STATIC FREQUENCY CONVERTER THAT CONTROLS
AN INDUCTION MOTOR

AI. ALEXANDRESCU, D. ALEXA, T. GORAŞ
„Gheorghe Asachi” Technical University of Iaşi

Abstract: This paper presents a static frequency converter that controls an induction motor according to the principle $V/f = \text{constant}$. Unlike the classic $V/f$ control scheme, the proposed method insures high dynamic performances from the adjustable speed drive system. The solution is based on certain behavior of the PWM self-control inverter in a transient state, which feeds the induction motor, thus simplifying the control circuit. In conclusion, the self-control method for the induction machine fed by inverter consist in controlling in conduction mode only two power transistors or GTO thyristors for the pause durations of phase voltage pulses, when these voltages should be 0.

Keywords: pulse with modulation, induction machine, AC/DC/AC converter, dynamic performances.

1. INTRODUCTION

The induction motor, thanks to its well-known advantages of simple construction, ruggedness, reliability and low cost, has found worldwide industrial applications.

When operated directly from the line voltage, a motor operates at nearly constant speed. By means of power electronic converters, induction motors can be used for adjustable-speed and servo drive applications. The control schemes of variable speed induction motors are the following:

1. Speed control by varying stator voltage and frequency according to the principle $V/f = \text{constant}$. This is the easiest method; nevertheless it has low dynamic performances. In numerous industrial applications, the requirements related to the dynamic properties of drive control are of secondary importance.

2. The high-performance induction control method, known as field-oriented control (FOC) or vector control has been constantly developed and improved by great researchers. In this method the motor equations are transformed in a coordinate system d-q that rotates with the rotor (stator) flux vector. Stator-flux-oriented control (S-FOC) has a simple structure when the induction motor is supplied from a voltage-controlled PWM (Pulse Width Modulated) inverter. The rotor-flux-oriented-control (R-FOC) is easily implemented in connection with a current-controlled PWM inverter [1, 2].

3. In search of a simpler and more robust control system capable of preserving high performance, the direct torque and flux control (DTFC) method was proposed. The DTFC principle for induction motors, generalized for all AC drives, is now used from 2 kW to 2 MW, with the controller basically implemented in the same hardware and using the same software [2, 3].

The paper presents a static frequency converter that controls an induction motor according to the principle $V/f = \text{constant}$. Unlike the classic control method $V/f$, the solution introduced in this paper insures high dynamic performances from the variable speed drive system. This control method can be explained by means of Figure 1, which shows the reduction of the durations of transient states in a RL parallel circuit. This circuit can be supplied with a voltage $v = V_m \sin \omega t$ in
steady state, producing a current \( i = I_m \sin(\omega t - \varphi) \). The frequency \( f \) and the amplitude \( V_m \) of the voltage can be modified instantaneously by means of a power converter, while the current \( i \) reaches a new steady state after the transient state has passed. In transient states, the converter also leads to the occurrence of additional voltages \( \Delta v \) at the input, which rapidly adjust the current waveform to a form appropriate for the new steady state. In Figure 1(b) and 1(c), transient states are reduced from frequency \( f_1 \) to frequency \( f_2 \) and the other way around (\( f_1 \) is considered higher than \( f_2 \)). Indexes (1) and (2), corresponding to frequencies \( f_1 \) and \( f_2 \), are attached to voltages \( v \), \( \Delta v \) and to the current. Figure 1(b) shows the step passage from \( f_2 \) to \( f_1 \) and Figure 1(c) illustrates the reversal of the frequency. By adding the additional voltages \( \Delta v^{(1)} \) or \( \Delta v^{(2)} \), the durations of the transient states shorten considerably.

When these states cease, the power converter brings the additional voltages to zero. If the reactive component of the current \( i \) is zero (consequently, the inductance \( L \) has an infinite value), no additional voltages occur in transient states.

The solution is based on a certain behavior of the PWM self-control inverter (PWM-SC inverter) in transient state, which feeds the induction motor, thus simplifying the control circuit. Due to an adequate control method of the semiconductor devices within the inverter, additional voltages appear at its outputs, which apply on the phases of the machine in transient state, leading to a considerable damping of transient currents. The goal for this control method for a PWM self-control inverter is to maintain constant amplitude for the excitation current \( i_0 \) of the induction motor, in transient operation, insensitive to variations of either the supply frequency or the load torque. Through this approach, a scalar control for the induction motor is obtained.

2. DESCRIPTION OF THE PWM WITH SELF-CONTROL INVERTER

In the following paragraphs, we shall describe the control method for a PWM-SC inverter according to the principle \( V/f = \text{constant} \) in steady state, which leads to an increase in the dynamic performances of the induction motor it feeds. Figure 2 presents the general circuit of a frequency
converter with a RNSIC-1 rectifier (Rectifier with Near Sinusoidal Input Currents) at the input and with a PWM three-phase inverter with 6 IGBT devices at the output [4, 5].

![Diagram of a static frequency converter with three-phase inverter](image)

**Fig. 2.** Basic diagram of a static frequency converter with three-phase inverter.

The output of a RNSIC-1 converter voltage $V_{dr}$ is 15%-20% higher than the reference voltage $V_{ref}$ obtained with a three-phase classical diode rectifier. This suggests that, at the output of the PWM inverter, one can get the rated voltages for the three phases supplying current to the induction motor drive. This way, there is no need to apply an overmodulation technique. The rectifier voltage $V_{dr} = V_{ref} / (1-2L_1C_o^2)$ surpasses the reference value $V_{ref}$ ($V_{dr} = kV_{ref}$, where $k = 1/(1-2L_1C_o^2)$ is an overvoltage coefficient varying between 1.15 and 1.20. This is why one can get stator phase voltages, $V_s$, applied to the induction machine, practically surpassing by the same coefficient $k$ the rated voltage $V_{sr}$.

The basic principle of the sinusoidal PWM is given in Figure 3. In order to obtain, at the inverter output, the waveforms of the voltages $v_{UV}$, $v_{VW}$, and $v_{WU}$, three sinusoidal modulating signals $v_r$, $v_2$ and $v_3$ are compared with a triangular signal $v_p$.

The cross points are used to determine the switching moments of the semiconductor devices $T_1 - T_6$. The instantaneous values of the phase voltages that apply to stator windings are noted with $v_{U0}$, $v_{V0}$ and $v_{W0}$ and $i_U$, $i_V$ and $i_W$ indicate the instantaneous values of the phase currents. Rotor currents $i_K$, $i_L$ and $i_M$ are similarly defined. The functioning of the inverter in Figure 2 is based on the sinusoidal PWM version. The inverter allows the variation of the frequency and amplitude of the output voltage fundamentals.
Fig. 3. Three-phase PWM waveforms

- output voltages $v_{U3}$, $v_{VP}$ and $v_{V0}$ for $m_f = 15$;
- controlling programme for transistors;
- principle of PWM self-control method.

Studying transistor command sequences, according to Figure 3(b), it can be concluded that, for the proposed self-control method, only two transistors need to be turned in zero voltage intervals ($\tau$).
The induction motor in steady state can be considered as a resistive-inductive load for the PWM-SC inverter. For such a load, phase currents $i_U$, $i_V$ and $i_W$ always have the same orientation as phase voltages $v_{U0}$, $v_{V0}$ and $v_{W0}$ for angles between $\pi/2$ and $(\pi/2 + \alpha)$ (therefore for the $\varphi$ angle varying between 0 and $\pi/2$). Of course, in transient state, this is no longer the case and this is the fundamental of the self-control method presented in this paper.

In Figure 3(c) the principle of the self-control method of the inverter is depicted for transistors $T_1$ and $T_4$, provided phase $R$ is considered. For an angle equal to $\alpha$, both $T_1$ and $T_4$ transistors are off. This angle can vary from 0 to $\pi/3$, the proper value being set by the command scheme, according to the desired dynamical performance for a given inertial moment of the operating system.

Figure 4 shows the effect of transistor control on the waveforms of voltages $v_{U0}$, $v_{V0}$ and $v_{W0}$ while the induction machine is supplied with current from the PWM-SC inverter.

![Fig. 4. Operation waveforms obtained in the self-control method:](image)

- $a$ – in the steady-state;
- $b$ – in the transient state for $f_2 < f_1$ and $\alpha = \pi/3$;
- $c$ – in the transient state for $f_2 < f_1$ and $\alpha = \pi/5$.

Figure 4(a) presents the waveforms of line $(v_{UV(1)})$ and phase $(v_{U0(1)})$ output voltages fundamentals, as well as the fundamental of the phase current $i_{U(1)}$ in steady-state at frequency $f_1$. The induction machine functions as a motor and the waveforms mentioned above coincide with the ones obtained by means of the classical sinusoidal PWM technique. The phase shift angle $\varphi$ between values $v_{U0(1)}$, $v_{U0(1)}$, and $i_{U(1)}$ is positive and varies between $0^\circ$ and $90^\circ$ in steady-state.

Additional voltages, represented by shaded spaces in Figure 4(b) and Figure 4(c), occur only in transient state and have two roles. The first is to induce a fast damping of the transient components of stator currents $i_U$, $i_V$ and $i_W$. The second is to determine an increase of the fundamental components of phase voltages $v_{U0}$, $v_{V0}$, $v_{W0}$ and, thus, to reach faster and to maintain the excitation current $i_0$ at the frequency $f_2$, current that corresponds to the new functioning steady-state. When $\alpha = \pi/3$, complying
with Figure 3(b), the additional voltages $\Delta v_{U0}^{(2)}$, $\Delta v_{V0}^{(2)}$ and $\Delta v_{W0}^{(2)}$ have maximum values and the self-control effect is high.

In case $\alpha$ is lower than $\pi/3$ (for instance $\alpha = \pi/5$ as illustrated in Figure 4(c), a partial self-control method is obtained, with weaker dynamical performance.

Here is why additional voltages occur, in angles $\omega t_1$, $\omega t_2$ etc. in Figure 3, after the transistors $T_6$, $T_1$ are blocked, the transistors $T_3$, $T_4$ etc. are not switched on. In the IM steady state, currents $i_U$, $i_U$, $i_W$ that flow through the blocking transistors, shift on diodes $D_3$, $D_4$ etc. phase voltages $v_{U0}$, $v_{V0}$ and $v_{W0}$ are brought to zero as in the classic PWM method. In transient state, currents $i_U$, $i_V$ and $i_W$ can flow in angles $\omega t_1$, $\omega t_2$ etc. through diodes $D_6$, $D_1$ etc. and, therefore, the blocking of $T_6$, $T_1$ etc. does not lead to the reduction to zero of the phase voltages. These voltages in pause intervals $(T - \tau)$ become $\pm V_d/3$ and $\pm 2V_d/3$, which constitute additional voltages according to Figures 4(b) and 4(c).

In conclusion, the self-control method for the induction machine fed by a PWM inverter consists in controlling in conduction mode only two power transistors or GTO thyristors for the pause durations of phase voltages pulses, when these voltages should be 0. According to Fig. 3(b), none of the controllable devices is controlled in conduction for angles between $\pi/2$ and $(\pi/2 + \alpha)$ of the fundamentals of phase voltages $v_{U0(1)}$, $v_{V0(1)}$ and $v_{W0(1)}$. It is possible to reduce the acceleration or deceleration of the system depending on the value of inertial moment. In order to obtain the desired value, a partial self-control method can be used, containing fewer time frames in which only two IGBT transistors or GTO thyristors are in conduction.

3. SIMULATION AND EXPERIMENTAL RESULTS

Therefore, in order to make a comparison between the classical S-FOC method and the proposed self-control method for equal electrical powers at the frequency converter outputs, the factor $m_a$ from the proposed version has to be reduced by a coefficient $k = 1/(1 - 2L_4C\omega^2)$. The best parameter $L_4C\omega^2$ is 0.07.

Fig. 5. Simulation waveforms of the machine driven by PWM inverter with self-control for 50% step decrease in inverter frequency, in the case $T_1 = 60 \text{Nm}$, $J = 0.8 \text{kgm}^2$. 
To analyze the performances of the proposed control technique, simulation waveforms of stator current, electromagnetic torque and rotor angular speed have been plotted for a 50% step decrease in inverter frequency.

Figure 5 shows transient responses of the system under constant load torque in the case of PWM with self-control technique. In this case, from inverter frequency $f_1 = 55.55$ Hz, $m_a = 0.926/k = 0.7964$, the command sequence changes to $f_2 = 27.78$ Hz, $m_f = 30$, $m_a = 0.3982$.

When voltage and frequency suddenly change within the constant $V/f$ ratio, the induction machine oscillates between the increased slip motor regime and the generator regime.

The same phenomenon of reduced oscillations occurs when the load torque changes suddenly. The reduction, to a lesser or a wider extent, of the oscillations of rotor IM can be obtained by the variation of the angle $\alpha$ between $\pi/3$ and 0.

References


