Comparative study between sliding mode and DTC of doubly fed induction machine

Estudo comparativo entre modo deslizante e DTC de máquina de indução duplamente alimentada

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ABSTRACT
Although the great advance in term of AC machine construction, control strategies are also necessary to be developed and improved continuously satisfying output torque/power. Hence the Doubly fed induction motor (DFIM) is widely used in industry, since it can operate in wide range of speed variation around the synchronous speed and the control of flux and torque is independent. In this paper, control of doubly fed induction motor (DFIM) has been investigated, which two control strategies have been studied and compared: the first strategy uses a sliding mode control (SMC); the second employs Direct Torque Control (DTC). Modeling
of DFIM and details of both control strategies have been presented. The mathematical description of different basic dynamic models of the DFIM have been carried out. The performances in terms of torque tracking, accuracy and robustness of both control techniques under normal and various speed and load conditions have been demonstrated and compared.

**Keywords:** double feed induction machine (DFIM), sliding mode control (SMC), flux estimator, direct torque control (DTC), comparative study.

**RESUMO**

Embora haja um grande avanço em termos de construção de máquinas CA, também é necessário desenvolver e melhorar estratégias de controle que satisfaçam continuamente o torque/potência de saída. Daí o motor de indução duplamente alimentado (DFIM) ser amplamente utilizado na indústria, pois pode operar em ampla faixa de variação de velocidade em torno da velocidade síncrona e o controle de fluxo e torque é independente. Neste artigo foi investigado o controle de motor de indução duplamente alimentado (DFIM), onde duas estratégias de controle foram estudadas e comparadas: a primeira estratégia utiliza um controle por modo deslizante (SMC); o segundo emprega Controle Direto de Torque (DTC). Foram apresentadas modelagem do DFIM e detalhes de ambas as estratégias de controle. foi realizada a descrição matemática de diferentes modelos dinâmicos básicos do DFIM. Os desempenhos em termos de rastreamento de torque, precisão e robustez de ambas as técnicas de controle sob condições normais e diversas de velocidade e carga foram demonstrados e comparados.

**Palavras-chave:** máquina de indução de alimentação dupla (DFIM), controle de modo deslizante (SMC), estimador de fluxo, controle direto de torque (DTC), estudo comparativo.

**1 INTRODUCTION**

The huge technological development of power electronics employed in control machine area has considerably facilitated and improved their performances. Therefore, the control of doubly fed induction motor (DFIM) became more and more efficiency since it supplied by both stator and the rotor part through two independent voltage sources. Due to several advantages of DFIM, a great interest has been given for its use in both applications as motor or generator especially in variable speed wind turbine (Zemmit et al., 2018). The main advantages of DFIM are the ability to operate in wide range of speed variation around the synchronous speed (until ± 30%), the stator and rotor currents are measurable, the independent control of flux, torque, and power factor,…etc (Lekhchine et al., 2015).
Over the last few years, many control strategies of DFIM have been proposed and improved continuously, the widely used methods are the field oriented control, adaptive backstepping control strategy, artificial neural network, the fuzzy logic control (FLC), direct torque control (DTC), sliding mode control (SMC) (Abderrahim et al., 2015), ...etc.

The field oriented control (FOC) was one of the best control technique, it can transform the nonlinear and coupled DFIM mathematical model to a linear model conducting to one attractive solution as well as under generating or motoring operations, However, it highly dependent on the parameters of the induction machine and fixed gain PI controllers may become unable to provide the required control performance. Hence PI controller limitations and its complexity of implementation are the most drawbacks. Later DTC and sliding mode control (SMC) methods were introduced to overcome the previous problems of PI limitations and reducing ripple and simplify the implementation.

In this paper, Direct Torque Control and sliding mode control have been studied and applied to doubly fed induction motor (DFIM), modeling of DFIM and details of both control strategies have been explained. Analysis and comparative study have been established.

2 MODELLING OF DFIM

The DFIM model can be expressed by following equations (Abderrahim et al., 2018):

\[
\begin{align*}
V_{sd} &= R_s I_{sd} \\
V_{sq} &= R_s I_{sq} + \omega_s \phi_{sd} \\
V_{rd} &= R_r I_{rd} - \omega_r \phi_{rd} \\
V_{rq} &= R_r I_{rq} + \omega_r \phi_{rq}
\end{align*}
\]

\[
\begin{align*}
\phi_{sq} &= 0 \Rightarrow I_{sq} = \frac{M}{L_s} I_{rq} \\
I_{sd} &= 0 \\
I_{rd} &= \frac{\phi_s^*}{M}
\end{align*}
\]

(1)

The flux equations are given respectively by:

\[
\begin{align*}
\phi_{sd} &= L_s I_{sd} + M I_{rd} \Rightarrow I_{sd} = \frac{1}{L_s} (\phi_{sd} - M I_{rd}) \\
\phi_{sq} &= L_s I_{sq} + M I_{rq} \Rightarrow I_{sq} = \frac{1}{L_s} (\phi_{sq} - M I_{rq})
\end{align*}
\]

(2)
\( \phi_{rd} = \sigma L_r I_{rd} + \frac{M}{L_s} \phi_{sd} \) \hspace{1cm} (4)

\( \phi_{rq} = \sigma L_r I_{rq} + \frac{M}{L_s} \phi_{sq} \) \hspace{1cm} (5)

The electromagnetic torque and its associated motion equation are expressed respectively by:

\( C_{em} = -\frac{pM}{L_s} \phi_s I_{rq} \) \hspace{1cm} (6)

\( C_e - C_r = \int \frac{d\theta}{dt} \) \hspace{1cm} (7)

Based on direct stator flux orientation control (Zemmit et al., 2018), the DFIM model can be described by:

\( V_{rd} = R_r I_{rd} + \sigma L_r \frac{dI_{rd}}{dt} + \frac{M}{L_s} V_{sd} - (\omega_s - \omega)\sigma L_r I_{rq} \) \hspace{1cm} (8)

\( V_{rq} = (R_r + \frac{M^2}{L_s I_s}) I_{rq} + \sigma L_r \frac{dI_{rq}}{dt} + \frac{M}{L_s} V_{sq} - \frac{M}{L_s} \omega \phi_{sd} + (\omega_s - \omega)\sigma L_r I_{rd} \) \hspace{1cm} (9)

The flux estimator can be obtained by the following equations [11]:

\( \phi_{sd} = L_s I_{sd} + MI_{rd} \) \hspace{1cm} (10)

\( \phi_{sq} = L_s I_{sq} + MI_{rq} \) \hspace{1cm} (11)

The position stator flux is calculated by the following equations

In which:

\( \theta_s = \int \omega_s \ dt, \quad \theta = \int \omega \ dt, \quad \omega = P. \Omega \) \hspace{1cm} (12)

Where:

\( \theta_s \) and \( \theta \) are the electrical stator position and the electrical rotor position.
A Sliding Mode Controller (SMC) is a Variable Structure Controller (VSC). Basically, a VSC includes several different continuous functions that can map plant state to a control surface, whereas switching among different functions is determined by plant state represented by a switching function (Ammar et al., 2018).

The design of the control system will be demonstrated for a following nonlinear system (Zemmit et al., 2018):

\[ \dot{x} = f(x, t) + B(x, t).u(x, t) \]  

(13)

Where:

\[ x \in \mathbb{R}^n \text{is the state vector,} \]
\[ u \in \mathbb{R}^m \text{is the control vector} \]
\[ f(x, t) \in \mathbb{R}^n, B(x, t) \in \mathbb{R}^{n \times m} \]

The control law satisfies the precedent conditions is presented in the following form:

\[ U = U_{eq} + U_n \quad \text{and} \quad U_n = k \cdot \text{sign}(S(x, t)) \]  

(14)

Where:

\[ u \text{ is the control vector,} \]
\[ u_{eq} \text{ is the equivalent control vector,} \]
\[ u_n \text{ is the switching part of the control (the correction factor),} \]
\[ k \text{ is the controller gain.} \]
\[ u_{eq} \text{ can be obtained by considering the condition } S(x, t) = 0. \]

The equivalent control keeps the state variable on sliding surface, once they reach it.

For a defined function \( \varphi \) (Fig. 1):

\[ \text{sign}(\varphi) = \begin{cases} 1, & \text{si } \varphi > 0 \\ 0, & \text{si } \varphi = 0 \\ -1, & \text{si } \varphi < 0 \end{cases} \]  

(15)
The controller described by the equation (15) presents high robustness, insensitive to parameter fluctuations and disturbances, but it will have high-frequency switching (chattering phenomena) near the sliding surface due to $sgn$ function involved. These drastic changes of input can be avoided by introducing a boundary layer with $\varepsilon$ (Zemmit et al., 2024). Thus replacing $\text{sign}(S(t))$ by $\text{Sat}(S(x)/\varepsilon)$ in (15), we have:

$$U = U_{eq} - K \ \text{Sat}(S(x, t))$$

(16)

Where:

$$\varepsilon > 0$$

$$\text{Sat}(S(x)) = \begin{cases} 
1, & \text{si } S(x) > \varepsilon \\
-1, & \text{si } S(x) < -\varepsilon \\
\frac{S(x)}{\varepsilon}, & \text{si } |S(x)| \leq \varepsilon
\end{cases}$$

(17)
Commonly, in using sliding mode control of DFIM, the surfaces are chosen as functions of the error between the reference input signal and the measured signals. The speed error is defined by:

\[ e = \Omega^* - \Omega \]  \hspace{1cm} (18)

For \( n = 1 \), the speed control equation can be obtained as follow:

\[ S(\Omega) = e = \Omega^* - \Omega \]  \hspace{1cm} (19)

\[ \dot{S}(\Omega) = \dot{\Omega}^* - \dot{\Omega} \]  \hspace{1cm} (20)

Substituting the expression of \( \Omega \) equation (12) in equation (20), we obtain

\[ \dot{S}(\Omega) = \dot{\Omega}^* - \left( -\frac{pM}{JL_s} (I_{rq}, \phi_{sd}) - \frac{c_r}{J} - \frac{f}{J} \Omega \right) \]  \hspace{1cm} (21)

We take:

\[ I_{rq} = I_{rq_{eq}} + I_{rq_n} \]  \hspace{1cm} (22)

During the sliding mode and in permanent regime, we have \( S(\Omega) = 0, \) \( \dot{S}(\Omega) = 0, \) \( I_{rq_n} = 0 \)

Where the equivalent control is:

\[ I_{rq_{eq}} = -\frac{JL_s}{pM \phi_{sd}} \left( \Omega^* + \frac{c_r}{J} + \frac{f}{J} \Omega \right) \]  \hspace{1cm} (23)

Therefore, the correction factor is given by:

\[ I_{rq_n} = K_{I_{rq}} \text{sat}(S(\Omega)) \]  \hspace{1cm} (24)

Where:
$K_{Irq}$: negative constant.

For the stator flux control, the following equation can be given by:

$$S(\phi_{sd}) = \phi_s^* - \phi_{sd}$$  \hspace{1cm} (25)

$$\dot{S}(\phi_{sd}) = \dot{\phi}_s^* - \dot{\phi}_{sd}$$  \hspace{1cm} (26)

Substituting the expression of $\phi_{sd}$ equation (11) in equation (27), we obtain:

$$\dot{S}(\phi_{sd}) = \dot{\phi}_s^* - \left( V_{sd} + \frac{M}{T_s} I_{rd} - \frac{1}{T_s} \phi_{sd} \right)$$  \hspace{1cm} (27)

The control current $I_{rd}$ is defined by:

$$I_{rd} = I_{rd_{eq}} + I_{rd_{n}}$$  \hspace{1cm} (28)

During the sliding mode and in permanent regime, we have:

$$S(\phi_{sd}) = 0, \quad \dot{S}(\phi_{sd}) = 0, \quad I_{rd_{n}} = 0$$

The equivalent control is:

$$I_{rd_{eq}} = \left( \dot{\phi}_s^* - V_{sd} + \frac{1}{T_s} \phi_{sd} \right) \frac{T_s}{M}$$ \hspace{1cm} (29)

Where the correction factor is given by:

$$I_{rd_{n}} = K_{Ir} \text{sat}(S(\phi_{sd}))$$  \hspace{1cm} (30)

Where:

$K_{Ir}$: positive constant.
4 DIRECT TORQUE CONTROL OF DFIM

A Direct Torque and Flux Control (DTC) for a double feed Induction Machine (DFIM) become one of the high performance control strategies for AC machine to provide a very fast torque and flux control. The performance of DTC strongly depends on the quality of the estimated actual stator flux and torque. The simulation results show the effectiveness and the robustness of the proposed method in both dynamic and steady state response.

The mathematical model for the electrical parts is written as a set of equations of state following

\[ \frac{dx}{dt} = \dot{x} = AX + BU \quad (31) \]

Where X is the state variable and U is control variable, the matrices A and B are given by:

\[
A = \begin{bmatrix}
-1 & \frac{1}{T_s} & \frac{1}{M} & 0 \\
0 & -\frac{1}{T_s} & 0 & -\frac{1}{T_s} \\
-\frac{1}{T_s} & 0 & 0 & 0 \\
0 & \frac{1}{T_s} & 0 & 0
\end{bmatrix}
\]

\[
B = \begin{bmatrix}
\frac{1}{M} & 0 & 0 \\
0 & \frac{1}{L_s} & 0 \\
0 & 0 & \frac{1}{L_s} \\
0 & 0 & 0
\end{bmatrix}
\]

The electromagnetic torque is given by:

\[ C_{em} = \frac{3pM}{2L_s} (\Phi_{sa}I_{r\beta} - \Phi_{sb}I_{r\alpha}) \quad (32) \]

Direct torque control is based on the flux orientation, using the instantaneous values of voltage vector. An inverter provide eight voltage vector, among which two are zeros. This vector are chosen from a switching table according to the flux and torque errors as well as the stator flux vector position. In this technique, we don’t need the rotor position in order to choose the voltage vector. This particularity defines the DTC as an adapted control technique of AC machines and is inherently a motion sensorless control method (Aissa et al., 2024).
The block diagram for the direct torque and flux control applied to the double feed induction motor shown in Figure 3.

The stator flux $\phi_{sref}$ and the torque $C_{emref}$ are compared with respective estimated values and errors are processed through hysteresis-band controllers. The eight possible voltage vector switching configurations are shown in Table 1:

<table>
<thead>
<tr>
<th>Flux</th>
<th>Torque</th>
<th>$N = 1$</th>
<th>$N = 2$</th>
<th>$N = 3$</th>
<th>$N = 4$</th>
<th>$N = 5$</th>
<th>$N = 6$</th>
<th>Corrector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cflx=0</td>
<td>Ccpl=1</td>
<td>$V_1$</td>
<td>$V_3$</td>
<td>$V_5$</td>
<td>$V_6$</td>
<td>$V_1$</td>
<td>$V_2$</td>
<td>2 levels</td>
</tr>
<tr>
<td></td>
<td>Ccpl=0</td>
<td>$V_0$</td>
<td>$V_2$</td>
<td>$V_0$</td>
<td>$V_7$</td>
<td>$V_4$</td>
<td>$V_7$</td>
<td>3 levels</td>
</tr>
<tr>
<td></td>
<td>Ccpl=1</td>
<td>$V_5$</td>
<td>$V_6$</td>
<td>$V_1$</td>
<td>$V_2$</td>
<td>$V_3$</td>
<td>$V_4$</td>
<td>3 levels</td>
</tr>
<tr>
<td>Cflx=1</td>
<td>Ccpl=1</td>
<td>$V_2$</td>
<td>$V_3$</td>
<td>$V_4$</td>
<td>$V_5$</td>
<td>$V_6$</td>
<td>$V_1$</td>
<td>2 levels</td>
</tr>
<tr>
<td></td>
<td>Ccpl=0</td>
<td>$V_7$</td>
<td>$V_0$</td>
<td>$V_7$</td>
<td>$V_0$</td>
<td>$V_7$</td>
<td>$V_0$</td>
<td>2 levels</td>
</tr>
<tr>
<td></td>
<td>Ccpl=-1</td>
<td>$V_6$</td>
<td>$V_1$</td>
<td>$V_2$</td>
<td>$V_3$</td>
<td>$V_4$</td>
<td>$V_5$</td>
<td>3 levels</td>
</tr>
</tbody>
</table>

Source: Authors
5 SIMULATION RESULTS

5.1 RESULTS OF SLIDING MODE CONTROL OF DFIM

The simulation results for both control strategies have been tested using 0.8 kW DFIM, which parameters are listed in appendix.

Simulation results of speed and torque control using sliding mode control are shown in Fig.4. From obtained results, it can be observed the high efficiency of sliding mode control for both parameters speed and torque.

Figure 4 – Results of speed and torque control using sliding mode control
(a) speed, (b) torque (c),(d) stator current ;(e),(f) rotor current.
5.2 RESULTS OF DTC-DFIM

The Figure 5 shows speed and electromagnetic torque obtained while starting up the induction motor initially under no load then connecting the nominal load. As can be seen during the starting up with no load the speed reaches rapidly its reference value without overtaking, however when the nominal load is applied a little overtaking is noticed and the command reject the disturbance. The excellent dynamic performance of torque and flux control is clearly demonstrated.
5.2.1 Simulation results under variable speed

The simulation results obtained for a speed variation for the values: \((\Omega_{\text{ref}}=157,130,157 \text{ rad/sec})\) with the load of 5N.m applied at \(t=2s\) are shown in Figure 6. Obtained results demonstrate that the speed variation lead to the variation in flux and the torque. The response of the system is positive; the speed follows its reference value while the torque returns to its reference value with a small error.

![Figure 6 – Robust control using DTC under reversal speed.](image)

5.2.2 Simulation results under various load conditions

For a load variation \((C_r = 3 \text{ N.m and 5 N.m})\), the simulation results obtained are shown in Figure 7. As can be seen the speed, the torque and the flux are influenced with the load variation. Indeed the torque and the speed follow their reference values.
5.2.3 Robustness control under stator resistance variation

In this test, variation of 50% in stator resistance have been applied at $t=2.5\text{s}$, the speed is fixed at 157 rad/s and a resistant torque of 5Nm is applied at $t=2\text{s}$. Figure 8 shows the torque, the current, the stator flux and the speed. The results indicate that the regulator is very sensitive to the resistance variation which results in the influence on the torque and the stator flux.
6 CONCLUSION

In this paper design and simulation of sliding mode control (SMC) and Direct Torque and Flux Control (DTC) of doubly fed induction motor (DFIM) have been presented. First, the modeling and the basic of both control strategies have been illustrated in details. Second, the simulation results were carried out under normal and specifics conditions using Matlab/Simulink software. Obtained results have proved good performances for both control methods. From simulation results, Direct Torque Control (DTC) has provided better performances since chattering still the main drawback of sliding mode control. However, the most drawbacks in DTC are ripples in the torque and stator flux and some case very high switching frequency.

On the academic front, this research offers significant insights and knowledge to professionals, scholars, and students specializing in electrical power systems. The findings can aid in the creation of more precise and sophisticated control models for these electrical equipment, which can be incorporated into power system simulations and analytic tools. This has the potential to enhance comprehension of the most efficient utilization of this equipment, particularly in the generation of electrical power from wind energy.

LIMITATION OF THE STUDY AND FUTURE RESEARCH

The study focused exclusively on examining the implementation of two control algorithms for the double-feed electric motor. Its objective was to determine the optimal, simplest, and most resilient approach for regulating speed and torque. Further research can extend and improve the existing study on optimal control of a Double Feed Induction Machine, which functions as motor / generator. This can be achieved by developing more robust control algorithms using biologically inspired optimization algorithms, artificial neural networks, and other techniques. These algorithms can then be implemented experimentally to assess their effectiveness and validate their performance.
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APPENDIX

DFIM parameters:
Pn = 0.8 kW , Un= 220/380 V , F=50 Hz , I= 3.8/2.2 A ,
Vr= 3×120 V ; 4.1 A , Ω =1420 tr/min , Rs = 11.98 Ω ,
Rr = 0.904 Ω ; Ls = 0.414 H , Lr = 0.0556 H ,
M = 0.126 H , P = 2 , J = 0.01 kg.m2 , f = 0.001 .