Dynamics Testing of an Industry Oriented Real Time DTC Induction Motor Drive Using Mathlab Simulink

Brahmananda Das
Department of EE
Spintronic Technology and Advance Research, Bhubaneswar, Odisha, India

Email-brahman315@gmail.com

Abstract—Direct Torque Control is a robust control technique which is insensitive to control parameters variations. This is a field oriented control technique in which the detail analysis of motor parameter are required as it is very difficult to measure the rotor time constant which varies with temperature. Though it is a basic control technique, but it is essential for understanding this technique to develop the advance control algorithm using fuzzy logic control, neural network algorithm etc.

A 149.2kw. 2pole cage induction motor of 460 volts, 60 Hz, 1800 rpm and inertia constant 10 Kg.m^2 was tested using Mathlab simulink. The torque developed was 790 N.m according to parameter. To make a real time model I had chosen ac source resistance 0.0056Ω and inductance 0.15mH and model was developed by MathlabR2016 simulink environment. A fan load was taken and the motor fed by a variable AC voltage and frequency produced by an inverter. The inverter used was the voltage source inverter (VSI) in the sense that this inverter was fed by a constant DC voltage. This constant voltage was provided by an uncontrolled diode rectifier and a capacitor (capacitive DC bus voltage).

After simulation I had found that From 0.02 second to 0.25 second, the fan speed increased because of the 600 N.m accelerated torque produced by the induction motor. When time was 0.25 second, the electromagnetic torque jumped down to 0 Newton-meter and the speed reduced because of the load torque opposed by the fan. When time was 0.5 second the motor torque developed a -600 Newton-meter torque and allowed braking of the fan. During braking mode, power was sent back to the DC bus and the bus voltage increased. As planned, the braking chopper limited the DC bus voltage to 700 V. At time is equal to 0.75 second, the electromagnetic torque jumped back to 0 N.m and the speed settleed around -10 rpm and reduced toward 0 rpm. It was found that the flux was attained around 0.8 Wb throughout the simulation. The flux and torque oscillation amplitudes are slightly higher than 0.02 and 10 N.m respectively. This was due to the combined effects of the 15 µs DTC controller sampling time, the hysteresis control, and the switching frequency limitation. I have used hysteresis modulation and PID controller. Here torque and flux from stator voltage and current.

Keywords—DTC, Field Oriented control , VSI, DC BUS, Hysteresis Modulation.

1. Introduction
on October 20, 1984 direct self-control (DSC) was developed by Manfred Depenbrock in the US[3] and Germany. However, Isao Takahashi and Toshihiko Noguchi developed a similar control technique called as DTC. The only difference between DTC and DSC is that the switching frequency of DTC is higher than DSC and DTC is applicable to low and medium rated machine drives whereas DSC is usually used for high rated machine drives. Since its mid-1980s DTC have been used for its simplicity and very fast torque and flux control response for high performance induction motor (IM) drive applications. DTC was then used in electric locomotives in German and then it is used in ac drives and the applied to many more applications.

This is a robust control method. This is a very simple method because there is no requirement of pi regulator, coordinate transformations, current regulators and pwm signals generators. but the dynamic response is very fast, here coordinate reference frame taken as alpha/beta, control variable taken as torque and stator flux the performance of neural network, fuzzy and genetic algorithm based torque controllers can be evaluated as the various sensorless dtc techniques of im. These adaptive intelligent techniques are applied to achieve high performance decoupled flux and torque control.

II. DYNAMIC BRAKING

As the DC bus is provided by a diode rectifier, the drive doesn't have a bidirectional power flow capability and therefore cannot perform regenerative braking. In this model a braking resistor connected in series with a chopper ensures the braking of the motor-load system. This braking scheme is called dynamic braking. It is placed in parallel with the DC bus in order to prevent its voltage from increasing when the...
motor decelerates. With dynamic braking, the kinetic energy of the motor-load system is converted into heat dissipated in the braking resistor.

II Modulation Techniques

It is possible to apply two types of modulation i.e. hysteresis modulation and space vector pulse width modulation (SVPWM). The hysteresis modulation is a feedback current control method where the motor current tracks the reference current within a hysteresis band. The following figure shows the operation principle of the hysteresis modulation. The controller generates the sinusoidal reference current of desired magnitude and frequency that is compared with the actual motor line current. If the current exceeds the upper limit of the hysteresis band, the upper switch of the inverter arm is turned off and the lower switch is turned on. As a result, the current starts to decay. If the current crosses the lower limit of the hysteresis band, the lower switch of the inverter arm is turned off and the upper switch is turned on. As a result, the current gets back into the hysteresis band. Hence, the actual current is forced to track the reference current within the hysteresis band.

III. Hysteresis Modulation

![Hysteresis Modulation](image1)

DTC drives utilizing hysteresis comparators suffer from high torque ripple and variable switching frequency. The space vector modulation technique differs from the hysteresis modulation in that there are not separate comparators used for each of the three phases. Instead, a reference voltage space vector $V_s$ is produced as a whole, sampled at a fixed frequency, and then constructed through adequate timing of adjacent nonzero inverter voltage space vectors $V_1$ to $V_6$ and the zero voltage space vectors $V_0$, $V_7$. A simplified diagram of a VSI inverter is shown below. In this diagram, the conduction state of the three legs of the inverter is represented by three logic variables, SA, SB, and SC. A logical 1 means that the upper switch is conducting and logical 0 means that the lower switch is conducting.

IV. VSI PWM Inverter

![VSI PWM Inverter](image2)
In this diagram, the conduction state of the three legs of the inverter is represented by three logic variables, SA, SB, and SC. A logical 1 means that the upper switch is ON and logical 0 means that the lower switch is ON.

The switching of SA, SB, SC results in eight states for the inverter. The switching states and the corresponding phase to neutral voltages are summarized in Inverter Space Voltage Vectors. The six active vectors are an angle of 60 degrees apart and describe a hexagon boundary. The two zero vectors are at the origin.

For the location of the \( V_s \) vector shown in Inverter Space Vector Voltages, as an example, the way to generate the inverter output is to use the adjacent vectors \( V_1 \) and \( V_2 \) on a part-time basis to satisfy the average output demand. The voltage \( V_s \) can be resolved as: \( V_a \) and \( V_b \) are the

\[
V_b = \frac{2}{\sqrt{3}} V_s \cdot \sin \delta
\]

(1)

\[
V_a = V_s \cdot \cos \delta - \frac{1}{2} V_b
\]

(2)

components of \( V_s \) along \( V_1 \) and \( V_2 \), respectively. Considering the period \( T_c \) during which the average output must match the command, write the time durations of the two states 1 and 2 and the zero voltage state as:

\[
t_a = \frac{3}{2} \frac{V_a}{V_d} \cdot T_c
\]

(3)

\[
t_b = \frac{2}{3} \frac{V_b}{V_d} \cdot T_c
\]

(4)

\[
t_z = T_c - (t_a + t_b)
\]

(5)

<table>
<thead>
<tr>
<th>State</th>
<th>SA</th>
<th>SB</th>
<th>SC</th>
<th>Inverter Operation</th>
<th>Space Voltage Vector</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>Freewheeling</td>
<td>( V_0 )</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>Active</td>
<td>( V_1 )</td>
</tr>
<tr>
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<td>1</td>
<td>1</td>
<td>0</td>
<td>Active</td>
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<td>0</td>
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<td>0</td>
<td>1</td>
<td>1</td>
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<td>0</td>
<td>1</td>
<td>Active</td>
<td>( V_5 )</td>
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<tr>
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<td>1</td>
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<tr>
<td>7</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Freewheeling</td>
<td>( V_7 )</td>
</tr>
</tbody>
</table>

Table-1 Inverter Space Vector

Fig-4 space vector
VI. Flux-Oriented Control:

The construction of a DC machine is such that the field flux is perpendicular to the armature flux. Being orthogonal, these two fluxes produce no net interaction on one another. Adjusting the field current can therefore control the DC machine flux, and the torque can be controlled independently of flux by adjusting the armature current. An AC machine is not so simple because of the interactions between the stator and the rotor fields, whose orientations are not held at 90 degrees but vary with the operating conditions. You can obtain DC machine-like performance in holding a fixed and orthogonal orientation between the field and armature fields in an AC machine by orienting the stator current with respect to the rotor flux so as to attain independently controlled flux and torque. Such a control scheme is called flux-oriented control or vector control. Vector control is applicable to both induction and synchronous motors. We will see now how it applies to induction motors.

Considering the d-q model of the induction machine in the reference frame rotating at synchronous speed $\omega_e$,

$$\phi_{ds} = L_s i_{ds} + L_m i_{dr}$$  \hspace{1cm} (14)

The field-oriented control implies that the $i_{ds}$ component of the stator current would be aligned with the rotor field and the $i_{qs}$ component would be perpendicular to $i_{ds}$. This can be accomplished by choosing $\omega_e$ to be the speed of the rotor flux and locking the phase of the reference frame system such that the rotor flux is aligned precisely with the d axis, resulting in

$$\phi_{dr} = \omega_e$$

And

$$\phi_{ds} = \omega_e$$

which implies that

$$\omega_s = (\omega_e - \omega_r) = \left(\frac{L_m}{L_r} \frac{R_r}{\phi_r} \frac{i_{qs}}{i_{ds}}\right)$$  \hspace{1cm} (15)

and that

$$T_e = 1.5 p \frac{L_m}{L_r} (\phi_r i_{qs})$$  \hspace{1cm} (16)

It also follows that

$$\frac{d}{dt} \phi_r = -\left(\frac{R_r}{L_r}\right) \phi_r + \left(\frac{L_m R_r}{L_r}\right) i_{ds}$$  \hspace{1cm} (17)

The analogy with DC machine performance is now clear. The electric torque is proportional to the $i_{qs}$ component, whereas the relation between the flux $\phi_r$ and the $i_{ds}$ component is given by a first-order linear transfer function with a time constant $L_r / R$. You cannot directly measure the rotor flux orientation in a squirrel-cage rotor induction machine. It can only be estimated from terminal measurements. An alternative way is to use the slip relation derived above to estimate the flux position relative to the rotor, as shown.
Rotor Flux Position Obtained from the Slip and Rotor Positions:

![Figure 5: Rotor Flux Position](image)

VI. Direct Torque Control

Though the field-oriented control is an attractive control method but it has a serious drawback that it requires deep rooted knowledge of the motor parameters and it is difficult to measure the rotor time constant as it varies with time.

So direct torque control method is a robust control first in estimating the machine stator flux and electric torque in the stationary reference frame from terminal measurements. The following relations are used

\[ T_e = 1.5p(\varphi_{ds}i_{qs} - \varphi_{qs}i_{ds}) \]  

(21)

The estimated stator flux and electric torque are then controlled directly by comparing them with their respective demanded values using hysteresis comparators. The outputs of the two comparators are then used as input signals of an optimal switching table. The following table outputs the appropriate switching state for the inverter.

**Table 2: Switching of Inverter Space Vectors**

<table>
<thead>
<tr>
<th>( H_{q} )</th>
<th>( H_{Te} )</th>
<th>S(1)</th>
<th>S(2)</th>
<th>S(3)</th>
<th>S(4)</th>
<th>S(5)</th>
<th>S(6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>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>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>( V_0 )</td>
<td>( V_7 )</td>
<td>( V_0 )</td>
<td>( V_7 )</td>
<td>( V_0 )</td>
<td>( V_7 )</td>
</tr>
<tr>
<td>-1</td>
<td>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>
</tr>
<tr>
<td>-1</td>
<td>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>
</tr>
<tr>
<td>-1</td>
<td>( V_5 )</td>
<td>( V_6 )</td>
<td>( V_7 )</td>
<td>( V_2 )</td>
<td>( V_3 )</td>
<td>( V_4 )</td>
<td>( V_5 )</td>
</tr>
</tbody>
</table>

\[ \varphi_{ds} = \int (V_{ds} - R_s i_{ds}) dt \]  

(18)

\[ \varphi_{qs} = \int (V_{qs} - R_s i_{qs}) dt \]  

(19)

\[ \dot{\phi}_s = \sqrt{\frac{\varphi_{ds}^2}{\varphi_{ds}^2} + \frac{\varphi_{qs}^2}{\varphi_{qs}^2}} \arctan\left(\frac{\varphi_{qs}}{\varphi_{ds}}\right) \]  

(20)
VI. MATLAB SIMULINK MODEL

Fig-6 Entire Model of DTC
VII. Simulation Results

Observe the motor's fast torque response to the torque set point changes. From 0.02 s to 0.25 s, the fan speed increases because of the 600 N.m acceleration torque produced by the induction motor. At t = 0.25 s, the electromagnetic torque jumps down to 0 Name and the speed decreases because of the load torque opposed by the fan. At t = 0.5 s, the motor torque develops a -600 Name torque and allows braking of the fan. During braking mode, power is sent back to the DC bus and the bus voltage increases. As planned, the braking chopper limits the DC bus voltage to 700 V. At t = 0.75 s, the electromagnetic torque jumps back to 0 Name and the speed settles around -10 rpm and decreases toward 0 rpm. Notice that the flux stays around 0.8 Wb throughout the simulation. The flux and torque oscillation amplitudes are slightly higher than 0.02 and 10 Name respectively as specified in the user interface. This is due to the combined effects of the 15 µs DTC controller sampling time, the hysteresis control, and the switching frequency limitation.

The following figure shows the simulation results of the XY scope. The rotating field is clearly visible. Its modulus is about 0.8 and its bandwidth is slightly bigger than 0.2.

VIII. Conclusions

For any IM drives, Direct torque control is one of the cheapest and simple controllers. It allows independent control of motor stator flux and electromagnetic torque. From the analysis it is proved that, this strategy of IM control is simpler to implement than other vector control methods as it does not require pulse width modulator and co-ordinate transformations. But it introduces undesired torque and current ripple. DTC scheme uses stationary d-q reference frame with d-axis aligned with the stator axis. Stator voltage space vector defined in this reference frame control the torque and flux. The main inferences from this work are: 1. In transient state, by selecting the fastest accelerating voltage vector which produces maximum slip frequency, highest torque response can be obtained. 2. In steady state, the torque can be maintained constant with small switching frequency by the torque hysteresis comparator by selecting the accelerating vector and the zero voltage vector alternately. 3. In order to get the optimum efficiency in steady state and the highest torque response in transient state at the same time, the flux level can be automatically adjusted. 4. If the switching frequency is extremely low, the control circuit makes some drift which can be compensated easily to minimize the machine parameter variation. The estimation accuracy of stator flux is very much essential which mostly depends on stator resistance because an error in stator flux estimation will affect the behavior of both torque and flux control loops.
torque and current ripple can be minimized by employing space vector modulation technique.

IX. REFERENCES


