International Journal of Enhanced Research in Science Technology & Engineering, ISSN: 2319-7463
Vol. 3 Issue 4, April-2014, pp: (15-20), Impact Factor: 1.252, Available online at: www.erpublications.com

Effect of High-Order Harmonics on Efficiency-Optimized Three-Phase Induction Motor Drive System Performance

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Abstract: In this paper, the influence of harmonic content in the output voltage of pulse-width modulated inverter on efficiency-optimized three-phase squirrel cage induction motor drive system has been studied and analyzed. The proposed drive system was efficiency-optimized by using a search model control principle using PIC microcontroller. A Matlab Simulink model of the drive system has been constructed and investigated to study the effect of high-order harmonics in the inverter output voltage on the defined optimal operating point and performance of the drive system. From simulation results, it was found that the harmonic content in the output voltage of the inverter has significant effect on the optimal operating point, and no effect on the dynamic performance of the system.

Keywords: Induction motor drive, pulse-width modulated inverter, harmonic content, efficiency optimization.

Introduction

Today, three-phase, squirrel-cage induction motor drives are employed in different industrial areas with a wide power range due to their strong and powerful structures, low costs, low sound and inertia levels, less need for maintenance, their ability to work in polluted and precarious environments and wider power and speed range. In AC drive applications it is most desirable to use the sinusoidal waveform. Voltage source inverters VSIs and current source inverters CSIs are widely used in variable voltage, variable frequency VVVF three-phase induction motor drive systems. The main drawback of inverters is the harmonic content in the output voltage, which leads to overheating of the motor and pulsation in the developed torque. When the motor operates at constant V/f ratio, it saturates at light loads and low speeds due to high V/f ratio, which causes additional overheating of the motor at low speeds [1,2]. In practice, the influence of harmonic content can be reduced by a proper modulation strategy. Several methods have been developed for this purpose, including simple six-step modulation, high frequency pulse-width modulation PWM and progressive space vector modulation SVM [3,4]. For small and medium sized drives, PWM voltage source inverters are the standard type of equipment nowadays. Until a few years ago, the highest switching frequencies available were offered by Power-MOSFET inverters. However, their rated power was modest. Bipolar transistors could be used for higher power rating, but had a lower stitching frequency. The IGBT based inverters combine the advantages of both power electronic components: High switching frequency and high power ratings. Power ratings up to several hundreds of KVA are available commercially. The switching frequency may be several kHz [5, 6].

From another point of view, electrical motors consume around 56% of the total consumed electrical energy, and of this, induction motors account for 96% [7, 8]. This shows that around 53% of the total electrical energy is consumed by induction motors. The very extensive use of induction motors implies that if losses in induction motor drives can be reduced by just a few percent, it will have a major impact on the total electrical energy consumption. The newest progresses are improvements made to the motor drive itself. The motor efficiency is improved for so-called high-efficiency motors or premium-efficiency motors by improved construction and by use of more material in the motors. Furthermore the efficiency of the total drive is optimized by on-line energy optimal control [9]. The effect of harmonic content in the output voltage of inverters, feeding induction motors is not well studied, especially, when applying efficiency optimization techniques. Usually, the inverter is considered to be ideal with pure sinusoidal output voltage and the effect of high-order harmonics on optimal operating point is ignored.

The objective of this paper is to study the influence of harmonic content in the output voltage of inverter on the optimal operating point of efficiency-optimized electric drive system, based on three-phase, squirrel cage induction motor fed from PWM inverter.

Description of Proposed Electric Drive System

The proposed drive system is shown in Fig. 1. It consists of three-phase, squirrel-cage induction motor, fed from IGBT-inverter-based AC-to-AC energy converter, constant torque Load and controller.

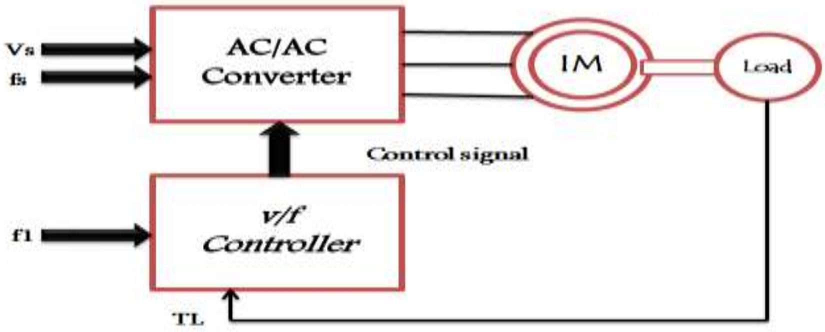

Figure 1. Block diagram of proposed electric drive system.

The controller operates according to constant V/f ratio to maintain the loading capacity (maximum torque) of the system constant. The motor ratings and parameters are given in Tab. 1.

Table 1: Induction Motor Ratings and Parameters

Parameter	Value
Nominal power, P_n	$7.5\,kW$
Nominal speed, n_n	$1440rpm$
Nominal voltage, $V_{1n(L-L)}$	$400V$
Nominal current, I_n	$18.75A$
Nominal torque, T_n	$49.74N.m$
Nominal frequency, f_n	$50Hz$
Number of poles, p	4
Stator resistance, R_1	0.738Ω
Stator reactance, X_1	0.003Ω
Rotor resistance, referred to the stator, R'_2	0.740Ω
Rotor resistance, referred to the stator, X'_2	0.003Ω
Moment of inertia, J	$0.034kg.m^2$

The inverter is considered ideal without harmonic content, except the fundamental harmonic, in its output voltage. The control command is the modulation index $m=V_1/V_n$. This system is to be efficiency optimized. The block-diagram of the optimized system is shown in Fig. 2.

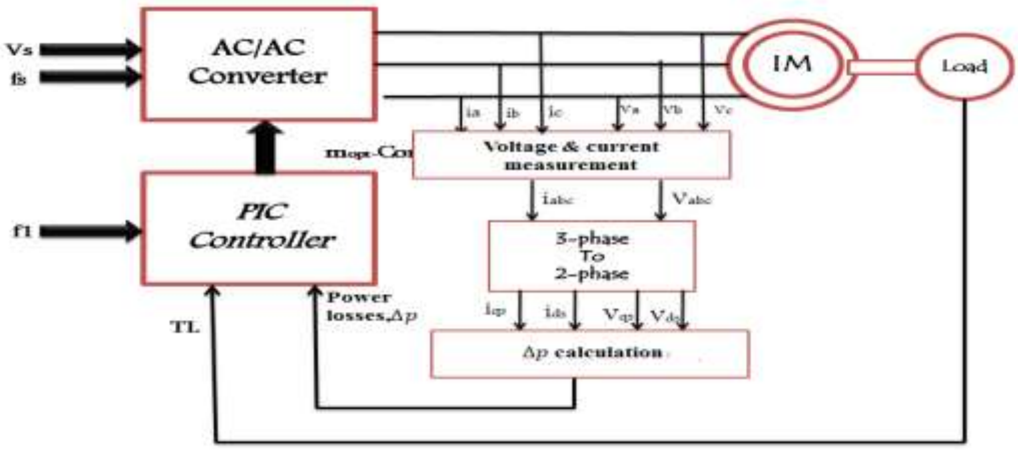

Figure 2. Block diagram of efficiency-optimized electric drive system.

Efficiency optimization is provided according to the search principle control, where the total power losses in the system is minimized by trial and error. For this purpose, a PIC microcontroller PIC-16F877A was used to find the optimal value of modulation index m_{opt}, corresponding to minimum (optimal) losses ΔP_{opt}. The controller operates according to the flow chart shown in Fig. 3 [9].
The total power losses ΔP in the system can be treated as the difference between the input power P_{in}, supplied to the stator, and the output mechanical power P_o:

$$\Delta P = P_{in} - P_o \tag{1}$$

The input power supplied to the stator P_{in} and the mechanical output power P_o can be calculated by the following equations [8,9]:

$$P_{in} = \frac{3}{2}[(I_{sq}V_{sq}) + (I_{sd}V_{sd})] \tag{2}$$

$$P_o = T_L \omega \tag{3}$$

where $I_{sq}, I_{sd}, V_{sq}, V_{sd}$ the d and q components of stator current and voltage, T_L the load torque, and ω the angular rotational speed.
The efficiency of the system is defined as:

$$\eta = \frac{P_o}{P_{in}} \tag{4}$$

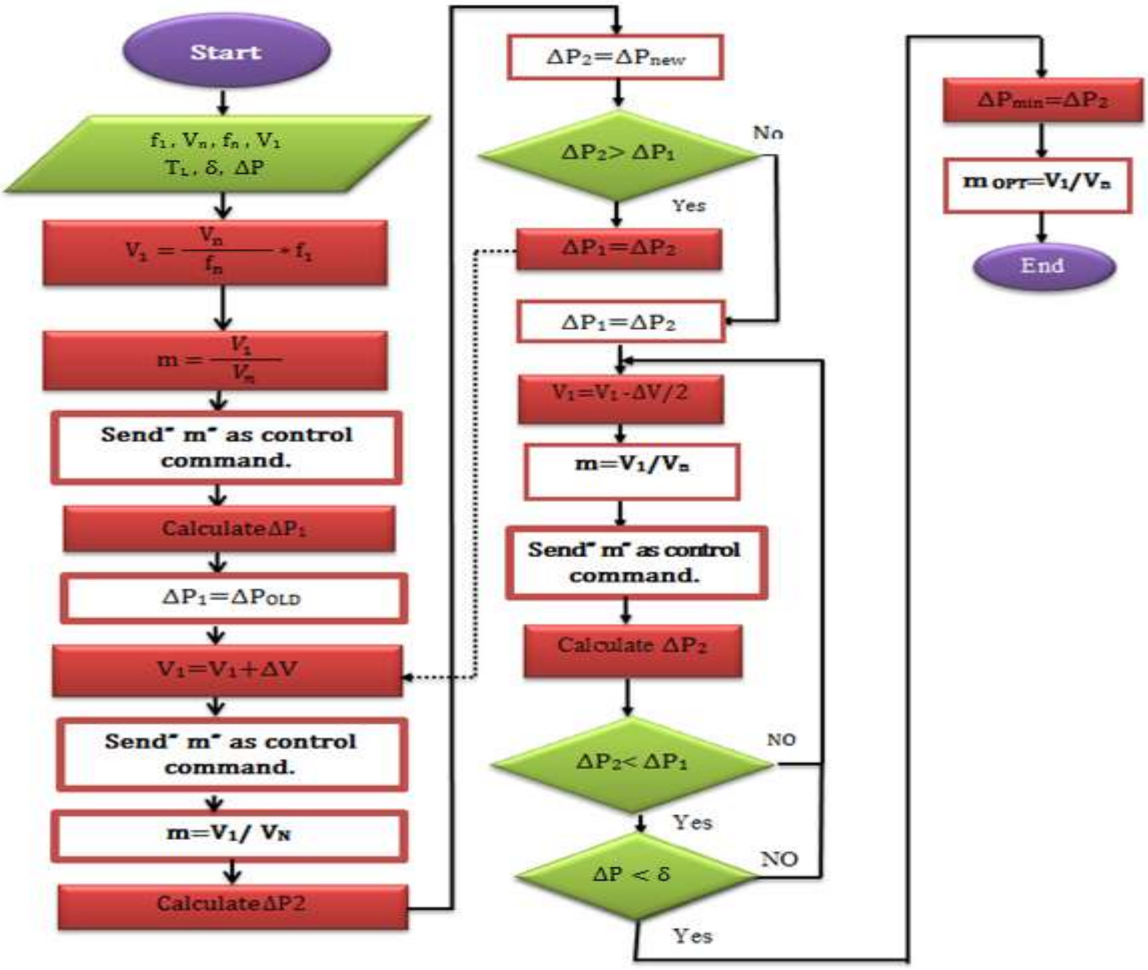

Figure 3. Optimization algorithm for search control.

To evaluate the influence of the high-order harmonics on the system behavior, the output voltage of the inverter can be treated as [6]:

$$v_{out}(t) = V_{m1}\sin(\omega t + \varphi_1) + V_{m3}\sin(3\omega t + \varphi_3) + V_{m5}\sin(5\omega t + \varphi_5) + \ldots \qquad (5)$$

The rms value of inverter output voltage can be calculated as:

$$V_{out} = \sqrt{\frac{V^2{}_{m1} + V^2{}_{m2} + V^2{}_{m3} + \ldots}{2}} \qquad (6)$$

and the modulation index will be defined as:

$$m = \frac{V_{out}}{V_n} \leq 1 \qquad (7)$$

The magnitudes of high-order harmonics as a percent of the magnitude of fundamental (first) harmonic are given in Tab. 2 [3].

Table 2: Magnitudes of High-Order Harmonics as a Percent of the Magnitude of Fundamental Harmonic

Harmonic Order	Value
3rd	7%
5th	4%
7th	2%
9th	1%
11th	0.5%

In this case, the search algorithm will remain the same, but the value of V_1 will be calculated by equation (6), which means that the value of modulation index will be increased, and when the system operates at frequencies near to the base frequency (50Hz), the optimization technique will not work, because the input voltage to the stator could not exceed the nominal value. In this study, the effect of harmonics higher than 5th order was neglected because of their low weight, compared with the fundamental one.

Simulation Results

The Matlab SIMULINK model of the proposed drive system was constructed and investigated. Simulation results were compared and analyzed. As indicators for steady state performance analysis, power factor, total power losses and efficiency were considered. Analysis was provided for different operating conditions. Tabs. (3, 4) and Figs. (4, 5) illustrate the effect of high harmonics on efficiency-optimized system. It was noticed that high-order harmonics at the whole range of frequencies and load torque decrease the efficiency of optimized system due to increase in total power losses, so, it is not recommended to consider the inverter as ideal when dealing with efficiency optimization, and the effect of high-order harmonics should be taken into consideration.

Table 3: Harmonic Effect on Total Power Losses

Load Torque, N.m	Frequency, 50Hz		Frequency, 20Hz	
	Without harmonics	With harmonics	Without harmonics	With harmonics
1	19.33W	20W	14.67W	19.86W
10	78.41W	100W	57.54W	149.9W
20	152.4W	207.8W	135.1W	212W
30	233.6W	327W	229.6W	391W
50	476.9W	695.4W	572.9W	1001W

Table 4: Harmonic Effect on Efficiency

Load Torque, N.m	Frequency, 50Hz		Frequency, 20Hz	
	Without harmonics	With harmonics	Without harmonics	With harmonics
1	0.891	0.889	0.811	0.760
10	0.953	0.932	0.917	0.810
20	0.954	0.937	0.913	0.817
30	0.954	0.938	0.921	0.818
50	0.963	0.941	0.936	0.825

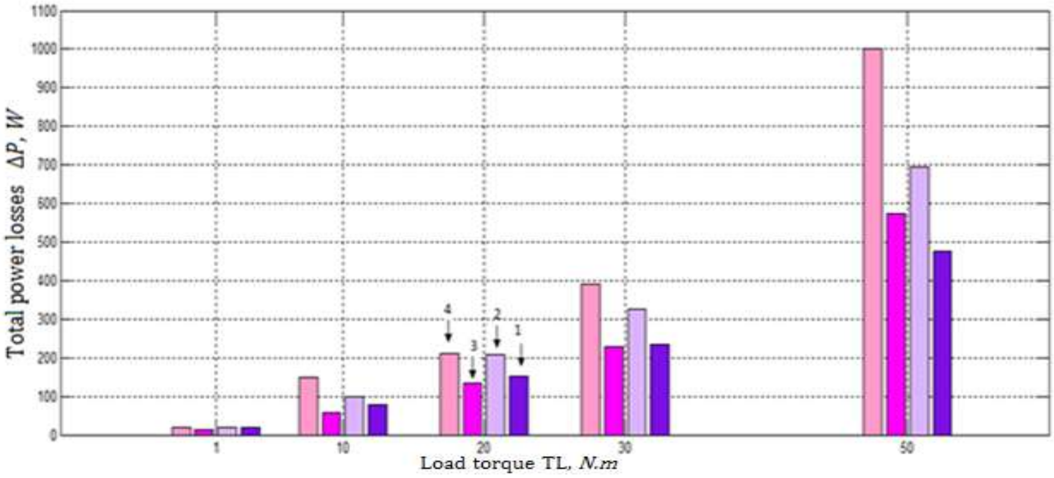

Figure 4. Effect of harmonics on total power losses.
(1 for 50Hz without harmonics, 2 for 50Hz with harmonics, 3 for for 20Hz without harmonics, 4 for 20Hz with harmonics)

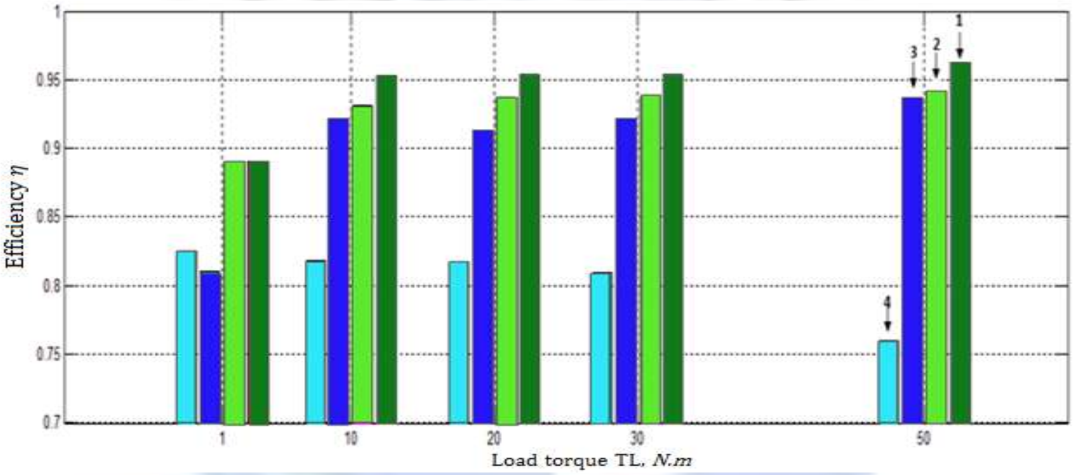

Figure 5. Effect of harmonics on efficiency.
(1 for 50Hz without harmonics, 2 for 50Hz with harmonics, 3 for for 20Hz without harmonics, 4 for 20Hz with harmonics)

Figs. (6, 7) show the dynamic response of the system at $T_L = 20N.m$ and $f_1 = 20Hz$, from which it is clear that high-order harmonics do not have significant effect on the dynamic performance of the system.

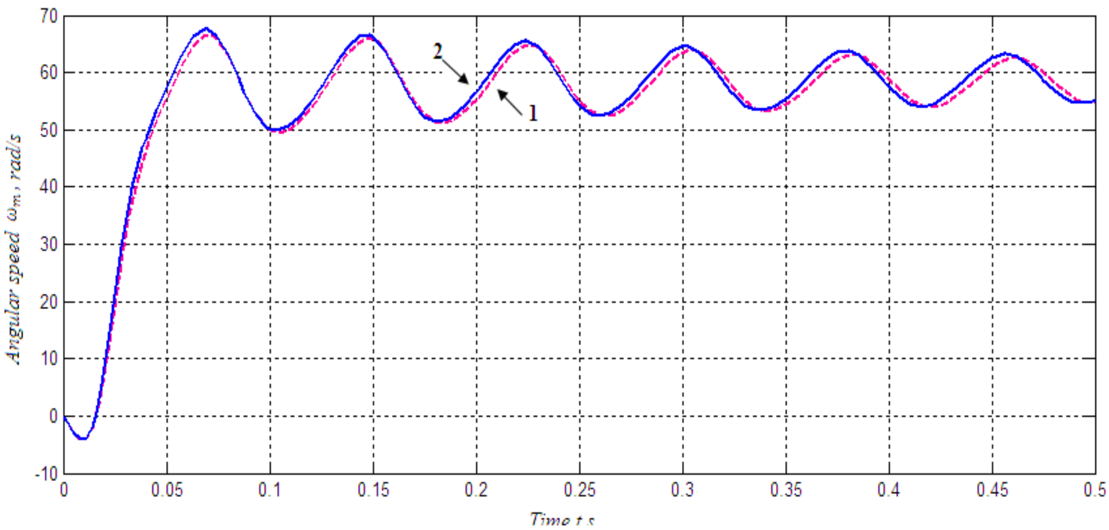

Figure 6. Dynamic response for angular rotational speed (1 without harmonics, 2 with harmonics).

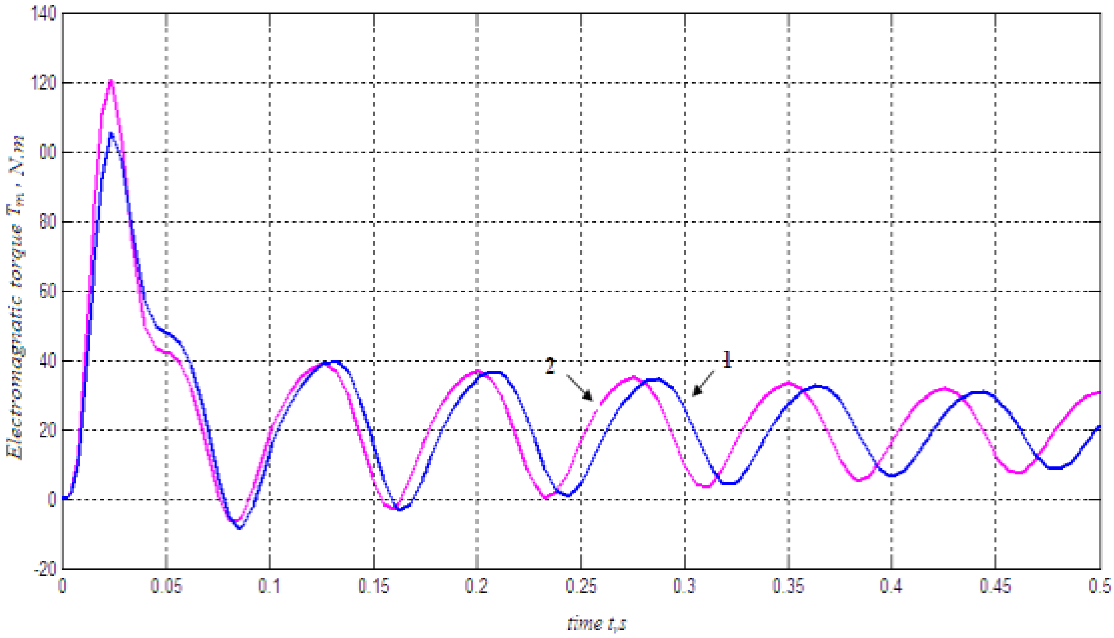

Figure 7. Dynamic response for electromagnetic torque (1 without harmonics, 2 with harmonics).

Conclusion

In this paper, the influence of harmonic content in the output voltage of inverter has been studied. It was found that the harmonic content significantly affects the optimal operating point of the electric drive system and reduces its efficiency. Thus, the effect of high-order harmonics should be considered when designing the optimal control algorithm of the electric drive system. Also, it was noticed that high harmonic content, practically, has no effect on the dynamic response of the system.

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