Abstract—In the field of high power drives, the double star synchronous machines constitute an advantageous choice compared to classical synchronous machines, because of the relatively low torque ripple produced. This study describes the control of double armature synchronous machine, using Direct Torque Control (DTC). The implementation of the DTC applied to a double star synchronous machine is validated with simulated results. In this paper a method for modeling and simulation of synchronous motor drives using MATLAB/Simulink with Graphical User Interface.

Index Terms—direct torque control (DTC), Double star synchronous Machine (DSSM), GUI.

I. INTRODUCTION

Since, years 80, double armature synchronous machine DSSM supplied by power electronic converter are widely used for marine applications [1], [4], [6]. The fist developed schemes consists to supply the motor by current source inverter. Nevertheless, this electrical propulsion exhibits a pulsating component of torque at twelve times the supply frequency. These causes excess mechanical vibration and poor system performances.

Nowadays, the actual development of power electronics devices allows supplying DSSM by PWM inverter [5], [7]. In the other hand, the vector control technique [8], [9] allows improving performances of this speed drive.

The difficulty to control the DSSM supplied by strong coupling is due to the strong magnetic coupling between.

II. ELECTRICAL DRIVE SCHEME

The electrical drive considered with this study is shown in figure (1). It is composed of double star synchronous machine supplied of two inverters, both columns. Leave sufficient room between the figures/tables and the main text. Figure captions should be centered below the figures;

A. Description

As every rotating electrical machine, the double star synchronous machine is composed of a stator and rotor. As shown in figure (2), the stator is a two three-phase windings, so called star, shifted up by an angle $\gamma = 30^\circ$.

B. Assumptions

The study presented in this paper is based upon he following assumptions:

- The two stars are identical shifted up an angle.
- The three windings of each star are shifted by $\theta=120^\circ$.
- The magnetomotive forces in the air-gap have a sinusoidal repartition;
- The mutual inductances are characterized by their fundamental.
- The saturation of the iron in the machine is neglected.
- Damper windings effect are neglected
- The rotor speed at any operating point is constant.
C. Electrical equations with (d, q) frames

By applying the Park transformation to each star, the (d, q) model of double star synchronous machine is obtained [11], [12]. Thus, the machine windings can be substituted by an equivalent scheme in the (d, q) frame as shown in figure (3):

\[
V_f = R_f i_f + \frac{d}{dt} \varphi_f
\]  

(5)

The flux equation

\[
\varphi_{d1} = L_d i_{d1} + M_d i_{d2} + M_{fd} i_f
\]  

(6)

\[
\varphi_{d2} = L_d i_{d2} + M_d i_{d1} + M_{fd} i_f
\]  

(7)

\[
\varphi_{q1} = L_q i_{q1} + M_q i_{q2}
\]  

(8)

\[
\varphi_{q2} = L_q i_{q2} + M_q i_{q1}
\]  

(9)

\[
\varphi_f = L_f i_f + M_{fd} i_{d1} + M_{fd} i_{d2}
\]  

(10)

Mechanical equation

\[
f \frac{d \Omega}{dt} = C_{em} - C_r - C_{fr}
\]  

(11)

Electromagnetic torque

\[
C_{em} = P(\varphi_{d1} i_{q1} - \varphi_{q1} i_{d1} + \varphi_{d2} i_{q2} - \varphi_{q2} i_{d2})
\]  

(12)

\[
C_{fr} = f_r \Omega
\]  

(13)

IV. DIRECT TORQUE CONTROL PRINCIPLE

The direct torque control of a double star synchronous machine is based on the direct determination of the sequence control used to switch a voltage inverter.

This choice is usually based on use of hysteresis comparators whose function is to control the system state, namely the amplitude of stator flux and electromagnetic torque. A Voltage Inverter delivers twelve distinct positions (figure 4) in the plan phase.

DTC in single inverter utilizes the \((2^3)\) eight possible stator voltage vectors, two of which are zero vectors, to control the stator flux and torque to follow the reference values within the hysteresis bands. The voltage space vector of a three-phase system is given by:

\[
V_s = \sqrt{2} U_d (S_1 + a S_2 + a^2 S_3)
\]  

(14)

Direct voltage.

The control sequences of the two inverters is done in a way that will have the voltage vectors at the exit of the second inverter offset by an angle of \(30^\circ\), the vectors of voltage at the output of first inverter figure 1.

Using the vector form of vectors of voltage at the output of two inverters, we can write the vector
$$V_s = \sqrt{\frac{2}{3}} U_d (S_1 + aS_2 + a^2 S_3 + e^{j\pi/6} (S'_1 + aS'_2 + a^2 S'_3))$$

This angle shift between the two stars of the machines, which is equal $\pi/6$.

A combinatorial analysis of switch states of the two inverters gives ($2^6 = 64$) switching modes, ie 64 different vectors $V_s$ possible. Hence there are sixty four possible combinations for controlling the switches of the two inverters. Table I.

We will therefore among the sixty-four sequences, twelve active sequences. These vectors define twelve combinations for controlling the switches of the two inverters. Table I.

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The truth table for the active sequences can be summarized in the following table:

<table>
<thead>
<tr>
<th>First star</th>
<th>Second star</th>
<th>First star voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_1$</td>
<td>$S_1$</td>
<td>$S_2$</td>
</tr>
<tr>
<td>$S_3$</td>
<td>$S_4$</td>
<td>$S_5$</td>
</tr>
<tr>
<td>$S_6$</td>
<td>$V_{ss1}$</td>
<td>$V_{ss2}$</td>
</tr>
<tr>
<td>$V_{ss3}$</td>
<td>$V_{ss4}$</td>
<td>$V_{ss5}$</td>
</tr>
<tr>
<td>$V_{ss6}$</td>
<td>$V_{ss7}$</td>
<td>$V_{ss8}$</td>
</tr>
<tr>
<td>$V_{ss9}$</td>
<td>$V_{ss10}$</td>
<td>$V_{ss11}$</td>
</tr>
<tr>
<td>$V_{ss12}$</td>
<td>$V_{ss13}$</td>
<td>$V_{ss14}$</td>
</tr>
</tbody>
</table>

The order by the DTC of DSSM can be represented by figure 5.
IV. NUMERICAL SIMULATION RESULTS

The paper describes a MATLAB graphical user interface with Simulink that provides facilities for investigation of algorithms for solving direct torque control problems of double star synchronous machine.

A. Program Plan of simulation (DTC-DSSM):
   The program consists of four parts:
   - The first part consists of (Chapter I): Modeling DSSM (in French MSDE).
   - The second part consists of (Chapter II): Rectifier, Filter, Inverter (two levels), Supply of the DSSM.
   - The third part consists of (Chapter III): The Direct torque control of DSSM (open loop). The Direct torque control of DSSM (closed loop).
   - In figure 6 shows the direct torque control of double star synchronous machine DSSM simulink blocks.
   - And in figure 7 shows Graphical User Interface (GUI).

B. Parameters for the Double Star Synchronous machine:
   Motor details: 5kW, 3phase, 50Hz, 1 pole, 200v,
In this paper, we presented the direct control of the torque of the synchronous double star machine supplied by two voltage inverters at two levels.

This study presents a control strategy for a double stator synchronous machine based on the direct control torque (DTC) using an PI regulator. The simulation results show that the DTC is an excellent solution for general-purpose DSSM double star synchronous machine drives, in very wide power range.

Simulation results on control realized by MATLAB/Simulink with Graphical User Interface that provides facilities shows the introduction simple Parameters for the Double Star Synchronous machine.