The dual three-phase open-end stator windings permanent magnet synchronous machine fed by four voltage source inverters

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Abstract: In this paper, the mathematical model in Park reference frame of the dual open-end stator winding salient-pole permanent magnet synchronous machine is described. The proposed machine is supplied by its four voltage source inverters based on PWM technique. Then, the feeding of this machine by four two-level cascaded inverters is presented. A multilevel PWM strategy is carried out to control the cascaded inverters. The simulation analyses using the THD voltage, THD stator current and the torque undulation are presented and show the benefits for the proposed machine.

Keywords: dual open-end windings synchronous machine; cascaded inverters; power segmentation; THD voltage; THD stator current; torque undulation.


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1 Introduction

The use of the AC machines with converters is mostly interesting in industrial drives with variable speeds such as railways applications, electrical propulsion of ships, electrical vehicle systems and aeronautics.

Nowadays, the power segmentation and the availability of the association asynchronous or synchronous machines-converters are a major interest in electrical engineering researches. Several researches have been developed in converter structures (Franquelo et al., 2008; Kouro et al., 2010), or in structures of asynchronous or synchronous machines (Mohammed and Fares, 2008; Hamid et al., 2011; Zebin et al., 2015), including multiphase machines where each phase is supplied by its own voltage inverter (Singh et al., 2003; Vukosavic et al., 2005; Abdel-Khalik et al., 2012), the multi-star machines where each star is supplied by its own three-phase voltage inverter (Ben Ammar and Guizani, 2008; Marouani et al., 2008; Yongle et al., 2010; Samuli et al., 2014) and the open-end stator winding machine where each entry is supplied by its own three-phase voltage inverter (Somasekhar et al., 2004; Mondal et al., 2007; Figarado et al., 2010; Alexandru et al., 2013; Guizani et al., 2014).

Generally, the multi-star machines are more advantageous than the conventional asynchronous machines. In addition, the researchers have developed the double star machine where each star is supplied by its own three phase voltage source inverter (VSI), which can ensure operation in passive or active redundancy. Furthermore, this machine structure offers the power segmentation and better availability of the drive system (Ben Ammar and Guizani, 2008).

In order to improve the availability of a variable speed drive, one of the solutions is the use of the open-end stator windings asynchronous machine which is supplied by its two three-phase VSIs, each inverter is dimensioned for half power of machine. This machine operates in degraded mode which obtains one degree of freedom. As well, the machine offers the highest levels of efficiency and availability (Guizani et al., 2014).

Recently, some researchers have developed a new machine structure, the dual three-phase open-end stator winding asynchronous machine supplied by four-VSIs. This machine ensures efficiency for the power segmentation, indeed the inverters are dimensioned for a quarter power of the machine. In addition, the operation of the machine in active or passive redundancy offers improved reliability and availability (Guizani and Ben Ammar, 2015). Moreover, the new machine presents the importance of the operation in degraded mode which obtained three degrees of freedom of system (Guizani and Ben Ammar, 2013).

In this paper, the authors present a novel structure of dual open-end stator winding permanent magnet synchronous machine (SM) ‘DOEWPMSSM’ with salient-pole.

The first part presents the mathematical modelling of this machine in the Park reference frame.

In the second part, the proposed machine is fed by four three-phase two-level inverters based on PWM technique in the environment «MATLAB Simulink».

Finally, the feeding by three-phase two-level cascaded inverters based on the phase disposition PWM strategy is described. An analysis of the different simulation results will be presented.

2 Modelling the dual open-end stator winding permanent magnet SM with salient-pole

Figure 1 represents the windings of the permanent magnet SM with dual open-end stator windings in the (d, q) Park reference (\(\alpha_{d(q)} = \alpha_d\)).

The relation that links the flux and the currents is described by:

\[
\begin{bmatrix}
\psi_{ad1} \\
\psi_{ad2} \\
\psi_{sq1} \\
\psi_{sq2}
\end{bmatrix} = \begin{bmatrix}
L_d & M_d & 0 & 0 \\
M_d & L_d & 0 & 0 \\
0 & 0 & L_q & M_q \\
0 & 0 & M_q & L_q
\end{bmatrix} \begin{bmatrix}
i_{ad1} \\
i_{ad2} \\
i_{sq1} \\
i_{sq2}
\end{bmatrix} + \begin{bmatrix}
\psi_f \\
\psi_f \\
0 \\
0
\end{bmatrix}
\]

(1)

With:

\(\psi_f\) the flux of the permanent magnets by pole.

The voltage of the machine is related by the following matrix:

\[
\begin{bmatrix}
V_{ad1} - V_{ad2} \\
V_{sq1} - V_{sq2}
\end{bmatrix} = \begin{bmatrix}
R_s & 0 & 0 & 0 \\
0 & R_s & 0 & 0
\end{bmatrix} \begin{bmatrix}
i_{ad1} \\
i_{sq1}
\end{bmatrix} + \begin{bmatrix}
di_{ad1}/dt \\
di_{sq1}/dt
\end{bmatrix}
\]

\[
\begin{bmatrix}
V_{ad1} - V_{ad2} \\
V_{sq1} - V_{sq2}
\end{bmatrix} = \begin{bmatrix}
0 & 0 & -\omega_{dq} & 0 \\
0 & 0 & 0 & -\omega_{dq}
\end{bmatrix} \begin{bmatrix}
i_{ad1} \\
i_{sq1}
\end{bmatrix} + \begin{bmatrix}
0 & \omega_{dq} & 0 & 0 \\
\omega_{dq} & 0 & 0 & 0
\end{bmatrix} \begin{bmatrix}
i_{ad2} \\
i_{sq2}
\end{bmatrix}
\]

(2)

where \(R_s\) is the resistance of the stator, \(L_d, L_q\) are the inductance of the stator, and \(d\) - and \(q\)-axis, respectively. \(M_d\) is mutual inductance of stator \(d_1\) and \(d_2\) axis. \(M_q\) is mutual inductance of stator \(q_1\) and \(q_2\) axis.

The system of state equations is placed in the following form:

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\[
\frac{d}{dt}[I] = [A][I] + [B][V]
\]  
(3)

**Figure 1** Representation of the machine in the (d, q) reference frame

\[
V_{d11} - V_{d12} \quad V_{q11} - V_{q12} \\
V_{d21} - V_{d22} \quad V_{q21} - V_{q22}
\]

With:

- State vector:
  \[
  X(t) = [i_{d11}, i_{d12}, i_{q11}, i_{q12}]^T
  \]

- Control vector:
  \[
  U(t) = [V_{d11} - V_{d12}, V_{d21} - V_{d22}, V_{q11} - V_{q12}, V_{q21} - V_{q22}, \psi_f]^T
  \]

The state matrix \([A]\) is:

\[
\begin{bmatrix}
R_{d}L_{d} & -\frac{\omega_{dq}}{L_{q}} & 0 \\
\frac{\omega_{dq}}{L_{d}} & 0 & 0 \\
R_{d}L_{q} & 0 & -\frac{\omega_{dq}}{L_{q}} \\
0 & -\frac{\omega_{dq}}{L_{q}} & 0
\end{bmatrix}
\]

The matrix \([B]\) is:

\[
\begin{bmatrix}
L_{d} & 0 & 0 & 0 \\
0 & -L_{q} & 0 & 0 \\
-\frac{I_{d}}{L_{d}} & 0 & 0 & 0 \\
0 & 0 & \frac{I_{q}}{L_{d}} & 0 \\
0 & 0 & \frac{I_{q}}{L_{d}} & 0 \\
0 & 0 & \frac{I_{q}}{L_{d}} & \frac{I_{q}}{L_{d}}
\end{bmatrix}
\]

\[
T_{em} = \frac{3}{2} p \left( (\frac{L_{d} - L_{q}}{I_{d11} - l_{q11}}) + \frac{2(I_{d12} - l_{q12})}{M_{d} - M_{q}} \right)
\]

(6)

### 3 Voltage supply of the dual open-end winding permanent magnet SM

#### 3.1 Supply by three phase two-level inverter

The feeding of the dual open-end stator winding permanent magnet SM with salient-pole «DOEWPMSM» by four three-phase two-level inverters is represented by Figure 2.

Figure 3 shows the principle of carrier PWM to supply the dual open-end winding SM by four two-level inverters.

Figure 4(a) shows the reference voltage \(V_{ref11}\) with the triangular signal for the control inverters \(A_1\) and \(B_1\). The reference signal \(V_{ref21}\) is compared with triangular carrier for the control inverters \(A_1\) and \(B_1\), as shown by Figure 4(b).

Figure 5 shows the voltage \((V_{s11} - V_{s12}), (V_{s21} - V_{s22})\) and phase-to-phase voltage \((U_1)\) of machine (stator windings A) which is 3 levels to supply with two three-level inverters; same simulation results for pole voltage of machine (stator winding B).

With:

- \(V_{S_{11}}, V_{S_{12}}\) and \(V_{S_{13}}\) simple voltage of inverter \(A_1\)
- \(V_{S_{21}}, V_{S_{22}}\) and \(V_{S_{23}}\) simple voltage of inverter \(A_2\)
- \(V_{S_{B1}}, V_{S_{B2}}\) and \(V_{S_{B3}}\) simple voltage of inverter \(B_1\)
- \(V_{S_{B1}}, V_{S_{B2}}\) and \(V_{S_{B3}}\) simple voltage of inverter \(B_2\)
- \((V_{S_{11}} - V_{S_{12}})\) pole voltage of inverter \(A_1\)
- \((V_{S_{21}} - V_{S_{22}})\) pole voltage of inverter \(A_2\)
- \((V_{S_{B1}} - V_{S_{B2}})\) pole voltage of inverter \(B_1\)
- \((V_{S_{B1}} - V_{S_{B2}})\) pole voltage of inverter \(B_2\)
- \(U_{11} = (V_{S_{11}} - V_{S_{12}}) - (V_{S_{21}} - V_{S_{22}})\) pole voltage of machine stator winding \(A\)
- \(U_{B1} = (V_{S_{B1}} - V_{S_{B2}}) - (V_{S_{B1}} - V_{S_{B2}})\) pole voltage of machine stator winding \(B\).

The evolution of the current, speed and the torque for the machine feeding by the two two-level inverters is shown by Figure 6.

Figure 7 shows the waveform and the harmonic content of the phase-to-phase machine voltage for the «DOEWPMSM» with THD voltage = 44.27%.

Figure 8 shows the evolution of the stator current of the proposed machine during the permanent mode.

Figure 9 shows the waveform and the harmonic content of the stator current for the machine «OEWPMSM», with THD current = 5.84%.
**Figure 2** Supply the «DOEWPMSM» by four two-level inverters (see online version for colours)

**Figure 3** Principle of the PWM sine triangle supply the «DOEWPMSM» by four two-level inverters (see online version for colours)
Figure 4  Signal of $V_{ref1}$ and $V_{ref2}$ with a triangular signal (see online version for colours)

Figure 5  Pole voltage inverters and phase-to-phase machine voltage

Figure 6  Evolution of the current, speed and torque with $P = 40$ kW

Figure 7  Waveform and harmonic ration of machine voltage (see online version for colours)

In order to analyse the torque undulations, we defined $\Delta Tem$ by the expression:

$$\Delta Tem = \frac{T_{\text{max}} - T_{\text{moy}}}{T_{\text{moy}}} \times 100$$  \hspace{1cm} (7)

Figure 10 shows the enlarging effect of the torque during the permanent mode for a load torque $T_r = T_n$. 
Then we can calculate the torque undulation:

$$\Delta Tem = \frac{213.7 - 180}{180} \times 100 = 18.72\%$$

Figure 8  Waveform of stator currents (see online version for colours)

![Waveform of stator currents](image)

Figure 9  Waveform and harmonic ration of current (see online version for colours)

![Waveform and harmonic ratio of current](image)

3.2  Supply by two two-level cascaded inverters

Figure 11 represents the «DOEWPMSM» where each entry is supplied by converter. Each converter is constituted by two three-phase two-level cascaded-inverters.

To control the two three-phase two-level cascaded inverters we used the phase disposition PWM strategy, the three reference signals of frequency $f_n = 50$ Hz and amplitude $A_m$ are compared with two triangular carriers of frequency $f_p = 5,000$ Hz and amplitude $A_p^2$, as shown by Figure 12.

Figure 13 shows two triangular carriers and a signal reference for controlled inverters 11 and 12.

Figure 14 shows the phase-to-phase voltage of converter $A_1$ ($V_{s1} - V_{s12}$), phase-to-phase voltage of converter $A_2$ ($V_{s21} - V_{s22}$) and phase-to-phase machine voltage $U_1 = (V_{s11} - V_{s12}) - (V_{s21} - V_{s22})$ which is five levels to supply with two three-level inverters.

Figure 15 shows the evolution of the stator currents, speed and the torque with $P = 40$ kW.

Figure 16 shows the waveform and the harmonic content of the phase-to-phase machine voltage for the «DOEWPMSM» with THD voltage = 26.79%.

For permanent mode, the evolution of the stator current of the proposed machine is shown by Figure 17.

The association two-level cascaded inverters with dual open end stator winding SM improves the THD voltage and increases the level of voltage between phases.

Figure 18 shows the waveform and the harmonic content of the stator current for the machine «DOEWPMSM», With THD current = 3.71%.

The feeding of DOEWPMSM by two-level cascaded inverters allows to give better THD stator current and extends the band-width.

Figure 19 shows the enlarging effect of the torque during the permanent mode for a load torque $Tr = T_n$.

Then:

$$\Delta Tem = \frac{194.2 - 180}{180} \times 100 = 7.88\%$$

Similarly, this association allows to obtain a best quality of torque.

Table 1 summarises the THD voltages (%), THD stator current and torque undulation (%) for the dual open-end winding permanent magnet SM with $P = 40$ kW and load torque $Tr = 180$ Nm.

The different results for THD voltage, THD stator current and torque undulation show the important advantage which presents the open-end windings SMs structures.

The proposed dual open-end winding permanent magnet SM is good solution for the power segmentation because the feeding of this machine by four inverters and these inverters are dimensioned to a quarter power of the machine.
Figure 11  Supply «DOEWPMSM» by two two-level cascaded inverters (see online version for colours)

Figure 12  Principle of the phase-disposition PWM for control two three-phase cascaded inverters (see online version for colours)
The dual three-phase open-end stator windings permanent magnet SM fed by four VSIs

Figure 13  Signal reference and 2 carriers vertically shifted (see online version for colours)

Figure 14  Simulation results for the Pole voltage inverter and phase-to-phase machine voltage (see online version for colours)

Figure 15  Evolution of the stator current, speed and torque

Table 1  THD voltages (%), THD stator current (%) and torque undulation (%) for DOEWPMSM

<table>
<thead>
<tr>
<th></th>
<th>DOEWSM by two-level inverters</th>
<th>DOEWSM by two-level cascaded inverters</th>
</tr>
</thead>
<tbody>
<tr>
<td>THD voltage (%)</td>
<td>44.27</td>
<td>26.79</td>
</tr>
<tr>
<td>THD current (%)</td>
<td>5.84</td>
<td>3.71</td>
</tr>
<tr>
<td>ΔTem (%)</td>
<td>18.72</td>
<td>7.88</td>
</tr>
</tbody>
</table>

The characteristics of the permanent magnet SM of $P = 40$ kW:

- Speed $n = 1,000$ tr/min
- Resistance of stator $R_s = 0.065 \, \Omega$.
- Inductance of stator $L_d = 0.655 \, \text{mH}$
- Inductance of stator $L_q = 0.555 \, \text{mH}$
- Mutual inductance of stator $d_1$ and $d_2$ axis $M_d = 0.545 \, \text{mH}$
- Mutual inductance of stator $q_1$ and $q_2$ axis $M_q = 0.545 \, \text{mH}$
- Magnet flux $\psi_f = 0.14 \, \text{Wb}$
- Inertia moment $J = 0.02 \, \text{kg \, m}^2$
- Viscous force $f = 2 \times 10^{-3} \, \text{N \, m \, s} / \text{rad}$.
4 Conclusions

The modelling of the dual open-end stator winding permanent magnet SM with salient-pole is described in the Park reference frame.

The supply of this machine by three-phase two-level inverters based on PWM sine triangle and three phase two-level cascaded inverters using the phase disposition PWM strategy is presented. We were able to view and analyse the dynamic behaviour of the proposed machine.

The association of two-level inverters with dual open-end stator winding permanent magnet SM gives a great advantage. Indeed, this association offers a better level in voltage between phases of the machine, a better rate of harmonic distortion of voltage, extends the band-width, best quality of torque and reduced dimensions of the inverters of the quarter power. This is a very good solution for the power segmentation, for reducing the space requirement and especially the increase of the degrees of redundancy in degraded mode.

The use of cascaded inverters with the proposed machine improves even more the performance, the level of voltage increase, the THD voltage and the quality of torque without forgetting increased degrees of freedom in the degraded mode.

References


The dual three-phase open-end stator windings permanent magnet SM fed by four VSIs


