Inverter Nonlinearities Estimation and Compensation for High Performance PWM VSI based AC Drives

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Abstract - AC drives based on pulse width modulation (PWM) voltage source inverters (VSI's) have many drawbacks, especially for high performance applications. The inverter nonlinearities such as dead time and power devices voltage drop are one of the main reasons. In this paper a new method to estimate and compensate inverter nonlinearities is presented. The proposed method is based on Model Reference Adaptive System (MRAS). The analysis of dead time and voltage drop effects is firstly performed, where a Logical operator's based representation is sketched to explain the nonlinearities insertion in a sinusoidal PWM. An MRAS algorithm which involves two active power models in stationary reference frame (\(a,\beta\)) is designed regarding nonlinearities estimation and compensation. The whole system is integrated in Direct Torque Control (DTC) based drive to know features and prove the effectiveness of the proposed method.

I. INTRODUCTION

Many inverter-nonlinearities compensation methods have been proposed for PWM VSI based AC drives \([1] - [10]\). Two main schemes are commonly used, which are the feed-forward and feed-back techniques. The nonlinearities are caused by a voltage drop across the power devices and the blanking time to prevent DC-source short circuit. Their effects are serious in some operation modes for high performance AC drive especially at low speeds, the stability issues should be discussed in that points. Many research works have been done in expounding how to estimate and compensate these phenomena. The principles and effects of voltage drop and blanking time insertion are widely discussed in \([1] - [4]\). A feedback and feed forward techniques are performed; the majority is based on average value of lost volt-second and load current direction. A low cost accurate method has been proposed in \([5] - [6]\). Adaptive dead-time compensation strategies are suggested in \([7] - [10]\).

In this paper, a new technique for PWM VSI nonlinearities estimation and compensation is devoted. The analysis of nonlinearities effects is firstly presented, than a model reference adaptive system which considers two active power models is adopted. The whole algorithm is tested for an AC drive based on induction motor DTC. The simulation results are done using Matlab-Simulink and experimental implementation which demonstrate the feasibility of these types of estimation and compensation are shown using a Texas Instruments TMS320F240 digital signal processor.

II. INVERTER NONLINEARITIES

![Fig. 1. Basic circuit of a three phase six switches VSI fed induction motor.](image)
sources and six bidirectional switches. Each one includes an IGBT mounted in antiparallel with a freewheeling diode. The switching signals are provided from a TMS320F240 digital signal processor. In practical cases, open or close the IGBT needs a finite times \((T_{on} \text{ and } T_{off})\) to be performed. Thus, to prevent DC-link short circuit, it is mandatory to consider a blanking time \((T_d)\) between upper and lower gate drive signals.

In Fig. 2 a comparison of ideal and real waveforms for one leg PWM implementation is illustrated.

![Real and ideal waveforms for one leg PWM implementation](image)

In overall, \(V_{LNR}\) is determined based on the following considerations

- Real switches behaviour
- State of the ideal gate drive signals \((g^*_{TL}, g^*_{BL})\)
- Motor current direction \((i_L)\)

On the other hand, the ideal inverter output voltage is given using only ideal upper switching signals and \(V_{dc}\)

\[
V_{LNR} = V_{dc} (g^*_{TL} - 0.5)
\]  

(4)

After comparing (1) and (4) over several switching periods \((T_s)\), it can be noted a voltage offset in all inverter phases \((V_{ANR}, V_{BNR}, V_{CNR})\). Therefore, an average voltage error \((\Delta V)\) is appeared in the space vector diagram as in Fig. 4.

![Inverter nonlinearities effect on the space vector diagram](image)
MRAS based inverter nonlinearities estimation and compensation. (MRAS) is proposed. The MRAS involves two active power models in stationary reference frame (α,β), the first does not include the quantity to be estimated (dead time and turn ON/OFF time delay) as reference model, whereas the second includes as adjustable model. The block diagram of the proposed MRAS estimation and compensation is illustrated in Fig. 5.

The model which reflects the active power estimation under ideal voltages is

\[ P_{LI} = V_{LNI} I_{LI} \]  

Similarly, the adapted model can be presented using the estimated real output voltages as follows

\[ P_{LR} = V_{LNRI} I_{LR} \]  

As in [3], a relationship between the reference and actual duty cycle signals \( d_{abc}^*, d_{abc} \) is established as

\[ d_{abc}^* = d_{abc}^* - \Delta d_{abc}^* \]  

Where

\[ \Delta d_{abc}^* = \begin{cases} T_{off} + T_c - T_d - T_{on} & \text{if } \varepsilon(t) \geq 0 \\ T_d + T_{on} - T_{off} - T_c & \text{if } \varepsilon(t) < 0 \end{cases} \]  

\( T_c \) is an estimate time can be used to control the average error of the output voltage [3]

\[ T_c = T_d + T_{on} - T_{off} + \frac{T_c}{V_{dc}} (V_{sat0} + V_f0) \]  

\( V_{sat0} \) and \( V_f0 \) are the IGBT’s and antiparallel diodes threshold voltages respectively given in Table. 2.

### IV. SIMULATION RESULTS

In order to know features of the whole algorithm, a computer simulation has been carried out using a flux linkages model of a 0.9Kw, 2 pole pairs squirrel cage induction motor, the necessary specifications and data are listed in Table. 1. The switching frequency was set at 2.5kH, while the sampling period was fixed to 70μs. However, when introduce the inverter nonlinearity and dead time delay into account; the sampling period has been reduced to 4μs, which represents the dead time value \( (T_d) \). The flux linkages reference value was given, according to the rotor speed profile, by its equivalent voltage \( (\psi_s=540V) \). The block diagram of the DTC SVM induction control is shown in Fig.6.

Figs. 7 and 8 show the line current waveform without and with nonlinearity compensation respectively. It can be seen in the same figure, the amplitude, phase and total harmonic distortion (THD) given by an FFT analysis tool available in Matlab/Simulink software. It should be noted that the current waveform has been improved with a mean MRAS proposed algorithm. Besides, this compensation method is simpler than other feed-forward and feed-back methods cited in [1], since it needs sparsely calculations. Moreover, it resolves the variable load current problems.
Fig. 7. Current waveform and its harmonic spectrum at f=40Hz before including inverter nonlinearity compensation.

Fig. 8. Current waveform and its harmonic spectrum at f=40Hz after including inverter nonlinearity compensation.

Fig. 9. The used Hardware setup Photography.

V. EXPERIMENTAL RESULTS

The effectiveness of the proposed algorithm has been verified by experimental setup which is arranged as in Fig. 9. The high speed TMS320F240 digital signal processor based dspace DS1104 controller board, is well suited to implement the whole algorithms code using Matlab/Simulink software. As stated previously, the controller signal outputs are sent to a six switches SEMITOP inverter, manufactured by SEMIKRON R&I, to fed the 0.9kw squirrel cage induction motor. It is noted that the same motor specification and data are used in simulation and in experimental (Table. 1), furthermore, the inverter parameters are available in the manufacturer catalog and given in Table. 2. The induction motor is tested under various operating conditions using a DSP6000 based programmable test bench. The switching frequency was set at 10kH. The obtained results are displayed using a LeCroy Wavesurfer 24MXs-B oscilloscope. The photograph of the experimental test bench is shown in Fig. 9.

Figs. 10 and 11 show the experimental line current waveforms without and with MRAS based nonlinearity compensation respectively. In Fig. 12, the estimated rotor speed and angle at ±10% of its synchronous speed is shown. It can be concluded that our proposed algorithm estimates and compensates the inverter nonlinearities and gives high performance drive.
In this work, an experimental investigation of dead time and voltage drop estimation and compensation has been proposed. An MRAS algorithm has been introduced to estimate and compensate the inverter nonlinearity and the dead time effect. The whole system was tested with wide operating range of DTC-SVM induction motor drive. The feasibility of the whole algorithm has been verified by experimental results using a DS1104 controller board which based on Texas Instruments TMS320F240 digital signal processor, even by using a DSP6000 based programmable test bench.

APPENDIX

TABLE I. MOTOR RATED SPECIFICATIONS AND DATA.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>900 W</td>
</tr>
<tr>
<td>Voltage</td>
<td>380/660 V</td>
</tr>
<tr>
<td>Current</td>
<td>2.6 A</td>
</tr>
<tr>
<td>Frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Torque</td>
<td>6N.m</td>
</tr>
<tr>
<td>Speed</td>
<td>1420 rpm</td>
</tr>
<tr>
<td>Pole-pairs</td>
<td>2</td>
</tr>
<tr>
<td>R_s</td>
<td>21.00 Ω</td>
</tr>
<tr>
<td>R_r</td>
<td>22.63 Ω</td>
</tr>
<tr>
<td>x_s</td>
<td>330.68 Ω</td>
</tr>
<tr>
<td>x_r</td>
<td>339.57 Ω</td>
</tr>
<tr>
<td>x_m</td>
<td>313.00 Ω</td>
</tr>
</tbody>
</table>

TABLE II. INVERTER SPECIFICATIONS DATA (FROM SEMIKRON R&D DATASHEET).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>I_n,max</td>
<td>35 A</td>
</tr>
<tr>
<td>V_d,max</td>
<td>750 V</td>
</tr>
<tr>
<td>V_e,max</td>
<td>1200 V</td>
</tr>
<tr>
<td>f_c,max</td>
<td>1/15 kHz</td>
</tr>
<tr>
<td>V_Lmax</td>
<td>2.2 V</td>
</tr>
<tr>
<td>V_L</td>
<td>1.8 V</td>
</tr>
<tr>
<td>R_s(125C)</td>
<td>26.10 Ω</td>
</tr>
<tr>
<td>R_r(125C)</td>
<td>16.10 Ω</td>
</tr>
<tr>
<td>T_s(Hardware)</td>
<td>4μs</td>
</tr>
</tbody>
</table>

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REFERENCES