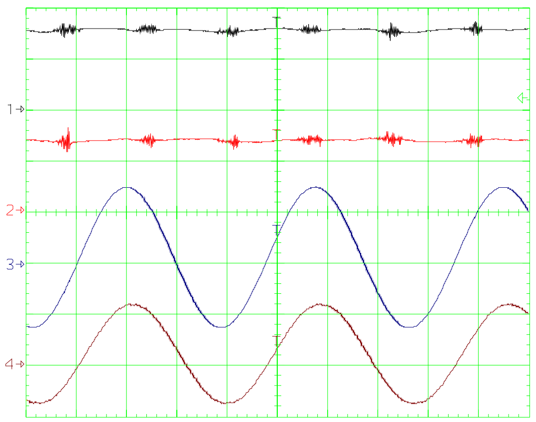

Fig. 7: Test 2 *CH1 – i_{qs} [1 A/div], CH2 – i_{ds} [1 A/div], CH3 – v_{as} [40 V/div], CH4 – i_{as} [2 A/div]; Time[100 ms/div]*

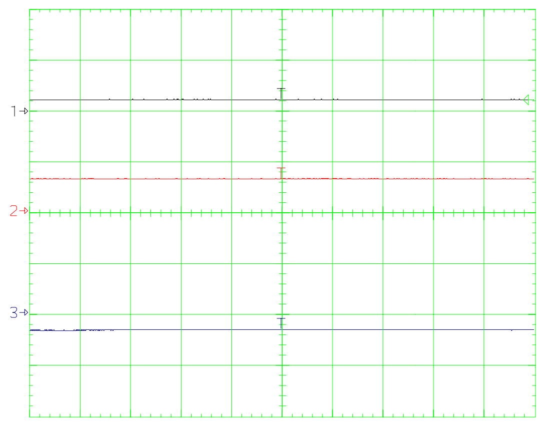

Fig. 8: Test 2 *CH1 – λ_{qs} [1 Wb/div], CH2 – λ_{ds} [1 Wb/div], CH3 – Constant B [1H/div]; Time[100 ms/div]*

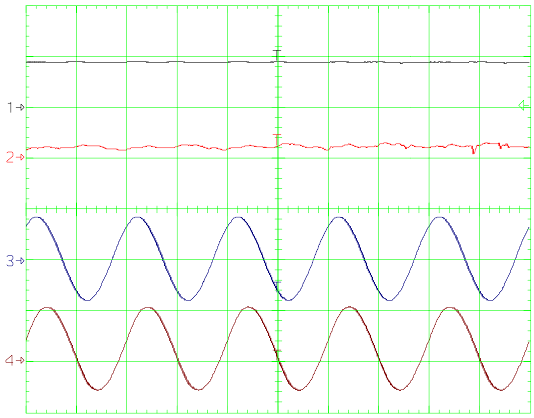

Fig. 9: Test 3 *CH1 – i_{qs} [1 A/div], CH2 – i_{ds} [1 A/div], CH3 – v_{as} [200 V/div], CH4 – i_{as} [5 A/div]; Time[10 ms/div]*

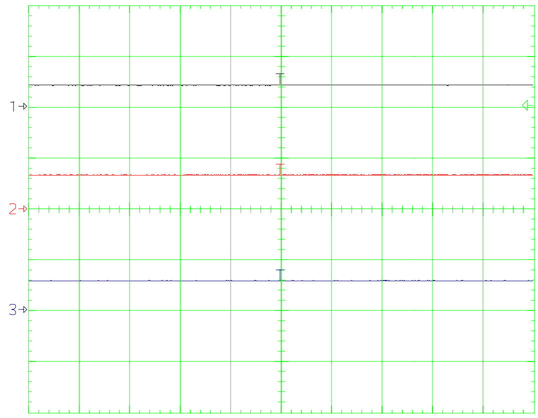

Fig. 10: Test 3 *CH1 – active power P_{cc} [100 W/div], CH2 – power factor cosf$_{cc}$ [1 1/div], CH3 – Constant C [0.1H/div]; Time[10 ms/div]*

IV. CONCLUSIONS

The main goal of this paper has been to provide a simple parameter estimation procedure which can be considered a valid alternative to other estimation methods, especially in terms of computational efforts. Simulations and experimental tests have confirmed the validity of the proposed approach with respect to other techniques.

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APPENDIX A – LIST OF SYMBOLS

- v_{qs}, v_{ds}, v_{0s} : stator voltages components in the q,d,0 reference frame rotating at ω.
- i_{qs}, i_{ds}, i_{0s} : stator currents components in the q,d,0 reference frame rotating at ω.
- v_{qr}, v_{dr}, v_{0r} : rotor voltages components in the q,d,0 reference frame rotating at ω, referred to stator.
- i_{qr}, i_{dr}, i_{0r} : rotor currents components in the q,d,0 reference frame rotating at ω, referred to stator.
- $\lambda_{qs}, \lambda_{ds}, \lambda_{0s}$: stator fluxes components in the q,d,0 reference frame rotating at ω.
- $\lambda_{qr}, \lambda_{dr}, \lambda_{0r}$: rotor fluxes components in the q,d,0 reference frame rotating at ω, referred to stator.
- R_s : stator resistor.
- R_r : rotor resistor, referred to stator.
- R_{fe} : iron losses resistor.
- L_{ls} : stator leakage inductance.
- L_{lr} : rotor leakage inductance, referred to stator.
- τ_r : rotor time constant.
- M : linkage inductance.
- T_e : motor Torque.
- T_r : load Torque.
- ω_r : rotor speed.
- $\overline{p}$: pole pairs.
- J : inertia.
- F : viscous friction coefficient.