Implementation of an alpha-beta Coordinates Speed Observer for a Squirrel Cage Induction Machine Using an Adaptive Scheme

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Abstract

This Master thesis appears from the requirement of design and implements a vector and sensorless speed controller for a squirrel-cage induction machine. The results achieved are supposed to be used in the electric powertrain of the Fiat Seicento Elettra vehicle belonging to the VIENA project.

The linearized state space model of the induction machine was first developed, the machine parameters determined, and the machine simulated. The voltage sensing circuits were designed and developed, as well as the data processing and the speed observer. For these last two steps, an Arduino Duo was used. Lastly, experimental tests were performed, with a direct connection to the power grid, and also using a inverter in between, with and without load, to validate the observer, together with the simulation.

Accordingly, the study of the observer was made by using an experimental bench, with an induction motor mechanically coupled to a DC generator, simulating the mechanical load. The experimental results show that this observer implementation can not correctly estimate the speed evolution during the motor starting when connected direct to the power grid. Moreover, the estimated torque values have a still significant error due to the fact that the state variables are not being accurately estimated, causing then a slightly deviation in the estimated motor speed 2% at maximum. The obtain simulations are in line with this behavior.

Keywords: Induction motor , Inverter, Observer, Sensorless control

1. Introduction

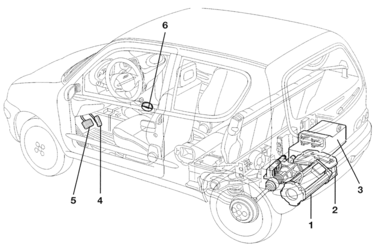

Figure 1: Fiat power train representation.

Ref.	Designation
1	Induction Machine
2	Differential
3	Inverter
4	Accelerator
5	Braking
6	Gear selector

Table 1: Fiat power train representation.

Regarding the electric car, and in particular the Fiat Seicento Elettra, Figure 1, which is the car in study, it is necessary to measure the motor's power signal, and speed in order to perform a speed control loop in the system. However, and given its electromechanical physics, a very appealing approach is to use its electrical quantities to estimate the motor's mechanical quantities, such as speed and torque. This approach, dismiss the need of using speed sensors, making the physical system more compact and simple, meanwhile and in order to drive the Fiat car again, some of the original components have been replaced.

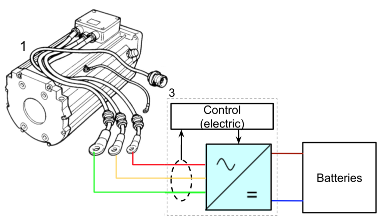

Figure 2: Power train.

The general scheme of the electric power train, where the induction motor, is controlled by the Siemens inverter, which is powered by the 600 V batteries.

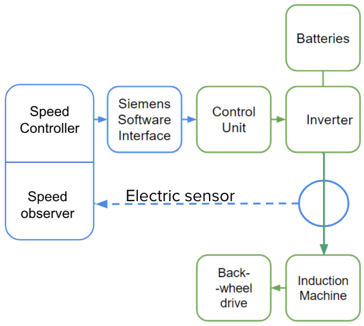

Figure 3: Hierarchy structure sensorless.

The more conventional way of making the speed control is with a speed sensor, in order to implement a simple feedback loop, with real time measurements of the speed. Finally it is also necessary use electric sensors for voltage and current measurement in each motor phase. Alternatively, it is possible to implement a sensorless controller using and speed observer, as shown in Figure 3, where the internal elements which are a physical part of the car's elements are highlighted in green, while the auxiliary elements are highlighted in blue. The mechanical speed would be estimated using the electrical quantities present in the motor, instead of measuring.

Regarding the speed observer, the most used method to estimated the speed of an induction motor is an Adaptive Speed Observer [1] and [3] , this method, the induction motor is treated as an linear system, in which the state variables $\mathbf{x}$ are the stator currents and the rotor fluxes or currents, and the applied voltage $\mathbf{u}$ is the input signal. However, this linear system is constantly being adjusted by the estimated speed value, which is not considered to be a system's state but it changes the differential equations coefficients. Hence a determined function $A\mathbf{x}+B\mathbf{u}$, can be used to compute the predicted state from the previous state, while another function $L(\mathbf{y})$ working in feedback loop, adjusts the predicted state with the actual state measurement $\mathbf{y}$.

2. Induction Motor

An induction motor, also known as an asynchronous motor, is an electric alternating current (AC) machine capable to produce rotation motion by electromagnetic induction from the magnetic field created in the stator winding. In the present application, the rotor used is a squirrel-cage which makes the motor self-starting, more reliable and more efficient [5].

2.1. Mathematical Representation

The following assumptions are considered for the present scenario:

1. Hypothesis of magnetic linearity, the material is characterized by having a proportionality relation between the magnetization and the magnetic field $\overrightarrow{M} = \chi_m \overrightarrow{H}$. Thus it is possible to write the following relation:

$$\overrightarrow{B} = \mu_0(\overrightarrow{H} + \overrightarrow{M}) = \mu_0(1+\chi_m)\overrightarrow{H} = \mu\overrightarrow{H} \quad (1)$$

2. Joule losses in the iron are neglected;
3. The electric source feeds the machine with sinusoidal distribution voltages;
4. The magneto-motive force has a sinusoidal distribution, the lumped parameters is only valid for sinusoidal qualities.
5. There is no change in temperature during operation, the change of temperature changes the electric parameters of the system.
6. The skin effect on conductors are negligible;

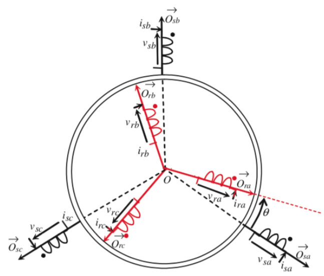

Figure 4: Concentrated parameters representation - source [2].

Writing the differential equations that govern the system in coordinates dqo:

Stator:

$$\begin{cases} \frac{d}{dt}[\phi_s^d] = v_s^d - R_s i_s^d + \omega_s \phi_s^q \\ \frac{d}{dt}[\phi_s^q] = v_s^q - R_s i_s^q - \omega_s \phi_s^d \end{cases} \quad (2)$$

Rotor:

$$\begin{cases} \frac{d}{dt}[\phi_r^d] = v_r^d - R_r i_r^d + \omega_r \phi_r^q \\ \frac{d}{dt}[\phi_r^q] = v_r^q - R_r i_r^q - \omega_r \phi_r^d \end{cases} \quad (3)$$

where ϕ_s is the stator flux, in each component d and q; ϕ_r is the rotor flux, in each component d and q; v_s is the applied stator voltage, in each component d and q; v_r is the rotor voltage, in each component d and q; R is the resistance of windings from stator or rotor; ω_{sr} is the angular speed of the stator frame or rotor frame.

Mechanical:

$$\begin{cases} \frac{d\omega_m}{dt} = \frac{1}{J}(T_e - T_{load} - T_{losses}) \\ T_e = \frac{3}{2}\frac{pM}{L_r}\left(\phi_r^d i_s^q - \phi_r^q i_s^d\right) \end{cases} \tag{4}$$

where ω_m is the mechanical angular speed; T_e is the electric torque; p the number of pare of poles; i_s is the stator current, in each component d and q; M mutual inductance; L_{sr} is self inductance, stator or rotor.

Using the state equations for the stator (2) and rotor (**??**) of the machine, and since the rotor windings are in short circuit, there is no voltage applied to them.

$$\begin{cases} v_s^d = R_s i_s^d - \omega_s\left(\sigma L_s i_s^q + \dfrac{M}{L_r}\phi_r^q\right) + \\ \quad + \left(\sigma L_s \dfrac{di_s^d}{dt} + \dfrac{M}{L_r}\dfrac{d\phi_r^d}{dt}\right) \\ v_s^q = R_s i_s^q + \omega_s\left(\sigma L_s i_s^d + \dfrac{M}{L_r}\phi_r^d\right) + \\ \quad + \left(\sigma L_s \dfrac{di_s^q}{dt} + \dfrac{M}{L_r}\dfrac{d\phi_r^q}{dt}\right) \\ 0 = \frac{R_r}{L_r}\left(\phi_r^d - M i_s^d\right) - \omega_r\phi_r^q + \frac{d\phi_r^d}{dt} \\ 0 = \frac{R_r}{L_r}\left(\phi_r^q - M i_s^q\right) + \omega_r\phi_r^d + \frac{d\phi_r^q}{dt} \end{cases} \tag{5}$$

2.2. Observer

Toward designing a speed observer, Figure 5, for the present induction motor, it is necessary to use the state space equations, with (5) it is possible to emulate the behavior of the system, when subjected to a certain input signal.

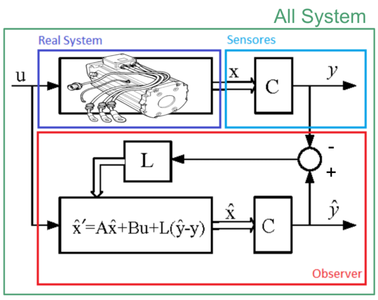

Figure 5: Luenberger observer representation.

Hence, and in order to estimate the value of the speed of the machine, it is necessary to know the electric quantities such as our state space variables, and also the applied voltages. In these equations, the electric quantities are described in dqo coordinates, known as a rotating frame, which is a general case for a $\alpha\beta$ stationary frame. The error between the currents of the stator measured and their estimations will guide the observer, while providing estimations for all the variables, due to the mathematical representation of the system behavior.

For a continues time linear system:

$$\begin{cases} \frac{d}{dt}\mathbf{x} = A\mathbf{x} + B\mathbf{u} \\ \mathbf{y} = C\mathbf{x} + D\mathbf{u} \end{cases} \tag{6}$$

The stator electrical quantities currents and volatges in the stator are being monitored by the sensors. So in $\alpha\beta$ frame ($\omega_{frame} \equiv \omega_s = 0$).

$$A = \tag{7}$$

$$\begin{bmatrix} -\frac{M^2R_r+L_r^2R_s}{\sigma L_s L_r^2} & \omega_s & \frac{MR_r}{\sigma L_s L_r^2} & \frac{M}{\sigma L_s L_r}p\omega_m \\ -\omega_s & -\frac{M^2R_r+L_r^2R_s}{\sigma L_s L_r^2} & \frac{M}{\sigma L_s L_r}p\omega_m & \frac{MR_r}{\sigma L_s L_r^2} \\ M\frac{R_r}{L_r} & 0 & -\frac{R_r}{L_r} & \omega_s - p\omega_m \\ 0 & M\frac{R_r}{L_r} & -\omega_s + p\omega_m & -\frac{R_r}{L_r} \end{bmatrix}$$

$$\mathbf{x} = \begin{bmatrix} i_\alpha \\ i_\beta \\ \phi_\alpha \\ \phi_\beta \end{bmatrix}; \quad B = \begin{bmatrix} \frac{1}{\sigma L_s} & 0 \\ 0 & \frac{1}{\sigma L_s} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \tag{8}$$

where

$$\sigma = 1 - \frac{M^2}{L_r L_s} \tag{9}$$

$$\omega_r = \omega_s - p\omega_m \tag{10}$$

And:

$$\mathbf{y} = \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}; \quad C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}; \quad D = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \tag{11}$$

Accordingly, as represented in the figure 5, the observer looks as:

$$\begin{cases} \frac{d\hat{\mathbf{x}}}{dt} = A\hat{\mathbf{x}} + B\mathbf{u} + L(\hat{\mathbf{y}} - \mathbf{y}) \\ \hat{\mathbf{y}} = C\hat{\mathbf{x}} \end{cases} \tag{12}$$

Where, $\hat{\cdot}$ means the estimation of the physical quantity, and the L is the observer gain matrix, that must be carefully chosen so the system remains stable.

$$\hat{\mathbf{x}} = \begin{bmatrix} \hat{i}_s^\alpha \\ \hat{i}_s^\beta \\ \hat{\phi}_r^\alpha \\ \hat{\phi}_r^\beta \end{bmatrix}; \quad \mathbf{u_s} = \begin{bmatrix} v_s^\alpha \\ v_s^\beta \end{bmatrix} \tag{13}$$

In order to estimate the motor's rotating speed, it is necessary to measure the stator currents, which are easily accessible and also the voltages values, which are our input signals.

Then it is necessary to ensure, that the present system is observable, meaning that any possible sequence of states can be determined, in finite time, using only the outputs. Consequently using the observability index $[O]$, it is possible to check whether the system is observerble or not.

The system is:

$$\begin{cases} rank[O] = k, & Observable \\ rank[O] < k, & Unobservable \end{cases} \tag{14}$$

Where,

$$[O] = \begin{bmatrix} CA^0 \\ CA^1 \\ \vdots \\ CA^{k-1} \end{bmatrix} \Rightarrow \begin{bmatrix} C \\ CA^1 \\ CA^2 \\ CA^3 \end{bmatrix}_{[8\times 4]} \tag{15}$$

$$rank[O] = 4 \Rightarrow Observable$$

Being that k is the number of linear independent rows of matrix A ($k = 4$), and $\forall \omega_{mec} \in \mathbb{R}$.

Despite unknowing one of the parameters of the matrix A, the rotor speed $\hat{\omega}_r$, it is possible to estimate the states $\hat{\mathbf{x}}$ and also the rotor speed all together. Accordingly, the adaptive scheme can be used, and the speed estimation, will be used to fill in the missing values of the matrix A.

The observer, is written as the following state space equation:

$$\frac{d}{dt}\hat{\mathbf{x}} = \hat{A}\hat{\mathbf{x}} + B\mathbf{u_s} + L(\hat{\mathbf{I_s}} - \mathbf{I_s}) \tag{16}$$

Toward determine the values assigned to the matrix L, derived by the adaptive scheme, it is necessary to use the Lyapunov's Therorem. Writing down the expression of the estimation error of the states:

$$\mathbf{e} = \mathbf{x} - \hat{\mathbf{x}} \tag{17}$$

$$\begin{aligned} \frac{d}{dt}\mathbf{e} &= \frac{d}{dt}\mathbf{x} - \frac{d}{dt}\hat{\mathbf{x}} \\ &= A\mathbf{x} + B\mathbf{u_s} - \hat{A}\hat{\mathbf{x}} - B\mathbf{u_s} - L(\hat{\mathbf{I_s}} - \mathbf{I_s}) \\ &= A\mathbf{x} - \hat{A}\hat{\mathbf{x}} + LC(\mathbf{x} - \hat{\mathbf{x}}) \\ &= (A + LC)\mathbf{e} - [\hat{A} - A]\hat{\mathbf{x}} \end{aligned} \tag{18}$$

where

$$[\hat{A} - A] = \begin{bmatrix} 0 & 0 & 0 & c\Delta\omega_m \\ 0 & 0 & -c\Delta\omega_m & 0 \\ 0 & 0 & 0 & -\Delta\omega_m \\ 0 & 0 & \Delta\omega_m & 0 \end{bmatrix} \tag{19}$$

$$\Delta\omega_m = \hat{\omega}_m - \omega_m; \qquad c = \frac{M}{L_s L_r - M^2};$$

Now, we define the following Lyapunov function candidate:

$$V = \mathbf{e}^T\mathbf{e} + \frac{(\hat{\omega}_m - \omega_m)^2}{\lambda} \tag{20}$$

where λ is a positive constant. Deriving the function candidate V

$$\begin{aligned} \frac{d}{dt}V = \mathbf{e}^T[(A + LC)^T + (A + LC)]\mathbf{e} - \\ - 2c\Delta\omega_m(e_s^\alpha \hat{\phi}_r^\beta - e_s^\beta \hat{\phi}_r^\alpha) + 2\Delta\omega_m \frac{d}{dt}\frac{\hat{\omega}_m}{\lambda} \end{aligned} \tag{21}$$

where $e_s^\alpha = I_s^\alpha - \hat{I}_s^\alpha$ e $e_s^\beta = I_s^\beta - \hat{I}_s^\beta$. When the matrix L is chosen so the first equation term $[(A + LC)^T + (A + LC)]$ is negative definite, the second and third term on the right hand side must cancel each other, so that (21) is negative definite

$$\frac{d}{dt}\hat{\omega}_m = c\lambda(e_\alpha \phi_r^\beta - e_\beta \phi_r^\alpha) \tag{22}$$

Since the motor speed can shift quite quickly, an integral and proportional adaptive scheme is used, so the system's response can be as improved as possible. Therefore, the estimated speed is determined by

$$\hat{\omega}_m = K_{Pes}(e_\alpha \phi_r^\beta - e_\beta \phi_r^\alpha) + K_{Ies}\int_0^t (e_\alpha \phi_r^\beta - e_\beta \phi_r^\alpha) \quad dt \tag{23}$$

whereas both variables K_{Pes} and K_{Ies} are a positive gain.

Regarding the value assign to the matrix L, there were chosen so the observer poles are proportional to those of the induction machine, according to the reference [3].

$$[L] = \begin{bmatrix} L_1 & -L_2 \\ L_2 & L_1 \\ L_3 & -L_4 \\ L_4 & L_3 \end{bmatrix} = \begin{bmatrix} L_1 & 0 \\ 0 & L_1 \\ L_3 & 0 \\ 0 & L_3 \end{bmatrix} + \begin{bmatrix} 0 & -L_2 \\ L_2 & 0 \\ 0 & -L_4 \\ L_4 & 0 \end{bmatrix} \tag{24}$$

where

$$L_1 = (k_L - 1)\left(\frac{1}{\sigma T_s} + \frac{1}{\sigma T_r}\right) \tag{25}$$

$$L_2 = \frac{(k_L - 1)}{2\pi}\hat{\omega}_m(p)^* \tag{26}$$

$$\begin{aligned} L_3 = (k_L^2 - 1)\left[\left(\frac{1}{\sigma T_s} + \frac{1}{\sigma T_r}\right)\frac{\sigma L_s L_m}{L_r} - \frac{L_m}{T_r}\right] + \\ + \frac{\sigma L_s L_m}{L_r}\left(\frac{1}{\sigma T_s} + \frac{1}{\sigma T_r}\right)(k_L - 1) \end{aligned} \tag{27}$$

$$L_4 = -(k_L - 1)\frac{\sigma L_s L_m}{L_r}\hat{\omega}_m(p)^* \tag{28}$$

*It was empirically verified, that the observer had a better performance when index L_2 and L_4 were not multiplied by the number of pair of poles (p), so the matrix [L] has this small modification.

In order to obtain the motor parameters of the machine used as a motor, it was done two motor's tests, in **No- Load test** and **Locked rotor test**, in order to obtain the induction machine equivalent circuit parameters. The results obtain are presented in the table 2.3, however the iron losses were assumed to be neglectable, reason why the value of the resistance R_m is equal to infinite.

Table 2: Equivalent circuit parameters motor.

R_s	l_s	M	R_r	l_r
3.34Ω	$15.7mH$	$232mH$	2.45Ω	$15.7mH$

The constant k_L is a empirical positive gain, while $T_r = L_r/R_r$, $T_s = L_s/R_s$ and $\sigma = 1 - L_m^2/L_sL_r$. When $k_L = 1.1$,

$$[L(\hat{\omega}_m)] = \begin{bmatrix} 19.0430 & -0.0159\ \hat{\omega}_m \\ -0.0159\ \hat{\omega}_{mec} & 19.0430 \\ 1.1992 & 0.0028\ \hat{\omega}_m \\ -0.0028\ \hat{\omega}_m & 1.1992 \end{bmatrix} \tag{29}$$

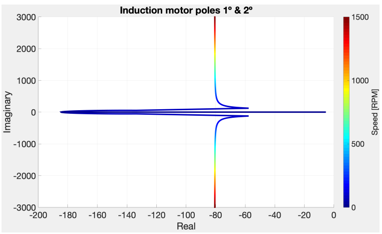

Figure 6: 1st and 2nd pole - Motor.

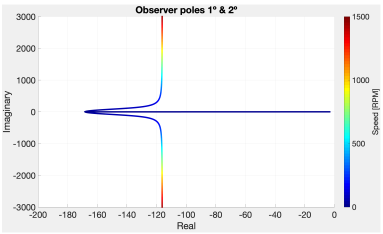

Figure 7: 1st and 2nd pole - Observer.

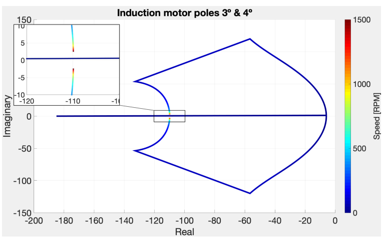

Figure 8: 3rd and 4th pole - Motor.

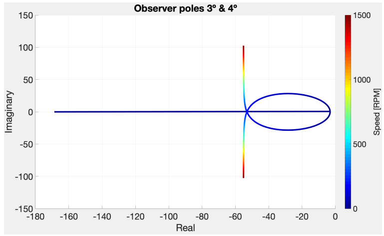

Figure 9: 3rd and 4th pole - Observer.

The induction motor poles can be determined by computing the eigenvalues of matrix $[A(\hat{\omega}_m)]$, which four values are presented in figure 6 and 8 as the mechanical speed increases. Meanwhile and regarding the observer poles, it can be computed by solving the eigenvalues of matrix $[A(\hat{\omega}_m) + L(\hat{\omega}_m)C]$, which values are represented in Figure 7 and 9.

2.3. Matlab Simaltation

When the motor is powered by an inverter system Figure 10, in order to change its operating speed, it is injected countless harmonics in the system since the voltage is no longer purely sinusoidal.

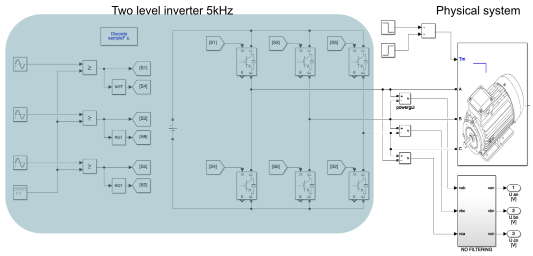

Figure 10: Simulated inverter system.

Where the parameters of table 2.3 were used.

Table 3: Simulation parameters physical system.

R_s	l_s	M	R_r	l_r
3.34Ω	$15.7mH$	$232mH$	2.45Ω	$15.7mH$

Motor	Inertia	Friction	p
Mechanical	$24g.m^2$	$0.006N.m.s$	2

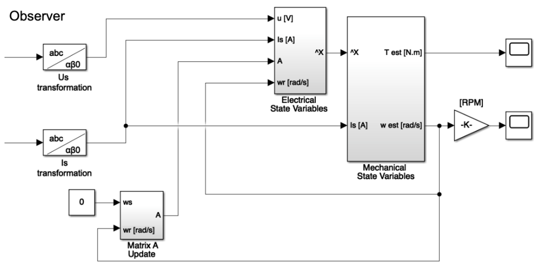

Figure 11: Simulated observer.

Table 4: Simulation parameters observer system.

R_s	L_s	M	R_r	L_r
3.34Ω	$247.7mH$	$232mH$	2.45Ω	$247.7mH$

System's	p	k_L	K_{Pes}	K_{Ies}	f_{sa}
constants	2	1.1	10	8000	100 kHz

Regarding the observer part, illustrated in the figure 11, it consists of the implementation of the computations of the acquired data from the physical model. Starting with the set of the values of the start up of the machine, with both voltages and currents present in the machine's stator, this electric quantities represented in abc time domain are firstly converted to $\alpha\beta$ reference. Meanwhile, the matrix A and L are update accordingly with the speed estimation from the last iteration. Thereupon, it is possible to compute the state variation using the equation 16 and system's state from the last iteration. Finally, and after updating the system's state it is possible to compute the new speed estimation using the equation 23. Repeating all this iterative process for each sample set of acquired data from the physical model. The parameters adopted in the construction of the observer are those presented in the table 2.3. Where the self inductance L_{sr} results in the sum of the mutual inductance M, with its respective inductance leakage l_{sr}.

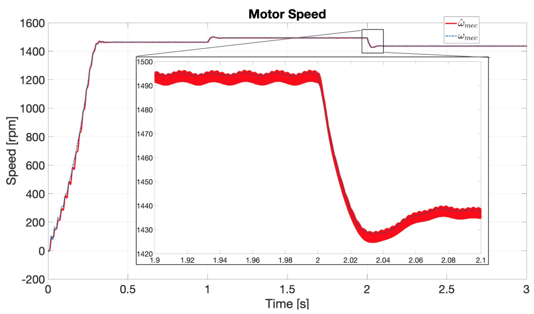

Figure 12: Observer performance - Speed with inverter.

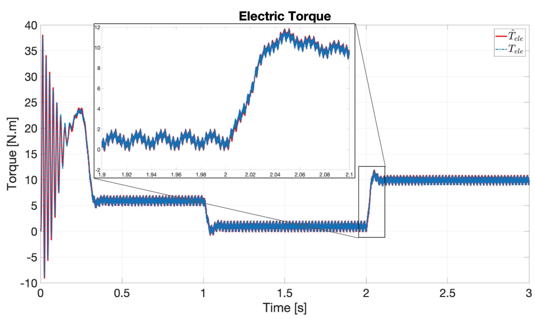

Figure 13: Observer performance - Torque with inverter.

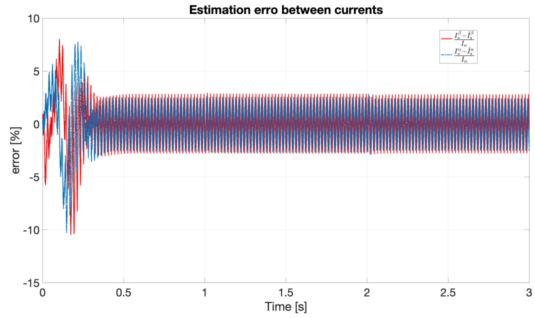

Figure 14: Error fluctuation with inverter.

In this situation figure 12, 13 and 14 the observer behaves as expected. However, there are some oscillation in the stationary values, due to the presence some harmonics in the current generated by the abrupt variations of the applied voltage.

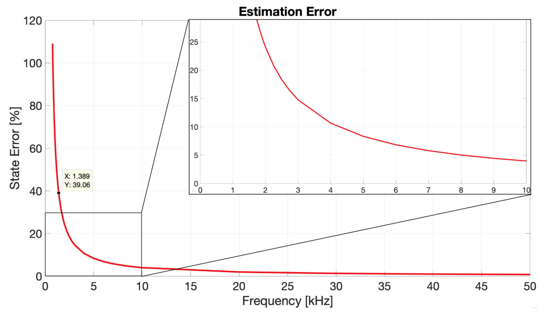

Figure 15: State error variation.

It was verified, by compering different simulations, that the reduction of the observer sampling frequency f_{sa} increased the deviation of the estimation value of the state variables, and consequently made the speed estimation worse. Thus, a sampling frequency sweep was made, in order to evaluate the offset torque error evolution with the sampling frequency. In figure 15, it is possible to check that the torque estimation error tends to zero when sampling frequency tends to infinity, according to the trend-line equation $165477 \times (f_{sa})^{-1.15}$ where $R^2 = 0.994$.

3. Implementation

The present chapter is dedicated to the implementation of the speed observer in an Arduino Due board. Sizing rest of the system in order to fulfil every specification. Finally a set of new simulation will be done according to the fixable system.

3.1. Voltage acquisition circuit

In the present application, the induction motor is set to operate at $230V_{RMS}$, meaning that each amplitude phase is set to alternate between $\pm 230\sqrt{2} \approx \pm 330V$, while the operating voltage of the Arduino is $+3.3V$. On the other hand the voltage signal is expected to have many high order harmonics, so it was chosen to implement a first order filter with a $-65dB$ of attenuation in the passing band. Then it was introduced an ampop (AMC1300) for isolation between the signals, and finally another first order filter to avoid aliasing effect, before converting the signal in digital, as shown in Figure 16.

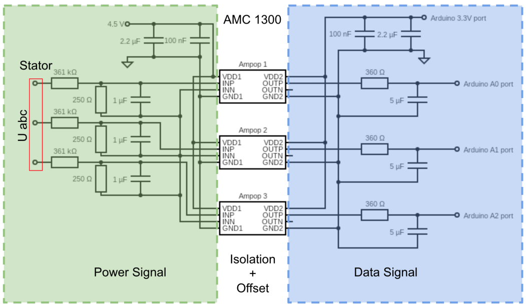

Figure 16: Voltage acquistion circuit.

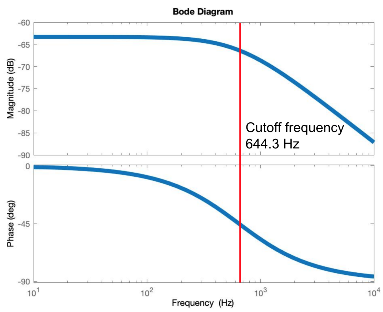

Figure 17: Filter at AMC1300 input.

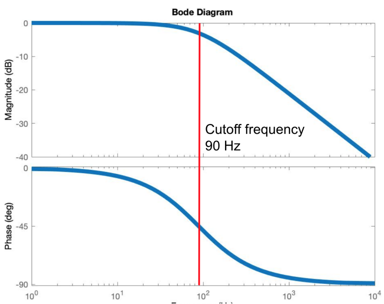

Figure 18: Filter at AMC1300 output.

Both filters used have the following bode diagram as presented in Figure 17 and 18.

3.2. Current acquisition

In order to measure the values of the current, it was used a set of three currents transducers one for each phase, in which this particular model has a full range of $\pm 80\ A$, and outputs a voltage proportional to the current passing through the device. The over all current acquisition circuit, is represented in Figure 19.

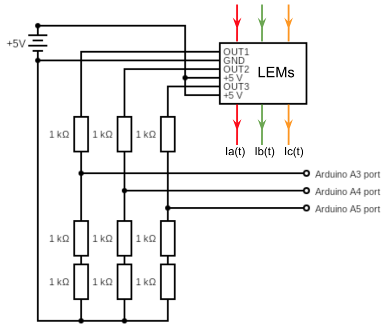

Figure 19: Filter at AMC1300 output.

3.3. Real Speed acquisition

At last it is also necessary to measure the value of the speed of the rotor, only this way it is possible to validate the data that is being produced by the observer. Hence it was used a small speed encoder, this encoder composed by a plastic disc with a shape of a cogwheel placed in the shaft of the motor, as shown in Figure 20.

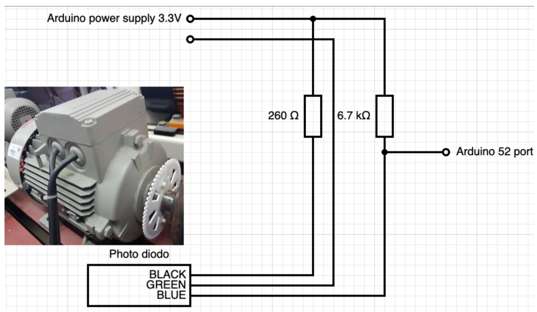

Figure 20: Speed encoder circuit.

3.4. Observer data processing

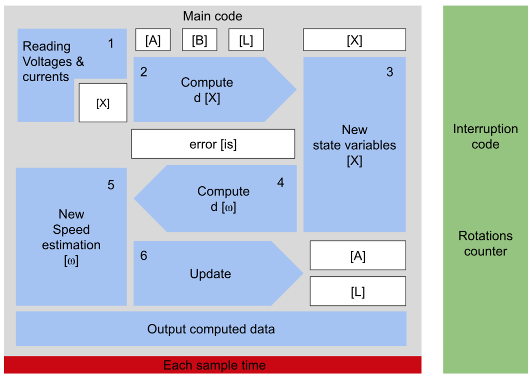

Figure 21: Observer code.

There are two main tasks that need to be performed in parallel by the Ardino. On the right hand, it is necessary to estimate the speed of the system, and in the other hand it is also necessary to measure the real speed of the motor. In the figure 21 in blue is highlighted the consecutive steps required to be performed, regarding the speed estimation, within one iteration. In the same figure in green is highlighted the real speed acquisition which is an interruption routine from the main one.

In each iteration the Arduino takes around $0.69ms$ in order to do all the computations which are the following:

1. Reading the voltage and current in each motor phase;
2. Compute the increments of state variables;
3. Update the state variable;
4. Compute the increment of mechanical speed;
5. Update the mechanical speed;
6. Update de matrices [A] and [L], using the new mechanical speed

In addition to this, it is also necessary to:

- Counting the number of revolutions of the motor's shaft - Interruption code ;
- Sending a 80 bit communication word, with the value of speed estimation, torque estimation and real value speed.

It was verified, that on average the total time for one iteration it is slightly higher than 0.68 ms. Thus, it was chosen a sampling time $T_{sa} = 0.72\ ms$, in order to give a 5% safety margin from the maximum value.

4. Results

In the present chapter, the prototype developed was tested. The set of tests started with the simplest configuration directly connected to the grid, and only after in the second set of tests the inverter was implemented in the system.

4.1. Test without inverter, no load

For the first test, the induction motor was directly connected to the electric grid, and no mechanical load was applied to its shaft.

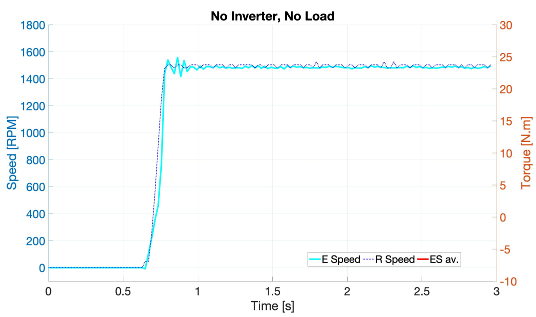

Figure 22: No inverter, no load test.

In figure 22, it is possible to check that the speed difference between its estimation and real measurement are very close from each other, with an error below 1%, however the estimation value does no converge on the accurate value.

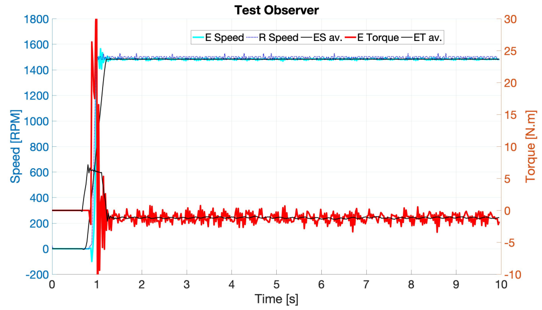

Figure 23: No inverter, no load test - Torque.

Lastly in figure 23, it is represented the motor starting, where it is possible to verify the initial torque necessary to speed up the motor, and when the motor stop accelerating that value returned to zero, approximately.

4.2. Test without inverter, with load

A direct current DC machine, which shaft is linked to the induction motor shaft, was set as a generator with its armature winding connected to a set of resistances. The induction motor in the other hand, was directly connected to the electric grid, so the motor when rotating had not only to overcome the system's inertia but also to produce the necessary torque. In the middle of the test the field excitation of the DC machine was removed, ceasing the mechanical load. This DC motor has a $K_T = 0.8$, so its applied mechanical torque is equal to

$$T_{load} = K_T\ I_{arm} \quad [N.m] \tag{30}$$

where $I_{arm}[A]$ is the DC machine armature current.

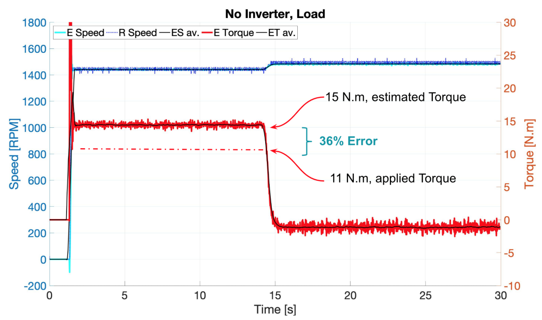

Figure 24: No inverter test with mechanical load.

In figure 24, it is possible to verify that there is a deviation in the applied torque value and its estimated value, computed by the observer. This deviation is approximately 36%, taking into account that the system's fiction torque is neglectable. This value in the order of 40% was already anticipated during the system' s simulation, figure 15. This event proves that the state variables are not being determined accurately, since the torque is computed by using all state space variables, as shown in equation 4. This error, justifies the error also verified in the motor speed estimation, which uses the motor's rotor flux and also the current error, as seen in equation 22.

4.3. Test with inverter, no load

In this test, figure 25, a inverter with a linear command V/f was introduced between the electric grid power source and the induction machine, and no extra mechanical load was produced. The motor speed was alternated by the changing of the stator voltage frequency.

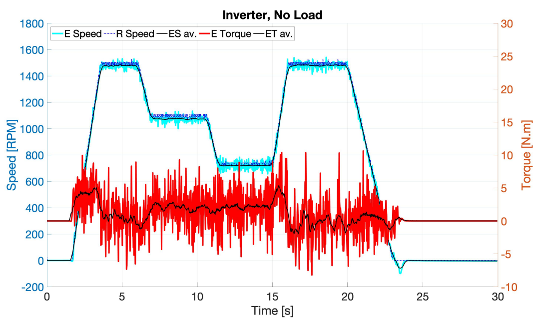

Figure 25: Inverter test, no load.

4.4. Test with invert and mechanical load

Finally in this set of tests, the invert was used and also the DC machine to generate a mechanical torque in the motor shaft, combining the two tests done before.

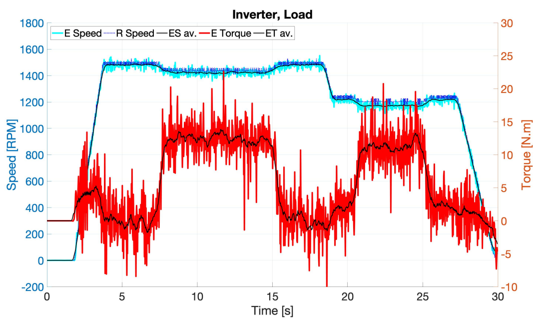

Figure 26: Inverter and load test - High speed.

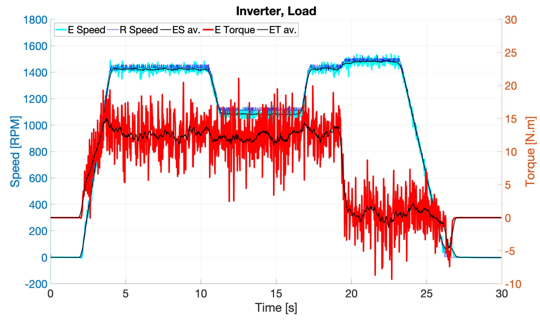

Figure 27: Inverter and load test - Torque step.

In the figure 26 and 27, the electric torque and motor speed evolution are represented however, both estimations have a deviation from its real value, $\approx 1\%$ for the speed and $\approx 40\%$ for the torque, in addition the torque estimation presents a high frequency oscillation.

5. Conclusions

The purpose of this thesis was to study the induction motor and to develop a speed observer, which by measuring the motor's input stator voltages and stator currents signals would estimate the motor's speed and torque.

It was initially expected that the implemented system could replicate the same results as it is presented in the Section 2.3. However, during the system's hardware implementation it was noticeable that some compromises needed to be made, such as the reduction of the sample frequency of the system and consequently the implementation of some filtering capabilities in the voltages acquisition circuit. The lower sample frequency, due to the limited computational power of the Arduino board, which must finish all computations necessary between samples. The filter needed is present in order to prevent aliasing from happening in the electric voltage signal, since the inverter introduces a lot of high order frequencies in the voltage signal. Notwithstanding, due to the implementation commitments, it was obvious that they played a pivotal role in the general outcome of the prototype and therefore alter the expected initial results which were very promising therefore, it was not possible to achieve the proper system performance which did not permit a convergence to the accurate value. Eventually, the final system produces state estimations which are not accurate enough, materializing in a 40% error in the torque estimation, and a 2% maximum deviation of the speed.

Nevertheless, this work greater achievement was the implementation of the adaptive observer system in a real time processing hardware, allowing an instant measurement of the speed and torque (estimated) in other words, emulating a speed and torque sensor. The results obtained are not far from the real ones, and the estimated values would have been better, if the observer's sampling frequency were higher.

5.1. Future work

As it was clear from the results presented in the previous chapter 4, there are some aspects that can be reevaluated and improved.

1. Evaluating the possibility of implementing the observer using another approach, just as the Extented Kalman Filter, which is more reliable implementation. In a EKF implementation the closed loop function, responsible for adjusting the forecast value with the measurement value, are determine in a optimally manner, considering the impressions in the estimation values and also noise in the electric measurements. Where, according to [4]:

$$[A_{EKF}] = \begin{bmatrix} A(\omega_r) & 0 \\ 0 & 0 \end{bmatrix}; \quad [\mathbf{x}_{EKF}] = \begin{bmatrix} i_s^d \\ i_s^q \\ \phi_r^d \\ \phi_r^q \\ \omega_r \end{bmatrix} \tag{31}$$

$$[B_{EKF}] = \begin{bmatrix} B \\ 0 \end{bmatrix}; \quad [C_{EKF}] = \begin{bmatrix} C & 0 \end{bmatrix}$$

2. **Adaptive observer implementation**.
   (a) Using a more selective voltage filter, capable to prevent aliasing, but does not affect the other harmonies that can be sampled by the system.
   (b) Increase the sampling frequency of the observer. By implementing a more efficient communication system, and using a more powerful processor in the hardware.
   (c) Implementing a *dqo* frame in instead of using $\alpha\beta$ frame. This implementation will help the system to converge, since in steady state the input signal, stator voltage, will be a constant value. However, this requirement demands the observer to know the inverter applied frequency, increasing the complexity of the system.
3. Implement the overall circuit in a Printed Circuit Board - PCB.

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