Andrzej Smoleń
Damian Mazur
Rzeszow University of Technology

EXAMINATION THE ROBUSTNESS OF SLIP-RING INDUCTION MOTOR DRIVE CONTROLLED BY DTC-SVM METHOD

Streszczenie: W artykule przedstawiono wyniki testów symulacyjnych układu sterowania maszyny indukcyjnej, wykorzystującego metodę DTC-SVM, pracującego w trybie utrzymywania zadanej wartości prędkości obrotowej. Symulację przeprowadzono w systemie Matlab z wykorzystaniem modelu matematycznego o stałych współczynnikach. Efektywność badanej metody regulacji została przetestowana w przypadku znacznych wahań momentu obciążenia oraz krótkotrwałych zapadów napięcia zasilania falownika. Uzyskane wyniki pokazują że badana metoda zapewnia bardzo dobrą dynamikę regulacji w przypadku zmian momentu obciążenia oraz jej znacznie większą wrażliwość w przypadku zaburzeń napięcia zasilania.

Abstract: The robustness of DTC-SVM control method applied to a maintain a speed reference value of induction machine has been analysed in this paper. The simulation study were performed based on ideal constant mathematical model of electrical drive implemented in Matlab. The linearized models of torque and flux control loops has been presented and examined in terms of frequency response. The performance of control method was tested in case of significant load torque variations and short-lived inverter supply voltage distortion. The obtained results showed that analysed control system reveals very good dynamic properties in case of load torque changes. Further studies have shown that DTC method is much more susceptible for a supply voltage distortions.

Słowa kluczowe: *maszyny elektryczne, izolacja zwojowa, badania diagnostyczne prądem stałym*
Keywords: *electrical machines, winding insulation, DC diagnostic tests*

1. Introduction

Due to their robustness, reliability and low cost the induction machines (IM) gradually replace a DC motors in many applications [1]. A number of studies have been made to develop the high performance and energy efficient method of IM control. Due to increase the availability of power electronic devices the inverter fed IM drives are most frequently used in appliances such as: conveyor belts, robots, etc. In recent years the direct torque control method (DTC) was increasingly used in industrial applications demanding a high performance speed control of IM [2]. The speed value maintaining mode of control is examined in this paper, the sensor less application is consider, which means that instantaneous value of rotor speed need to be estimated by a control system based on mathematical model. The estimation method, presented among others in [7 ,6 ,3] has been discussed briefly. The mathematical model of IM-DTC-SVM electric drive has been linearized according with a method presented in [10]. Obtained models has been tested in terms of frequency and time responses. In purpose of investigate the robustness of analysed automatic control system the simulation tests were performed for two different kinds of distortions: significant changes of load torque and the short-lived supply voltage dip. All simulations has been performed using ideal constant parameter machine model with were presented in [3].

2. Methods

A. Estimation the state of induction machine in sensorless DTC control

There are many approaches to applied DTC method for sensorless control of induction machine, reported in a literature [8], [12], [13]. The differences between them arise from efforts to improve the main disadvantages, which are: torque ripple [11], current oscillations and variable inverter switching frequency [9]. In principle the idea of DTC method is to control the stator flux and the motor torque directly, by setting a proper state of supplying voltage source inverter (VSI). The main problem in sensorless control is to obtain the actual state of controlled object [14], [15], [16], [17] the methodology is compactly quoted below. The most important information about current state of machine in terms of any DTC application are:

- stator flux error
- motor torque error
- location of stator flux vector on the complex plain

When the drive is torque controlled there is no need to inspect a speed, otherwise it is calculated based on the rotor flux vector location. The obtained value is subtracted from a reference one and the result is used as an input of PI controller, with produce the reference value of motor torque. The current value of generated electromagnetic torque is estimated based on stator currents measurements and supply voltages. In purpose of analyse the susceptibility of DTC control strategy to a short-lived supply voltage dip, the way of IM state estimation is presented below. Those methods were described in details in: [1], [3], [6].

The base description of stator flux is given by:

$$\vec{\Psi}_s = L_s\vec{i}_s + L_m\vec{i}_r \quad (1)$$

In the given time interval the stator flux vector is calculated based on it's value in a previous time step and a stator winding voltage equation, as follows:

$$\vec{\Psi}_s(t) = \vec{\Psi}_s(t-\Delta T) + \int(\vec{v}_s - R_s\vec{i}_s)d\tau$$
$$\ldots = \hat{\Psi}_s e^{j\theta_s} \quad (2)$$

The rotor flux vector can be represented as a function of stator flux and current.

$$\vec{\Psi}_r = \frac{L_r}{L_s}(\vec{\Psi}_s - \sigma L_s\vec{i}_s) = \hat{\Psi}_r e^{j\theta_r} \quad (3)$$

Where dissipation factor σ is given by:

$$\sigma = 1 - \frac{L_m^2}{L_s L_r} \quad (4)$$

In a given period of operating time the rotor flux vector can be calculated similarly as $\vec{\Psi}_s$, but in case of slip-ring motor $\vec{v}_r = 0$.

$$\vec{\Psi}_r(t) = \vec{\Psi}_r(t-\Delta T) + \int(-R_r\vec{i}_r)d\tau$$
$$\ldots = \hat{\Psi}_r e^{j\theta_r} \quad (5)$$

The generated electromagnetic torque is estimated as follows:

$$T_e = (\frac{2}{3})\frac{p}{2}\Im(\vec{\Psi}_s\vec{i}_s) \quad (6)$$

The rate of slip changes is represented as a function of electromagnetic torque and a rotor flux:

$$\omega_s = \frac{2}{p}(\frac{3}{2}R_r\frac{T_e}{\hat{\Psi}_r^2}) \quad (7)$$

The actual electrical speed is calculated as:

$$\omega_{re} = \omega_e - \omega_s \quad (8)$$

Where ω_e is an instantaneous value of θ_r numerical derivative, calculated from $-\pi$ to π . In order to calculate a mechanical speed the number of pols need to be taken into account.

It is noticeable that all of estimated values are, directly or indirectly, dependent of $\vec{\Psi}_s$ and $\vec{i}_s$. It makes DTC method inherently susceptible to a supply voltage distortions.

B. Linearized model of DTC-SVM drive

In order to investigate frequency characteristic of torque and flux control loop of analysed drive, the linearization has been performed in accordance with method presented in[10]. The obtained, for a torque loop, second order transfer function is:

$$G_{Te}(s)=\frac{T_e(s)}{u_{sq}(s)}=\frac{A_{Te}s}{s^2+B_{Te}s+C_{Te}} \qquad (9)$$

Where the coefficients are as follows:

$$A_{Te}=\frac{3}{2}\frac{P_b\Psi_s(1-\sigma)}{\sigma L_s} \qquad (10)$$

$$B_{Te}=\frac{1}{\sigma T_r+\dfrac{1-\sigma}{\sigma T_s}} \qquad (11)$$

$$C_{Te}=\frac{3}{2}\frac{P_b^2\Psi_s^2(1-\sigma)}{\sigma L_s J} \qquad (12)$$

In case of stator flux control loop the transfer function $G_{\Psi s}(s)=\dfrac{\Psi_s(s)}{u_{sd}(s)}$ has the same structure, but the coefficients are:

$$A_{\Psi}=\frac{1}{\sigma T_r} \qquad (13)$$

$$B_{\Psi}=\frac{1}{\sigma T_r}+\frac{1}{\sigma T_s} \qquad (14)$$

$$C_{\Psi}=\frac{1}{\sigma T_r T_s} \qquad (15)$$

The frequency response has been calculated for each loop, the results showed that the flux loop has a strict low pass filter character. The maximum values of torque damping are shifted toward higher frequency. The obtained curves are presented below.

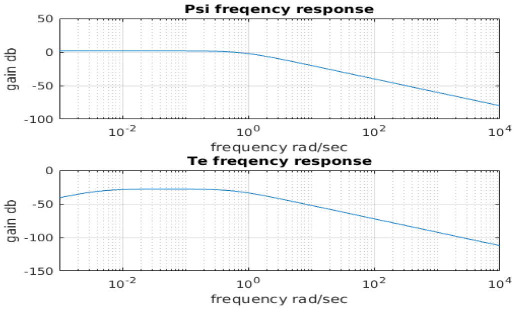

Fig. 1: The frequency response of stator flux and electromagnetic torque

As it was mentioned before the PI controller has been used in torque regulation loop, which is most common solution [4], [5]. The controller gains has been adopted in accordance with [6] and the values being: $Ki = 21875$ and $Kp = 1515.5$. The open loop frequency response has been calculated for a controller and the control system separately and compare. Obtained results showed that due to high value of $\dfrac{Ki}{Kp}$ ratio the controller gain in high frequency portion is substantial. It is noticeable that amplification zone of control system become wide and the unity gain is achieved for $75.7 rad/sec$. This can potentially make system sensitive for a higher frequency distortions.

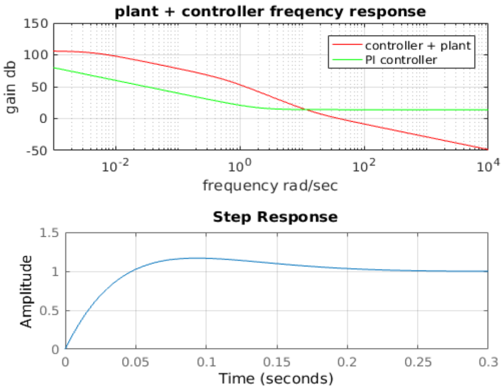

Fig. 2: Up: open loop controller and control system frequency response. Down: close loop step response.

The investigated system reveals very good dynamic properties in view of reference value tracking. Calculated step response achieved set point after 0.03 sec with an overshoot of 10% and become stabile after next 0.17 sec.

C. Simulation of load torque changes.

The simulation was performed for a undisturbed supply voltage and rapid changes of load torque. The initial conditions of simulation were determined for a steady state with rotor speed $\omega_{ref} = 124.4\frac{rad}{s}$, load torque $T_{L0} = 15899.47 Nm$ and inverter supply voltage $Vd = 1000V$. Applied vector of load torque values is presented in table 1 .

Table 1: Load torque changes

T_L	0	0	$-0.5T_{L0}$	$-0.5T_{L0}$	$0.5T_{L0}$	$0.5T_{L0}$
time	$0sec$	$0.5sec$	$0.51sec$	$1.5sec$	$1.51sec$	$2.99sec$

The parameters of IM mathematical model are shown in table 2 .

Table 2: Induction machine model parameters

parameters	values
R_s	0.002Ω
X_{Ls}	0.05Ω
R_r	0.002Ω
X_{Lr}	$0.047\ \Omega$
X_m	0.86Ω
Pb	$3\ [-]$
J	$70\ kg * m^2$
f	$60\ Hz$

The results show that DTC method very well fulfil the task of maintaining a preset value of rotor speed, even in case of significant load torque variations. Analysed system is able to restore a speed set point very quickly, with a slight overshoot. For load torque change from $-0.5T_{L0}$ to $0.5T_{L0}$ during $0.01sec$ the rotor speed is adjusted and stabilized after 0.5 sec. The absolute value of load torque change 100% of T_{L0} , but the speed overshoot is on the level of 1.6% reference value. These results prove that analysed control system can be considered as robust in view of load torque distortions.

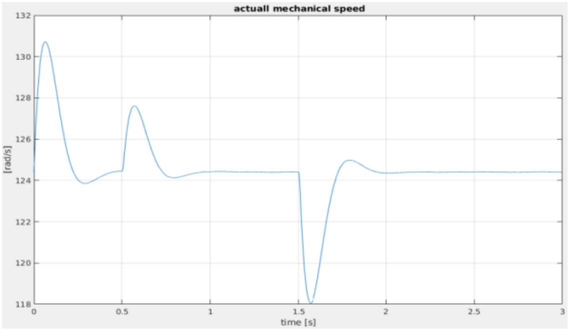

Fig. 3: IM rotor speed during load torque

D. Simulation of short-lived supply voltage dip

As it was mentioned before, analysed control method is sensor less which means that instantaneous value of rotor speed is calculated based on position of rotor flux vector 7. According to a relation 3 the $\vec{\lambda}_r = f(\vec{i}_s)$ and relation 6 the estimated value of electromagnetic torque $T_e = f(\vec{\lambda}_r, \vec{i}_s)$. It means that any distortions in a stator supply voltage are transferred into control system with a inertial dynamic corresponding to electrical time constant of stator windings T_s . Additionally the error of torque estimation caused by voltage distortion has a direct influence on a inverter control because it is taken into account while calculating the torque error, based on which the inverter switching vector is chosen. In purpose of investigate the susceptibility of DTC control method in respect of supply voltage distortions the short-lived voltage dip has been simulated. The same initial conditions and a constant value of load torque has been applied. The voltage dip time duration was defined as shown in table below.

Table 3: Load torque changes

$V_d - [\%]$	100%	100%	90%	90%	100%	100%
time	$0sec$	$0.2sec$	$0.21sec$	$0.26sec$	$0.27sec$	$0.999sec$

In accordance with the expectations tested distortion result with a very high and rapid increase of reference electromagnetic torque. In considered case achieved about 175% of its initial value and then decrease much less steeply.

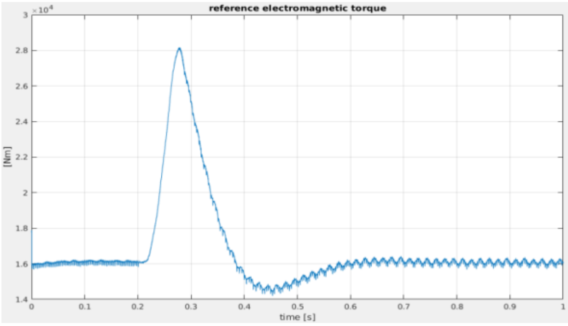

Fig. 4: Reference value of electromagnetic

The character of torque reference signal causing the rapid increase of stator currents, which achieved in a peak almost 200% of initial value. This leads to a conclusion that it can be potentially harmful in view of current overload. As it was shown previously the system is able to restore speed value with a very good dynamic, even for very significant change of load torque the overshoot aren’t greater then 1.6% . However in case of supply voltage distortions even slight changes can causing overshoots. Results presented below has been obtained for a 10% supply voltage dip, speed overshoot is on the level of 2% which proves that analysed system is much more susceptible for a voltage distortions, than for a load torque variation.

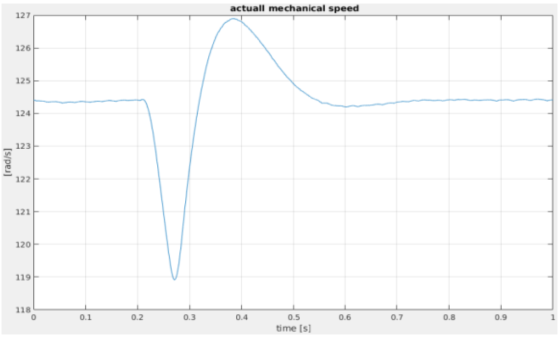

Fig. 5: IM rotor speed during supply

3. Conclusion

The examination of DTC-SVM induction motor drive dynamic in case of rapid changes of load torque, as well as in terms of short-lived supply voltage distortions was a purpose of this study. Simulations has been performed using the ideal constant mathematical model of three phase induction machine, the dynamic of inverter has been neglected because of significant difference of its time constant in reference to motor. In order to investigate and compare the frequency response of both torque and flux control system branches the model has been linearized. It was notice that large value of controller gains ratio $\frac{Ki}{Kp}$ needed to provide high performance dynamic in case of load torque changes, make the system susceptible for a higher frequency distortions. The results of simulation studies shows that inverter feed induction machine is able to restore a speed reference value quickly and with a slight overshoot, even in case of significant load torque variation the obtained speed overshoot has been on the level of 1.6% . This method is inherently susceptible to a disruptions of supply voltage. Even short-lived and shallow distortion cause significant variations of rotor speed.

4. References

[1] P. Kazmierkowski, R. Krishnan, Frede Blaabjerg . *Control in power electronics selected problems*. An imprint of Elsevier Science, 2002.

[2] Chiasson. *Modeling and High Performance Control of Electric Machine*. Wiley-IEEE Press. May 2005.

[3] Mohan. *Advanced electric drives*. John Wiley & Sons, 2014.

[4] C., Rajeevan P. P., Dey A., Ramchand R., Gopakumar K., Kazmierkowski M. P. *fast Direct Torque Control of en Open-End Induction Motor Drive Using 12-Sided Polygonal Voltage Space Vector*. IEEE Transactions of Power Electronics, 27(1), 400-409, Jan. 2012.

[5] G. Orzechowski T. Sykulski R. *Dobor parametrow regulatora predkosci w bezposrednim sterowaniu momentem silnika indukcyjnego*. Elektrotechnika i Elektronika, 24(1) 85-92, 2005.

[6] Abu-Rub, Atif Iqbal, Jaroslaw Guzinski. *Highperformance control of AC drives with Matlab/Simulink models*. John Wiley & Sons, 2012.

[7] Marian P. Kazmierkowski, Henryk Tunia *Automatic control of converter fed drives*. Elsevier, PWN Warszawa 1994.

[8] G. S., Kazmierkowski M. P *Direct torque control of PWM converter-fed ac motors-a survay*

IEEE Transactions on Industrial Electronics (Volume:51 , Issue: 4), Aug. 2004

[9] Seung-Ki Sul. *New direct torque control of induction motor for minimum torque ripple and constant switching frequency* IEEE Transactions on Industry Applications (Volume:35 , Issue: 5), 2002

[10] Sieklucki, Tadeusz Orzechowski, Rajmund Sykulski. *Model matematyczny napedu z silnikiem indukcyjnym metoda DTC-SVM* Elektrotechnika i Elektronika, Tom 29, Zeszyt 1-2, 2010.

[11] Kai Shyu , Juu-Kuh Lin ; Van-Truong Pham ; Ming-Ji Yang ; Te-Wei Wang. *Global Minimum Torque Ripple Design for Direct Torque Control of Induction Motor Drives* IEEE Transactions on Industrial Electronics (Volume:57 , Issue: 9), 2010

[12] Kenne , Tarek Ahmed-Ali, FranCoise Lamnabhi-Lagarrigue ; Amir Arzande. *Real-Time Speed and Flux Adaptive Control of Induction Motors Using Unknown Time-Varying Rotor Resistance and Load Torque* IEEE Transactions on Energy Conversion (Volume:24 , Issue: 2), 2009

[13] Casadei, G. Serra, A. Tania, L. Zarri. *Assessment of direct torque control for induction motor drives* Bulletin of polish academy of sciences, Technical Sciences (Volume: 24, No 3), 2006

[14] Maes, J. A. Melkebeek. *Speed-sensorless direct torque control of induction motors using an adaptive flux observer* IEEE Transactions on Industry Applications (Volume:36 , Issue: 3), 2000

[15] J. *Sensorless Control of Induction Motor Drives* Proceedings of the IEEE, 80(8) (2002) 1359-1394

[16] Lascus C, Andreescu G.-D *Sliding-mode observer and improved with dc offset compensation for flux estimation in sensorless controlled induction motors* IEEE Transactions on Industrial Electronics., 53 (2006) 785-794.

[17] P. Kazmierkowski, D. Stando *Novel speed sensorless DTC-SVM scheme for induction motor drives* IEEE Compatibility and Power Electronics (CPE), 2013.

Authors

dr hab. inż. Damian Mazur
e-mail: mazur@prz.edu.pl

mgr inż. Andrzej Smoleń
e-mail: a.smolen@prz.edu.pl