STATIC FREQUENCY CONVERTER THAT CONTROLS AN INDUCTION MOTOR

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Abstract: This paper presents a static frequency converter that controls an induction motor according to the principle *V*/*f* = 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* = 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* = 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 Δv at the input, wich 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, Δv 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.

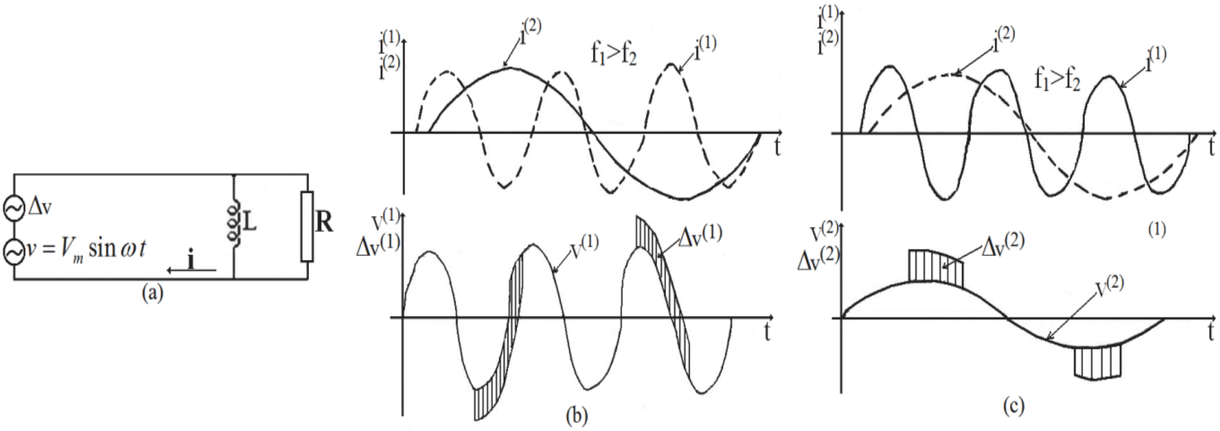

Fig. 1. Reducing transient states in a RL circuit by means of additional voltages:
a – circuit configuration; *b* – transition from f_2 to f_1; *c* – transition from f_1 to f_2.

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 = 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].

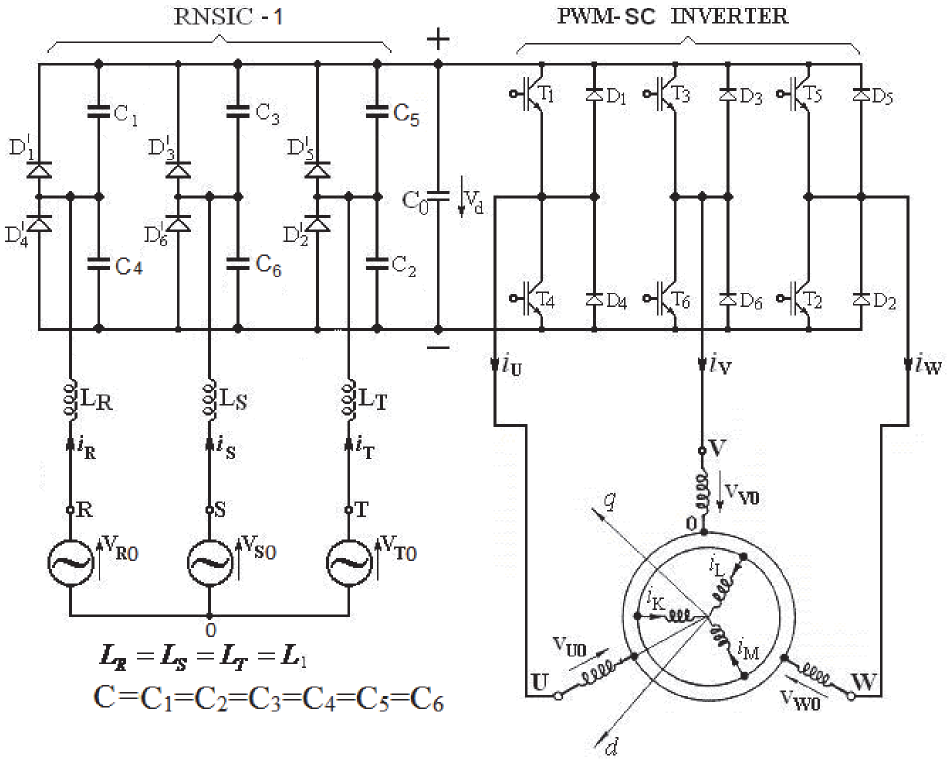

Fig. 2. Basic diagram of a static frequency converter with three-phase inverter.

The output of a RNSIC-1 converter voltage V_{dr} is 15%-20% higher then 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 phase supplying current to the induction motor drive. This way, there is no need to apply an overmodulation technique. The rectifier voltage $V_{dr} = V_{ref} / \left(1 - 2L_1C\omega^2\right)$ surpasses the reference value V_{ref} ($V_{dr} = kV_{ref}$, where $k = 1/\left(1 - 2L_1C\omega^2\right)$ 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_{r1}, v_{r2} and v_{r3} 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.

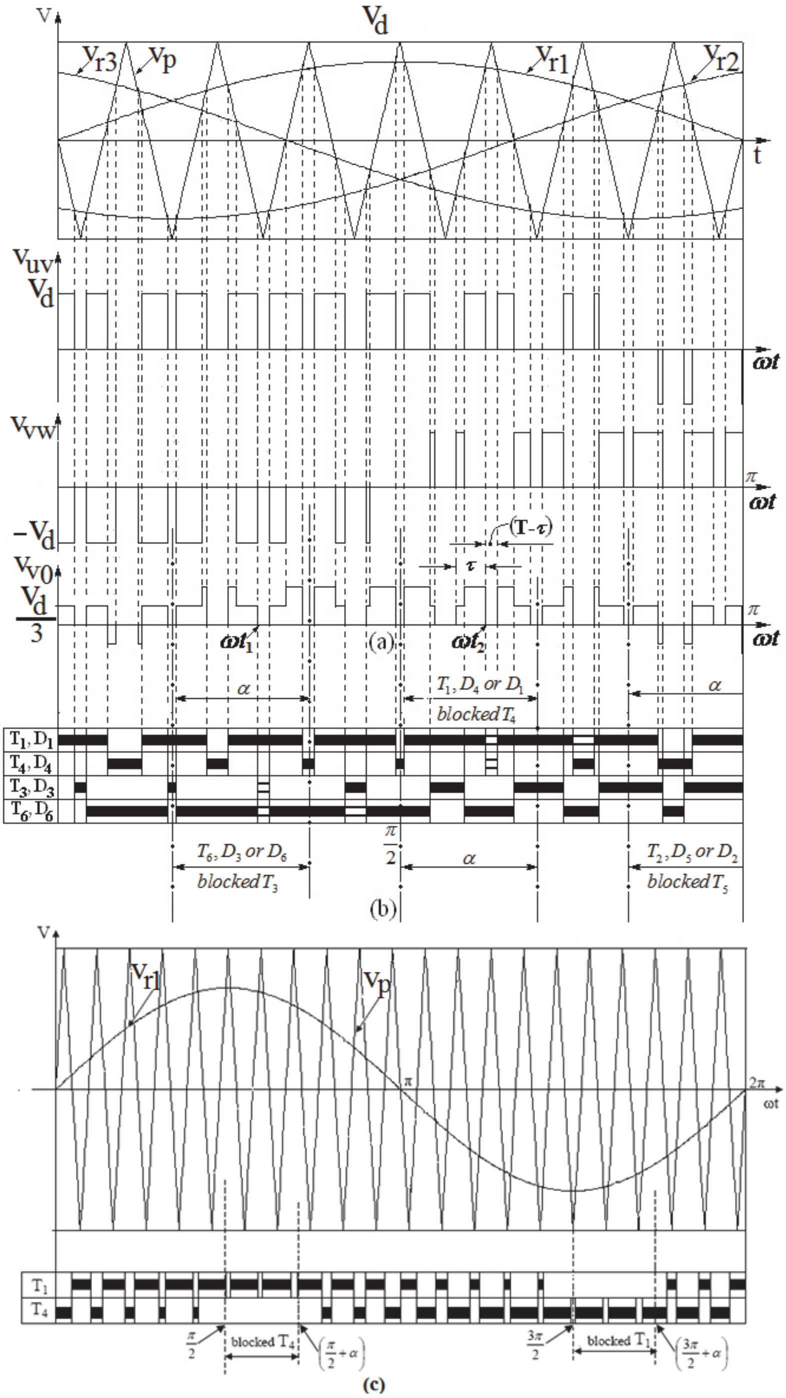

Fig. 3. Three-phase PWM waveforms
a – output voltages v_{UV}, v_{VW} and v_{U0} for $m_f = 15$; *b* – controlling programme for transistors;
c – principle of PWM self – control method.

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 $(T\text{-}\tau)$.

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 φ 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. Forn an angle equal to α, 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.

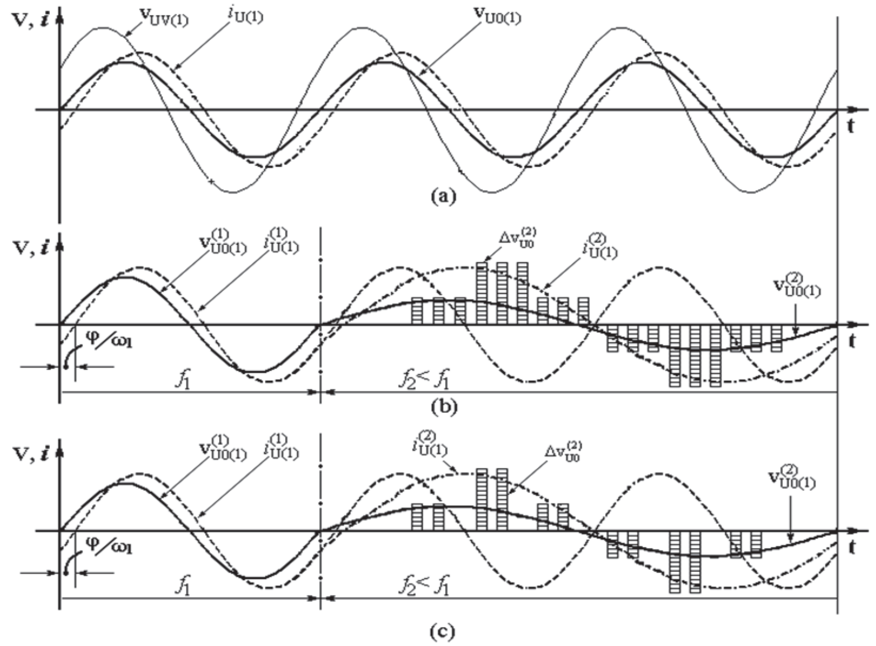

Fig. 4. Operation waveforms obtained in the self-control method:
a – in the steady-state; *b* – in the transient state for $f_2 < f_1$ and $\alpha = \pi/3$;
c – in the transient state for $f_2 < f_1$ and $\alpha = \pi/5$.

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 φ between values $v_{U0(1)}$ $\mathrm{v}_{\mathrm{U0(1)}}$ and $i_{U(1)}$ is positive and varies between 0° and 90° 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 α is lower than π/3 (for instance α = π/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 ωt_1, ωt_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_V, 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 ωt_1, ωt_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 $\pm 2V_d / 3$, wich 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 π/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 $k = 1/(1 - 2L_1 C\omega^2)$. The best parameter $L_1 C\omega^2$ is 0.07..

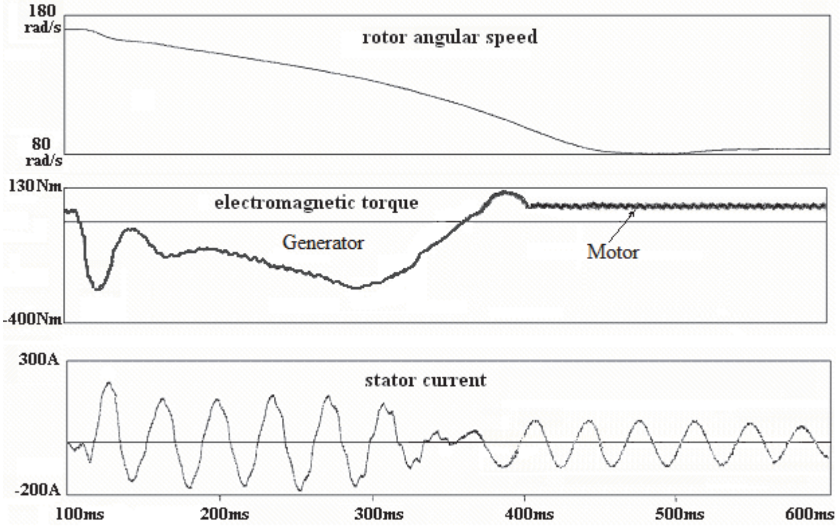

Fig. 5. Simulation waveforms of the machine driven by PWM inverter with self-control for 50% step decrease in inverter frequency, in the case $T_1 = 60$ Nm, $J = 0.8$ kgm^2.

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 α between π/3 and 0.

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