Flux Observation of Induction Machine Based on the Enhanced Sensorless Voltage Model

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Abstract. This paper presents the identification of the rotor flux of the induction machine. In the field-oriented control topology, since the terminal stator voltages are a pulsating voltage, so the only way is to calculate the reference values of the voltages from the inverter states phase. At very low speed, the reconstructed voltages are nearly not real, so that, the range of speed rotation of an encoder-less field-oriented control is not quite enough to cover all the speed range. However, the design of a 3-phase inverter which is prepared by silicon carbide (SiC)-MOSFETs with inserting an output filter between the inverter and the machine may supply sinusoidal voltages and currents at the output. The high switching frequency which can be applied with the SiC MOSFETs permits the proposal and implementation of a small low pass LC filter that can be equipped with the inverter output side. With this structure, it is possible to reduce the harmonic of the output voltages in addition to reduce the content of the current harmonics causing in a practically sinusoidal voltage as confirmed in the experimental results of this work. The main goal of this outline is two points, on the first side it can be reduce the winding machine stress, therefore, it is minimizing the harmonic in the voltages at the machine terminals. And on the other hand, is to use the measured voltages as an alternative of the recalculated ones to enhance the voltage model and the performance of the control scheme. It is predictable that the range of machine speed of an encoder-less field-oriented control can be extended.

1. Introduction
In the field of control, the most important technique, which is used to control the induction machine, is the sensor-less field-oriented control. Due to the increased reliability and the lower cost of a system by minimizing the sensor cost, a research focuses on the removal the sensors of the speed or position in the variable-frequency drives was done [1] and [2]. For the deriving of a three-phase machine, the high switching frequency is dispensable in traditional tasks.
To reduce the undesirable effects of the non-sinusoidal voltage; a high-frequency inverter is used, whereas the output voltage can be filtered and turned into a nearly sinusoidal voltage which may enhance the act of the sensorless control. Moreover, the two-level, three-phase, Voltage Source Inverter (VSI) prepared with
2. Methods controlling the IM based on the fundamental model

In a real application, the non-sinusoidal power reduces the efficiency of the motor and it is lifetime. The mathematical model in a complex form for the induction machine has been widely proposed for the controlling of the machine [5]. Vector control that also called field oriented control (FOC), was considered in the seventies of the last century [5]. Field orientation and vector control of an asynchronous motor, among other things, are explained in the publications [6]-[9]. In order to avoid the using of a speed sensor, a sensor less voltage model control the induction machine is applied [8], [9] and [10]. The most considerable disadvantage of this method is the attendance of the two integrators, which are used for the determination of the rotor fluxes. To overcome the problem of the integrator, many different modified voltage models were presented [11]. Some of the sources for the error reading include errors of the measurement in the current sensor such as offsets or noise, in addition to the change of temperature that effect on the value of the stator resistance R1 [12]. All these parameters lead to an inaccurate estimation of the stator flux, according to the integration, in particular at very low stator frequencies and unloaded machine. Various approaches pursue a way to make a pure integration less sensitive to these effects, e.g., a first-order delay element sets the integrator.

The classical field-oriented control block diagram shown in Figure 1. All the control process in addition to the transformation and inverse transformation are mentioned.

Figure 1. Block diagram of the classical FOC-scheme

3. Field Oriented Control

The control techniques of the induction machine use the rotating reference frame aligned with the rotor flux space phasor. So, it is important to identify the angular position of the stator flux space phasor for field-oriented control [13] and [14]. The rotor flux space phasor angular must be calculated from the corresponding machine models. In sensor-less mode, the models may only be determined by on the electrical measurable quantities, such as the currents and voltages, for calculation of the magnetic flux. The mechanical speed can be involved in the calculation at the operation with a speed sensor, as well. Normally, to calculate the position
of the rotor flux space phasor there are two possible models, which are well known and widespread in use: the current and the voltage model.

4. Current Model
This model is thought out as a simple approach to assume the rotor flux space phasor by using the position of the rotor angular along with the measured stator currents. In addition, the angular position of the rotor may acquire by employing an encoder that is involved to the induction machine shaft [15]. Figure 2 shows the block diagram of the current model. It is clear to notice that at constant flux, the quadrature current component is relative to the angular frequency that represents the rotor flux rotation. Due to the proportionally of the quadrature current component to the develop torque, is normally named the torque producing factor.

![Figure 2. block diagram of the current model](image)

The current model depends on the rotor voltage equation:

$$0 = R_2 \cdot \dot{i}_2 + j \cdot (\varphi_2 \cdot \dot{\varphi}_2) \cdot \psi_2 + \frac{d\psi_2}{dt}$$ (1)

Regarding the imaginary part equation, tracks to the rotor flux angle:

$$\varphi_2 = \int \left( \dot{\varphi}_2 + \frac{i_{q2}}{i_{\mu2} \cdot \tau_2} \right) dt = \int \dot{\varphi}_2 dt + \int \left( \frac{i_{q2}}{i_{\mu2} \cdot \tau_2} \right) dt = \varphi + \int \left( \frac{i_{q2}}{i_{\mu2} \cdot \tau_2} \right) dt$$ (2)

The magnetizing current $i_{\mu2}$ can be calculated from $i_{d2}$ and the rotor time constant $\tau_2$ as follows:

$$i_{\mu2} = i_{d2} - \tau_2 \cdot \frac{di_{\mu2}}{dt}$$ (3)

By transformation from the $uvw$ system to the $\alpha\beta$ coordinate system, $i_\alpha$ and $i_\beta$ may be obtained, and then directly to the second transformation between the $\alpha\beta$ and the $dq$ coordinate systems by using the rotor flux angle $\varphi_2$:

$$i_{d2} = i_{d2} \cdot \cos(\varphi_2) + i_{\beta2} \cdot \sin(\varphi_2)$$ (4)
\[ i_{iq} = i_{i\beta} \cdot \cos(\varphi_2) - i_{i\alpha} \cdot \sin(\varphi_2) \]  

These currents could be employed with the rotor angular position in order to calculate the rotor flux as follows:

\[ \psi_i = i \cdot \left( L_2 - \frac{L_{ih}^2}{L_2^2} \right) + \psi_{i^2} \cdot \left( \frac{L_{ih}}{L_2} \right) \]  

While this model has a wide range along with various velocity values, it shows some serious disadvantages such as the sensitivity to machine parameters which means more sensitivity to the rotor time constant that can be changeable due to the temperature and saturation. Furthermore, the presence of an additional speed sensor had been expected to reduce system reliability and increase its cost.

5. Voltage Model

The rotor flux and angular position can be obtained by using a simple method and neglecting the additional speed sensor. It can be obtained by using the voltage model technique that depends on voltages of the stator terminals and currents of the induction machine. As a consequence, this flux estimator model is considered to be a convenient method due to its simplicity as it is only a stator resistance parameter dependent. To understand the operation of this model, it’s useful to illustrate the stator windings voltage equation:

\[ u = R_i \cdot i + \psi_i \]  

The stator flux space phasor could be written as follows:

\[ \psi_i = \int (u - R_i \cdot i) \, dt \]  

The stator voltage is composed of both the induced voltage and the voltage drop across the winding resistance:

\[ u_{i\alpha}(t) = R_i \cdot i_{i\alpha}(t) + \frac{d\psi_{i\alpha}(t)}{dt} \]  
\[ u_{i\beta}(t) = R_i \cdot i_{i\beta}(t) + \frac{d\psi_{i\beta}(t)}{dt} \]  

The stator flux \( \alpha\beta \) coordinate system can be stated as follows:

\[ \psi_{i\alpha} = \int (u_{i\alpha} - R_i \cdot i_{i\alpha}) \, dt \]  
\[ \psi_{i\beta} = \int (u_{i\beta} - R_i \cdot i_{i\beta}) \, dt \]  

Where \( u_{i\alpha}, u_{i\beta}, i_{i\alpha}, i_{i\beta}, \psi_{i\alpha}, \psi_{i\beta} \) are the \( \alpha, \beta \) components of the stator voltage, stator current, and stator flux phasors respectively, \( R1 \) is the stator winding resistance. By using the stator voltages and current in addition
to the stator resistance, the stator flux can be simply calculated and then the rotor flux could be calculated from the stator flux as illustrated in Figure 3 and the machine equations:

\[ \psi_{2\alpha} = \frac{\sigma}{\sigma - 1} \cdot L_{\alpha h} \cdot i_{1\alpha} + (1 + \sigma_2) \cdot \psi_{1\alpha} \]  

\[ \psi_{2\beta} = \frac{\sigma}{\sigma - 1} \cdot L_{\beta h} \cdot i_{1\beta} + (1 + \sigma_2) \cdot \psi_{1\beta} \]  

The main advantages of the voltage model are represented by obtaining the rotor angular position \( \varphi_2 \) by using only the voltages and currents of the stator machine. However, it is easy to compensate the stator resistance for changes in the temperature.

In the traditional (VSI), nevertheless, the output voltage of this kind of inverters is quasi-square waveform and not sinusoidal, so, the output of the controller which represents the reconstructed voltages are supposed to be the stator voltages of the machine and addressed to the modulator.

6. Enhanced voltage model

It has been analyzed that is using a sensorless control topology based on the commercial voltage model of the 3-phase induction machine is a proper way to avoid using an angular sensor. As this model is used to detect the flux space phasor of the rotor and is considered to function until minimum stator frequency; different improvements have been applied as shown in Figure 4.

The main goal of this work is to evaluate the effect of replacing the reconstructed voltage with measured ones. As depicted in Figure 3, the voltage reference values (with a star), which are known as the Standard Voltage Model (SUM) is fed by the voltage model, while, the measured voltages of the induction machine (without a star) are forwarded the enhanced one and known as the enhanced voltage model (EUM) that is engaged to the machine after the low pass filter. As a result, considering the smooth measured sinusoidal voltage, it is predictable that the sensorless control will have the ability to function on a widely speed range.
Due to the machine speed signal is not obligatory, the voltage model is an acceptable flux estimator for the induction machine drives. The stator fluxes are calculated by integrate the back electromotive force (back EMF), which means, integrate the value, which found after the calculation of the voltage drop over the resistance of the stator is subtracted from the stator voltages. These two integrators are representing the main problem in the voltage model in charge of the rotor flux calculation. Due to these two integrators, a slight DC offset in measured voltages and currents causes drift problem. Therefore, this problem considered. This is the first problem, whereas the second one that is at zero speed and because of there is no value of the inductance characteristics, the machine appears as an ohmic character. So, for overcoming the first problem, there are some modified models are offered [16], these voltage models are as a weakening method, that in its place of using a pure integrator, the modified one could be used in some many forms such as:

1. Low gain feedback
2. PI element feedback

It is important to note that the correction of the angle error, which resulted by the attenuation should be done with confident limits by appropriate methods [17].

The frequency converter presents an output voltage as sequencing rectangular pulses or quasi-square waveform that differ in the width (PWM). A low pass filter has been added in order to eliminate the switching frequency noise when frequency converter feds a machine. This noise is caused by the pulse width modulated (PWM) voltage that is applied to the machine. In addition to the switching noise, the switching frequency harmonics, (especially the double of the switching frequency) has also resulted. However, adding a sine-wave filter will clean the pulse fashioned voltage from the frequency converter and yield a sinusoidal line to line terminal voltage of the induction machine. Otherwise, when no filters are used, the main source of the high-frequency noise is the pure voltage overshoot that appear at the motor terminals. This can be seen in Figures 5 and 6 that shows the inductor filter voltage and the terminal stator voltage respectively.
7. Implementation of the setup
The behavior of a system that consists of a fast-switching silicon carbide SiC-Inverter, which is equipped with an output low pass filter that feeds an asynchronous machine (IM) was experimentally confirmed. The three-phase induction machine is controlled by a digital signal processor (DSP) controller (TMS320F28335 eZdsp). The pulse width modulation was carried out with a modulation frequency of 50 kHz. The conventional two-level inverter topology that is equipped with silicon carbide switches was implemented in the laboratory is shown in

Figure 7. Conventional two-level inverter

The most important matters in the designing of this inverter are the choice of the power SiC MOSFETs that is used in the inverter, thus, eventually CCS020M12CM2 SiC MOSFET 1,2kV/20A module by CREE company was carefully chosen due to their fitness in commerce with the essential design characteristics that are listed in Table 1.

Table 1. Electrical specifications of the inverter

| Parameter                      | Value     |
|--------------------------------|-----------|
| DC link voltage, $U_{dc}$      | 560V      |
| Output power                   | 7.5kW     |
| Switching frequency $f_{sw}$   | 50kHz     |
| Fundamental frequency $f_o$    | 50Hz      |

In order to exam the enhancement of a field oriented sensorless control scheme, the laboratory induction machine has an installed encoder on the shaft, which allows easy appointing and run of the machine and sensorless drive concept. Furthermore, the encoder delivers a reference measurement signal of the frequency response as a comparison value between identification and encoder. The SiC inverter supplies a 7.5 kW of power to the induction motor (400 V, 17 A). A braking 21 kW field-oriented controlled Siemens motor drive was used as a loaded machine in the current work.

For the inverter that working with the high switching frequency, the values of the LC output filter inductor and capacitor could be smaller, thus, the total size and cost of the inverter is decreased. Also, it has a lower loss since the number of turns is decreased. In this work, the filter inductors were implemented by using a copper litzen-wire, while the capacitors that are used in a filter of six polypropylene capacitors for high switching frequency applications. Since the switching frequency which used in the inverter is $f_s = 50kHz$, ...
the capacitor and the inductor values were fixed to $C = 1.32 \mu F$ and $L = 0.1 \, mH$ respectively. The filter was considered to handle a 15 $A$ as a rated current while the saturation current was set to 35 $A$.

8. Experimental results

The investigations in the following results were made based on the input parameters are given in Table 2. The commercial two-level inverter usually delivers pulsating voltages as the output. For the high switching inverter that is integrated with a small filter at the output, the output voltages can be nearly sinusoidal as shown in Figures 6 and 7. Because of the 50 kHz switching frequency, the output voltage quality was improved and the total harmonic distortion would be reduced as shown in Figures 8 and 9.

| Parameter or variable         | Value          |
|------------------------------|----------------|
| $U_{dc}$                     | 300 V          |
| Reference speed              | 500 min$^{-1}$ |
| Switching frequency $f_{SW}$ | 50 kHz         |
| Fundamental frequency $f_o$  | $f_o = 50Hz$   |
| Sampling period              | 60             |

![Figure 8. Currents of the inductor filter](image)

![Figure 9. Currents of the stator](image)

9. Rotor flux space phasor

The field-oriented control technique using the voltage model in high-speed range is achieve the target. Based on this consideration, the achievement option was validated experimentally in this section. For this purpose, the induction machine at no load was controlled with the FOC. Figure 10 to Figure 13 are shows the rotor flux in the coordinate system of the induction machine at constant speed of $n^* = 500 \, \text{min}^{-1}$ and at low speed of $n^* = 10 \, \text{min}^{-1}$ as well. The results of the current model were used as a reference model in order to compare all other models’ behavior.

In addition to the fluxes that calculated by the voltage model, the figures contain the rotor fluxes in a coordinate system which are obtained from the current model as well. At $n^* = 500 \, \text{min}^{-1}$, which is high speed, the voltage model runs similar to a current model, i.e., the likeness in the performance becomes clearer from the unillustrated experimental results shown in Figure 10. The alpha, beta rotor fluxes were obtained by using the standard voltage model are in the same phase with the fluxes which are already obtained from the current model.

On the other hand, the SUM shows a very week behavior with an ununiformed rotor fluxes at low reference speed, $n^* = 10 \, \text{min}^{-1}$ as showed in Figure 11. The physical explanation for that is based on the fact that there
is no induced voltage at low speed while the voltages which were used in the machine model were the
reconstructed voltages obtained from the current controller output and not the measured voltages.
A measured sinusoidal voltage was gotten by inserting a small low pass filter between the inverter output and
the machine which were used as an alternative to the recalculated ones in order to improve the voltage model.
An Enhanced voltage model that presented in Figure 4 can be used for obtaining the rotor fluxes, at high
speed, \( n^* = 500 \text{ min}^{-1} \), the EUM acts an excellent result which are look similar to the current model, i.e.,
the experimental consequences shown in Figure 12 show that the rotor fluxes in alpha, beta coordinate system
were calculated from the enhanced voltage model are a very good agreement calculation.
At low reference speed and with the low pass filter used at the output of the fast-switching inverter, the
terminal voltages could be measured and, therefore, can be used in a machine model in the calculation of the
angle of the rotor flux space phasor. Different the results which are calculated from the commercial model,
which is presented in Figure 13, a well performance at low speed, \( n^* = 10 \text{ min}^{-1} \) can be obtained by using the
modified voltage model, the rotor flux that calculated from the Enhanced UM at 10 min\(^{-1}\) were presented in

10. Conclusion
The electric drive consists of the electric machine or the motor, and according to the modern understanding;
it consists of converters, sensors, control, and other instrumentation. The pulsed voltage outputs on the
converters which are fed the machines produce a broad harmonic spectrum and lead to undesirable losses,
which can be reduced by increasing the switching frequency.
A SiC MOSFET inverter with a small filter for driving a 3-phase induction machine is presented in this work. The goal is to get a sinusoidal on the machine terminals. The quality improvement of the voltages used for the improvement of the voltage model, which is employed for the rotor flux space phasor estimation. The experimental results were approved on a laboratory setup, which confirms that this control scheme can also be enhanced and showed a good steady state and dynamic performance in the torque control mode.

In order to control the induction machine, the signal of the rotor position or the position of a machine flux is needed. Since the mechanical sensors are highly sensitive to the pollution that can be resulted from aggressive environment, it is desirable to replace the speed sensor by the already existing resources in the drive. Using the sensorless control method is an alternative to the conventional method with a mechanical sensor (encoder system). Thus, using a speed estimation will increase the reliability of a drive system and eliminate the cost of a speed sensor usage.

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