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Symmetrical and Asymmetrical H-Bridge Multilevel Inverter for DTC Induction Motor Drive Automotive Applications

F. Khoucha1,2, S.M. Lagoun2, A. Kheloui2 and M.E.H. Benbouzid1
1University of Brest, EA 4325 LBMS
2IUT of Brest – Rue de Kergoat – CS 93837, 29238 Brest Cedex 03, France
E-mail: m.benbouzid@ieee.org

II. CASCADeD H-BRIDGES STRUCTURE AND OPERATION

The cascaded H-bridge inverter consists of power conversion cells, each supplied by an isolated DC source on the DC side, which can be obtained from batteries, fuel cells, or ultracapacitors [15-16], and series-connected on the AC side. The advantage of this topology is that the modulation, control and protection requirements of each bridge are modular. It should be pointed out that, unlike the diode-clamped and flying-capacitor topologies, isolated DC sources are required for each cell in each phase. Figure 1 shows a three-phase topology of a cascade inverter with isolated DC voltage sources. An output phase voltage waveform is obtained by summing the bridges output voltages.
\[ v_o(t) = v_{o,1}(t) + v_{o,2}(t) + \cdots + v_{o,N}(t) \]  
(1)

where \( N \) is the number of cascaded bridges.

The inverter output voltage \( v_o(t) \) may be determined from the individual cells switching states.

\[ v_o(t) = \sum_{j=1}^{N} (\mu_j - 1) V_{dc,j} \quad \mu_j = 0,1, \ldots \]  
(2)

If all DC voltage sources in Fig. 1 are equal to \( V_{dc} \), the inverter is then known as a symmetric multilevel one. The effective number of output voltage levels \( n \) in symmetric multilevel inverter is related to the cells number by

\[ n = 1 + 2N \]  
(3)

For example, Fig. 2 illustrated typical waveforms of Fig. 1 multilevel inverter with two DC sources (5-levels output). The maximum output voltage \( V_{o,\text{MAX}} \) is then

\[ V_{o,\text{MAX}} = NV_{dc} \]  
(4)

To provide a large number of output levels without increasing the number of inverters, asymmetric multilevel inverters can be used.

In [17-18], it is proposed to choose the DC voltages sources according to a geometric progression with a factor of 2 or 3. For \( N \) of such cascade inverters, one can achieve the following distinct voltage levels.

\[
\begin{align*}
N & = 2^{N+1} - 1 \quad \text{if } V_{dc,j} = 2^{j-1}V_{dc}, \ j = 1,2,\ldots,N \\
N & = 3^N \quad \text{if } V_{dc,j} = 3^{j-1}V_{dc}, \ j = 1,2,\ldots,N
\end{align*}
\]
(5)

For example, Fig. 3 illustrated typical waveforms of Fig. 1 multilevel inverter with two DC sources \( (V_{dc} \text{ and } 2V_{dc}) \) (7-levels output).

The maximum output voltage of these \( N \) cascaded multilevel inverters is

\[ V_{o,\text{MAX}} = \sum_{j=1}^{N} V_{dc,j} \]  
(6)

Equation (6) can be rewritten as

\[
\begin{align*}
V_{o,\text{MAX}} = 2^{N-1}V_{dc} & \quad \text{if } V_{dc,j} = 2^{j-1}V_{dc}, \ j = 1,2,\ldots,N \\
V_{o,\text{MAX}} = \frac{3N-1}{2}V_{dc} & \quad \text{if } V_{dc,j} = 3^{j-1}V_{dc}, \ j = 1,2,\ldots,N
\end{align*}
\]
(7)

Comparing (3) to (7), it can be seen that asymmetrical multilevel inverters can generate more voltage levels and higher maximum output voltage with the same number of bridges. Table 1 summarizes the number of levels, switches, DC sources and maximum available output voltages for classical cascaded multilevel inverters.

### III. INDUCTION MOTOR DIRECT TORQUE CONTROL

DTC is an alternative method to flux oriented control [12]. However, in the standard version, important torque ripple is obtained even at high sampling frequencies. Moreover, the inverter switching frequency is inherently variable and very dependent on torque and shaft speed. This produces torque harmonics with variable frequencies and an acoustic noise dependent on torque and shaft speed. This produces mechanical variables and particularly gratings at low speed.
The additional degrees of freedom (space vectors, phase configurations, etc.) provided by the multilevel inverter should therefore be exploited by the control strategy in order to reduce these drawbacks [6].

A. Nomenclature

\[ v_s = \text{Stator voltage vector}; \]
\[ \phi_s, (\phi_r) = \text{Stator (rotor) flux vector}; \]
\[ T_e = \text{Electromagnetic torque}; \]
\[ R_s = \text{Stator resistance}; \]
\[ L_s, (L_r) = \text{Stator (rotor) inductance}; \]
\[ L_m = \text{Magneting inductance}; \]
\[ \sigma = \text{Total leakage coefficient, } \sigma = 1 - L_m^2/L_s L_r; \]
\[ \theta_{sr} = \text{Angle between stator and rotor flux vectors}; \]
\[ p = \text{Pole pair number}. \]

B. Torque and Flux Estimation

The stator flux vector an induction motor is related to the stator voltage and current vectors by:

\[
\frac{d\phi_s(t)}{dt} = v_s(t) - R_s i_s(t) \tag{8}
\]

Maintaining \( v_s \) constant over a sample time interval and neglecting the stator resistance, the integration of (10) yields

\[
\Delta \phi_s(t) = \phi_s(t) - \phi_s(t - \Delta t) = \int_{t-\Delta t}^{t} v_s \Delta t \tag{9}
\]

Equation (9) reveals that the stator flux vector is directly affected by variations on the stator voltage vector. On the contrary, the influence of \( v_s \) over the rotor flux is filtered by the rotor and stator leakage inductance [19], and is, therefore, not relevant over a short-time horizon. Since the stator flux can be changed quickly while the rotor flux rotates slower, the angle between both vectors \( \theta_{sr} \) can be controlled directly by \( v_s \). The exact relationship between stator and rotor flux shows that keeping the amplitude of \( \phi_s \) constant will produce a constant flux \( \phi_r \) [20].

Since the electromagnetic torque developed by an induction motor can be expressed by [21]

\[
T_e = \frac{3}{2} p \frac{L_m}{\sigma L_r} \phi_s \phi_r \sin \theta_{sr} \tag{10}
\]

It follows that change in \( \theta_{sr} \) due to the action of \( v_s \) allows for direct and fast change in the developed torque. DTC uses this principle to achieve the induction motor desired torque response, by applying the appropriate stator voltage vector to correct the flux trajectory.

C. Voltage Vector Selection

Figure 4 illustrates one of the 127 voltage vectors generated by the inverter at instant \( t = k \), denoted by \( v_s^k \) (central dot). The next voltage vector to be applied to the load \( v_s^{k+1} \) can be expressed by

\[
v_s^{k+1} = v_s^k + \Delta v_s^k \tag{11}
\]

where \( \Delta v_s^k = \{v_i \mid i = 1, \ldots, 6\} \). Each vector \( v_s \) corresponds to one corner of the elemental hexagon illustrated in gray and by the dashed line in Fig. 7. The task is to determine which \( v_s^{k+1} \) will correct the flux trajectory.

Using (10) and (11), and analyzing, for example, sector (2) illustrated in Fig. 5: the application of \( v_s \) to the load will always be one of the six closest vectors to the previous \( v_s^k \), this will soften the actuation effort and reduce high dynamics in torque response due to possible large changes in the reference.

Table 2 summarizes vector selections according to the above criterion, for the different sectors and comparators output (desired \( \phi_s \) and \( T_e \) corrections).

![Fig. 4. Possible voltage changes \( \Delta v_s \).](image)

![Fig. 5. Voltage selection \( \Delta v_s \) in sector 2.](image)

<table>
<thead>
<tr>
<th>Sector</th>
<th>( \text{sign}(e_s^k, e_r^k) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(+,+), (+,+), (+,-)</td>
<td>(+,+), (+,+), (+,-)</td>
</tr>
<tr>
<td>1</td>
<td>( V_2 )</td>
</tr>
<tr>
<td>2</td>
<td>( V_4 )</td>
</tr>
<tr>
<td>3</td>
<td>( V_4 )</td>
</tr>
<tr>
<td>4</td>
<td>( V_4 )</td>
</tr>
<tr>
<td>5</td>
<td>( V_6 )</td>
</tr>
<tr>
<td>6</td>
<td>( V_1 )</td>
</tr>
</tbody>
</table>

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Once the space is chosen, the sequence of phase levels can be selected. To ensure this task, one should detect the position of the space vector in $\alpha-\beta$ frame ($Q^k$ at sampling time $t_k$). The proposed algorithm must then select the next position $Q^{k+1}$ to be achieved before next sampling instant $t^{k+1}$ (Fig. 6) in order to reduce voltage steps magnitude. This task allows the commutation number reduction in the same phase order to minimize losses and consequently the torque ripple. Finally, the configuration of each phase will be selected and must be able to generate the phase levels.

IV. SIMULATION AND EXPERIMENTAL RESULTS

For the validation of the above discussed control approach, simulations and experiments have been carried out. Figures 7 to 9 and 10 to 12 show simulation results for 5-levels cascaded and 7-levels H-bridge inverter, respectively. For further verification, a three-phase DSP (TMS320LF2407A) controlled 5- and 7-levels cascaded H-bridge multilevel DTC induction motor drive system prototype was built and tested (Fig. 13). The induction motor was rated at 1-kW / 380V / 5.2 A / 1420 rpm. The control cycle is 120 µs. It should be noted, as illustrated by Fig. 13a, that the experimental setup was built to slightly emulate an automotive application (electric vehicle).

Figures 14 to 16 and 17 to 19 illustrate experimental results for 5-levels cascaded and 7-levels H-bridge inverter, respectively built-up in the laboratory (Fig. 13).

The output voltages form with 7-levels stepped multilevel waveform can be clearly appreciated; the motor currents complete the overview of the performance of the drive. They appear completely sinusoidal, since the low pass nature of the load has filtered the high frequency content of the applied voltage. The stator flux with constant amplitude imposed by the flux controller confirms the good dynamic performance of the drive. The most important results are that torque ripple has been almost eliminated in comparison to 5-levels classic DTC.

V. CONCLUSIONS

This paper has presented a comparison of two cascaded H-bridge multilevel topologies feeding a DTC induction motor. Using the asymmetrical cascade multilevel inverter, which has reduced the number of DC voltage sources and switches, provides more flexibility to designers and can generate more voltage levels.
Fig. 11. 7-levels cascaded H-bridge inverter phase current FFT analysis.

Fig. 12. 7-levels cascaded H-bridge inverter phase voltage waveform.

Fig. 13. The experimental setup.

Fig. 14. Torque waveforms for a 5-levels cascaded H-bridge.

Fig. 15. 5-levels cascaded H-bridge inverter output current waveforms.

Fig. 16. 5-levels multilevel inverter output voltages during DTC.

Fig. 17. Torque waveforms for 7-levels cascaded H-bridge.
This association results in the reduction of the number of switches, losses and coast of the inverter. Based on the DTC the most important achieved results are significant reduction in the torque ripple, sinusoidal output voltages and currents, and a high-performance torque and flux regulation. The asymmetrical multilevel inverter enables a DTC solution for high-power motor drives, not only due to the higher voltage capability provided by multilevel inverters, but mainly due to the reduced switching losses and the improved output voltage quality, which provides sinusoidal current without output filter.

REFERENCES


