Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

Application of Sliding-Mode Control to Drive Systems Fed by a Three-Level Voltage-Source Inverter

Sergey Ryvkin*. Richard Schmidt-Obermoeller.Andreas Steimel*****

*Trapeznikov Institute of Control Sciences, Russian Academy of Sciences, Moscow, 117997 Russia (Tel: 495-334-2310; e-mail: rivkin@ipu.rssi.ru).
, * Institute for Electrical Power Engineering and Power Electronics, Ruhr-University Bochum, Bochum, D-44780, Germany (Tel: +49/234-32-23890)
**e-mail: schmidt-o@eele.rub.de, ***e-mail: steimel@eele.rub.de

Abstract: The paper explains basic ideas related to the design of a sliding-mode controller for an electromechanic drive system consisting of an induction motor and a three-level voltage-source inverter. A comprehensive investigation of possible "switched structures" of the drive was carried out. Based on this analysis an original two-step design procedure allows to use the "classical" result of sliding-mode theory for the real switched system with more then 2^m switched structures (*m* is the control space order). The performance of the considered control structure has been examined by simulation.

1. INTRODUCTION

Progress in the area of industrial control systems during the last quarter-century, namely the transition from thyristors to power transistors and from analog to digital technology, opens new possibilities thanks to the complete controllability of the power flux, quick control computation, big memory and the possibility to integrate into data networks. But to use all these possibilities, new advanced control techniques are needed. A standard item of modern high-power induction motor (IM) drives (power >3…4 MW) is the IM fed by three-level inverters (3LVSI) (Nabae et al.). 3LVSI are equipped with power semiconductor switches as Insulated Gate-Commutated Transistors (IGCTs) or with high-voltage Insulated-Gate Bipolar Transistors (IGBTs) (Krafft et al.), operating in switch-mode with distinctly higher switching frequency, than known from force-commutated thyristors. The IM behaviour can be described using non-linear differential equations that connect the motor variables (Leonhard). There are different machine models in dependence upon the chosen reference frame and space variables. Due to the complexity of this switched non-linear control plant having a series coupling of two non-linear objects different by nature, many different control techniques were proposed, such as e.g. Field-Oriented Control (Blaschke), Direct Self Control (Depenbrock) and Indirect Stator-Quantity Control (Depenbrock et al.) or Direct Torque Control (Buja et al., Tiitinen et al.). But nearly all these techniques have in common the decomposition of the main high-order control task to several separated lower-order tasks, using linear control technique and heuristic solutions.

The switching nature of the IM drive with 3LVSI opens the possibility to use the principal operational mode of this class of control systems – sliding mode – for solving the control task. Due to its property of order reduction and its robustness against disturbances and plant parameter variations, Sliding-Mode Control (SMC) is an efficient tool to control electromechanical systems, as it is well known (Ryvkin, Vittek et al., Utkin et al.). The primary aim of this paper is to show the possibility of using the sliding-mode technique for the control design of the electromechanical system consisting of IM and 3LVSI. The main problem is that opposite to the "classical" sliding mode theory (Utkin et al.) and the vector simplex approach to sliding-mode design (Baida et al.), in the real switched system there are more than 2^m switched structures (*m* is the control-space order). The directions of the discontinuous controls are fixed, and for the solving of the control task only the 3LVSI dc-link voltage value could be used.

The paper can be outlined as follows. Section 2 deals with a brief introduction of used sliding-mode control background. A presentation and discussion of the used IM and 3LVSI models is given in Section 3. Section 4 presents the formulation of the control task and describes a two-step sliding-mode control design technique. The design result is the control for the above-mentioned drive system. The results of the numerical simulation examination, that illustrate the properties of the suggested SMC, are presented in Section 5, followed by conclusions.

2. SLIDING-MODE CONTROL BACKGROUND

Sliding Mode is a special type of behaviour of a control plant with switched structures. None of the used general switched structures can realize such behavior, which is a result of the used special switched structures. The switching function F that controls the switching of the structures is a function of the system variables, usually an error function that must be led to zero. Switching of the structures with high frequency attains this condition.

Formally, the control aim is: The system state

$$F = 0 \tag{1}$$

978-1-1234-7890-2/08/$20.00 © 2008 IFAC

10.3182/20080706-5-KR-1001.0283

and "slides" on the manifold into the zero point, independently of the system dynamic.

It must be noted, that depending on the used control structure there are two types of variable structure systems, for which SMC has been considered: Variable-structure control systems with switching of the feedback gains, and systems with discontinuous control or "relay" systems with switching of the control outputs. From the viewpoint of the switch mode of the 3LVSI semiconductor switches the above-mentioned IM drive belongs to the second type.

A typical sliding-mode control has the form

$$u = -U(x)\,\mathrm{sgn}(F),\, u \in R^m\,, \tag{2}$$

where x is the system state vector, $x \in R^n$, $n \geq m$; $U(x)$ is the square diagonal matrix of the control magnitude; sgn(F) is the vector of the signs of the switching functions, $\mathrm{sgn}(F) \in R^m$. It guarantees that the system state will reach the sliding manifold in finite time from the initial condition, which has been bounded by the value of the constituent of matrix $U(x)$, and will keep to it. This magnitude bounds the uncertainty of the system, the load value unto which the system is commonly robust.

The motion on the sliding manifold can be described by using the equivalent control $u_{eq}(x)$ (Utkin et al.). It is calculated from the condition that: the time-derivative of the switching function F on the system trajectories is equal to zero.

The equivalent control $u_{eq}(x)$ is a continuous control that would guarantee the same motion, if all needed information about the load and the system uncertainty were available. In this case the system behaviour can be written with a vector equation of reduced order. The full order is reduced to the order of the sliding-mode manifolds.

3. IM AND 3LVSI MODELS

3.1. IM model

The two-phase equivalent model of a squirrel-cage induction machine in the stationary (α, β) reference frame and with all rotor quantities referred to stator is used (Leonhard):

$$\begin{aligned}
\frac{d(\omega/p)}{dt} &= \frac{1}{J}(M - M_L) \\
\frac{d\Psi_{s\alpha}}{dt} &= -R_s i_{s\alpha} + u_{s\alpha} \\
\frac{d\Psi_{s\beta}}{dt} &= -R_s i_{s\beta} + u_{s\beta} \\
\frac{di_{s\alpha}}{dt} &= \frac{1}{\sigma}\Big(\frac{R_r}{L_s L_r}\Psi_{s\alpha} + \frac{p}{L_s}\omega\Psi_{s\beta}\Big) - p\omega i_{s\beta} - \frac{\gamma}{L_s} i_{s\alpha} + \frac{1}{L_s} u_{s\alpha} \\
\frac{di_{s\beta}}{dt} &= \frac{1}{\sigma}\Big(\frac{R_r}{L_s L_r}\Psi_{s\beta} - \frac{p}{L_s}\omega\Psi_{s\alpha}\Big) + p\omega i_{s\alpha} - \frac{\gamma}{L_s} i_{s\beta} + \frac{1}{L_s} u_{s\beta},
\end{aligned} \tag{3}$$

where ω is the electrical angular velocity; J the inertia and M the electromagnetic torque

$$M = 3p(\Psi_{s\alpha} i_{s\beta} - \Psi_{s\beta} i_{s\alpha})/2\,, \tag{4}$$

M_L is the load torque; $\Psi_s^T = (\Psi_{s\alpha}, \Psi_{s\beta})$ the stator-flux space vector, $i_s^T = (i_{s\alpha}, i_{s\beta})$ the stator-current space vector and $u_s^T = (u_{s\alpha}, u_{s\beta})$ the stator-voltage space vector; R and L denote resistance and self inductance, subscripts s and r stand for stator and rotor; p is the pole number; $\sigma = 1 - L_m^2 / L_s L_r$ the leakage factor with L_m being the mutual inductance; $\gamma = (L_s R_r)/L_r - R_s$.

3.2. 3LVSI model

The 3LVSI model (Fig. 1 (Nabae et al.) has three input rails: the positive (L+) one, the negative (L-) one of the dc link and the middle potential (M) between positive and negative potential (neutral point). The output terminals *a, b, c* can be connected to each of them by semiconductor switches (S1, S2, S3).

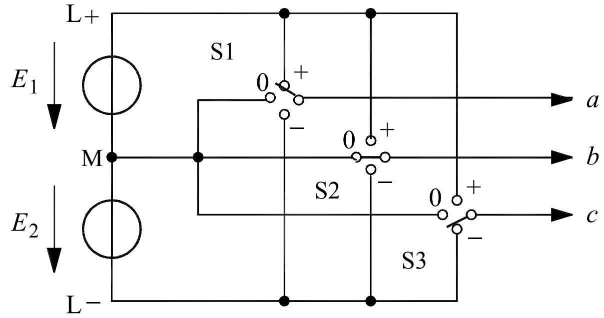

Fig. 1. Canonical schema of neutral-point-clamped 3LVSI

The switch has three positions: "+"means the connection with the positive rail, "–"with the negative one and "0" with the neutral point M. In this case there are 27 possible switching combinations. Assuming that the middle potential is balanced ($E1 = E2 = U_d/2$), they make up 19 different output-voltage space vectors with four different magnitudes parts of them multiply redundant. Fig. 2 gives an overview.

There are six full-voltage space vectors (A) with magnitude $B_A = 2U_d/3$; six intermediate-voltage space vectors (Z) with magnitude $B_Z = \sqrt{3}U_d/3$; six half-voltage space vectors with magnitude $B_H = U_d/3$, attained each by two switch combinations (control redundancy), and the zero-voltage vector (N), with three possible switch combinations. The positions of the switches [S1, S2, S3] producing the space vectors are entered in Fig. 2 near the vectors.

4. SLIDING-MODE CONTROL DESIGN

The main goal of each drive control is the equality of the average value of the mechanical output variable (for example rotor speed or position) and the set value (which has subscript z in the equations), in a suited interval. But this task is reduced in a more obvious or a more implicit kind to the task of maintaining the target torque M at the motor shaft. As the number of the independent controls (in our case the components of the space vector of the stator voltages) is equal to the order of the control space and higher as one, it is possible to control two variables: not only one mechanical one, but another variable which describes electrical or power requirements of the IM. Usually the stator-flux modulus

$$\left|\Psi_s\right| = \sqrt{\Psi_{s\alpha}^2 + \Psi_{s\beta}^2} \tag{5}$$

is chosen. So, for control design the error function F must be formed, the dimension of which is equal to the control dimension and the components represent the functions of the control error, which must be led to zero:

$$F = \begin{vmatrix} F_\Psi \\ F_M \end{vmatrix} = \begin{vmatrix} \left|\Psi_{sz}\right| - \left|\Psi_s\right| \\ M_z - M \end{vmatrix}. \tag{6}$$

The main problem using sliding-mode technique for this control task is that all “classic” results have been received for the case that the number of discontinuous controls is equal to the control order. In the electrical system here, the situation is different: the number of discontinuous controls is bigger than the control order. But they have constant directions that cannot be changed; it is only possible to change the control magnitude. In our case only the above-mentioned 19 different output-voltage space vectors can be used for solving the control task. The main problem of control design is the synthesis of the switching law that produces the sliding-mode motion on the manifold (1), (6).

In this case a two-step design technique (Ryvkin) is fruitful. It allows solving the control design task for the 3LVSI that has 19 different output-voltage space vectors, in a two-dimensional control space. The main idea of this technique is the decomposition of the control task, taking separately into account the nonlinearities of IM and 3LVSI. At the first step only the two-phase equivalent model of the IM has been used. In this case the number of discontinuous controls is equal to the order of the voltage plane, the sliding-mode control can be designed by using the standard technique. As design results the magnitudes of the needed stator-voltage components and the switching law are obtained.

At 2nd step the real discontinuous output voltage of 3LVSI has to be taken into account, and the realization task of the above-mentioned sliding mode has to be solved with them.

4.1 First step

The control aim is to design such a control law that the state reaches the sliding manifold (1), (6), which is the same as the error function being zero, in finite time from the bounded initial conditions, and then remain on it. In this case the control task has been fulfilled. For solving the equation of the error function variation is used:

$$\frac{d}{dt}\begin{vmatrix} F_\Psi \\ F_M \end{vmatrix} = \begin{vmatrix} \dfrac{d\left|\Psi_{sz}\right|}{dt} + \dfrac{R_s(\Psi_{s\alpha} i_{s\alpha} + \Psi_{s\beta} i_{s\beta})}{\left|\Psi_s\right|} \\ \dfrac{dM_z}{dt} + \dfrac{1}{\sigma}\left(\dfrac{\gamma}{L_s} + \dfrac{p}{L_s}\omega\Psi_s^2\right) - p\omega(\Psi_{s\alpha} i_{s\alpha} + \Psi_{s\beta} i_{s\beta}) \end{vmatrix} - \begin{vmatrix} 1 & 0 \\ \dfrac{M}{\left|\Psi_s\right|} & \dfrac{1}{\sigma}\dfrac{\left|\Psi_s\right|}{L_s} + \dfrac{(\Psi_{s\alpha} i_{s\alpha} + \Psi_{s\beta} i_{s\beta})}{\left|\Psi_s\right|} \end{vmatrix} \times \begin{vmatrix} u_\Psi \\ u_M \end{vmatrix}, \tag{7}$$

where $U_F^T = (u_\Psi, u_M)$ is the control vector that is connected to the phase voltages using the transformation

$$\begin{vmatrix} u_a \\ u_b \\ u_c \end{vmatrix} = \begin{vmatrix} \cos\rho & -\sin\rho \\ \cos(\rho - 2\pi/3) & -\sin(\rho - 2\pi/3) \\ \cos(\rho + 2\pi/3) & -\sin(\rho + 2\pi/3) \end{vmatrix} \times \begin{vmatrix} u_\psi \\ u_M \end{vmatrix}, \tag{8}$$

where $\rho = \arctan(\psi_{s\beta}/\psi_{s\alpha})$, the stator-flux angle.

Recalling that for a well-designed IM σ is typically small (some 5%), the sliding motion on the manifold (1), (6) can be designed using the sliding-mode control technique for the singularly-perturbed systems (Heck), by which controllers are designed for slow and fast subsystems. Due to the discontinuous nature of the slow controller, the time-scale separation argument does not hold during switching. Therefore, additional technical conditions have to be satisfied to guarantee stability. In this case the problem of sliding domain is reduced to a sequential analysis of two scalar cases. The scalar sliding-mode condition is

$$\lim_{F\to+0}(dF/dt) < 0 \ \& \ \lim_{F\to-0}(dF/dt) > 0. \tag{9}$$

The control vector components u_Ψ and u_M are selected depending upon the sign of the components of the error function F:

$$u_\Psi = U_\Psi \operatorname{sgn} F_\Psi, \tag{10}$$

$$u_M = U_M \operatorname{sgn} F_M. \tag{11}$$

Their magnitudes U_Ψ and U_M can be selected using the following inequalities

$$U_\Psi \ge U_{\Psi eq} = \left|\frac{d\left|\Psi_{sz}\right|}{dt} + \frac{R_s(\Psi_{s\alpha} i_{s\alpha} + \Psi_{s\beta} i_{s\beta})}{\left|\Psi_s\right|}\right|, \tag{12}$$

$$U_M \geq U_{Meq} = \left| \frac{dM_z}{dt} - \frac{M}{\left|\Psi_{sz}\right|} \times \frac{d\left|\Psi_{sz}\right|}{dt} + \frac{1}{\sigma}\left(\frac{\gamma}{L_s} + \frac{p}{L_s}\omega\Psi_s^2\right) - \left(p\omega + \frac{R_s M}{\Psi_{sz}^2}\right)\left(\Psi_{sa} i_{sa} + \Psi_{sb} i_{sb}\right) \right| \quad (13)$$

The magnitudes U_Ψ and U_M bound the initial condition, from which the state will reach the sliding manifold in finite time, and the uncertainty of the system and the load value to which the system is robust in general.

4.2. Second step

But in reality there are only 19 different output voltage space vectors with four different magnitudes, produced by discontinuous control (switching) of the 3LVSI. The question is whether it is possible to attain the above designed sliding motion with these output vectors. Of course it is possible to use the inverse transformation of (8) to generate three-phase voltage references and use feed-forward PWM. The sine-wave voltages would be the mean values per switching period of the output voltages of the semiconductor 3LVSI with high-frequency switches. But for the calculation of PWM information as the average value of the output-voltage space vector U_{eq} during any time period would be needed, the switching time for each switch and the sequence of their switching. Such an approach requires additional calculations and does not reach any of the basic properties of sliding mode, namely simplicity of realization.

The alternative approach to design of 3LVSI output voltages control, i.e. transferring the two-dimensional control (10) – (13) to the 3LVSI control, is based on the fact, that the selection conditions of the amplitudes of the formally entered controls in the reference frame rotating with stator-flux uses the inequalities (12) and (13). In this case there is the area of allowable controls U^* in the space of the formally entered controls u_Ψ, u_M. It is obvious, if we design the real discontinuous voltages thus that their projections on suitable axes of the stator-flux-fixed frame have their marks and sizes, which are needed by the control algorithm with the formally entered controls, the sliding mode on crossing before the chosen surfaces will take place. Of course, the sizes of the formally entered controls will change during work. Using the rule of contraries and the inverse to (8) transformation could prove this claim very easily.

Inequalities (12), (13) and control (10), (11) determine in the control space rotating with stator-flux four control areas $U_1^*, U_2^*, U_3^*, U_4^*$ that guarantee sliding motion (Tab. 1):

$U^* = \left\{U^*\right\} = U_1^* \cup U_2^* \cup U_3^* \cup U_4^*$, $U_1^* \cap U_2^* = 0$,
$U_1^* \cap U_3^* = 0$, $U_1^* \cap U_4^* = 0$, $U_2^* \cap U_3^* = 0$, $U_2^* \cap U_4^* = 0$,
$U_3^* \cap U_4^* = 0$.

These four control areas $U_1^*, U_2^*, U_3^*, U_4^*$ can be transformed to the three-phase stator-winding-fixed frame (*a, b, c*) by using (8). In this frame they have the same form, but move with the stator-flux angular velocity (Fig. 2).

Tab. 1. Sliding-mode control areas

	U_1^*	U_2^*	U_3^*	U_4^*
$\operatorname{sgn} F_\Psi$	1	1	−1	−1
$\operatorname{sgn} F_M$	1	−1	1	−1

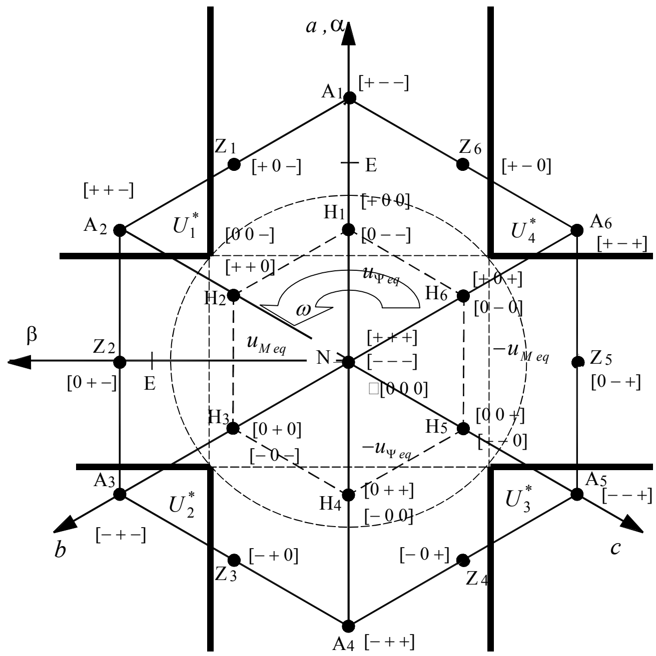

Fig. 2. SMC areas and voltage space vectors of 3LVSI

The sliding-mode behavior, which has been synthesized in the stator-flux-fixed frame, will be secured by using the discontinuous voltages of the 3LVSI, if each control area has at any time at minimum one of the 3LVSI output voltage space vectors. This condition is fulfilled by the calculation of the 3LVSI input dc voltage, the design of the transition law between the designed controls (10), (11) and the switching control of 3LVSI switches. Both are made upon the following assumptions that have been used for the simplification of the control design:

- The selected magnitudes U_Ψ and U_M are equal: $U_\Psi = U_M = U$.
- The used 3LVSI output-voltage space vectors are full ones and intermediate ones.
- The value of the 3LVSI dc-link voltage has been calculated, using the magnitude of the intermediate-voltage space vectors. In this case this voltage is: $B_A - B_Z = (2-\sqrt{3})U_d/3$.

By the above assumptions the selection condition of the minimal possible 3LVSI input dc-voltage value is, for geometrical reasons:

$$\arcsin\left(U/B_z\right) \leq \pi/6, \quad (14)$$

and the 3LVSI dc-link voltage value can be calculated as

$$U_d \geq 2\sqrt{3} \cdot U. \quad (15)$$

The transfer strategy from the controls $\operatorname{sgn} F_M$ and $\operatorname{sgn} F_\Psi$ to control S_a, S_b, S_c of the switches S1, S2 and S3 is presented in the Tables 2 and 3. There are 12 stator-flux-angle zones ρ where switch control is equal to one of the controls $\operatorname{sgn} F_M$ and $\operatorname{sgn} F_\Psi$ or their opposite values.

Table 2. Switch controls

ρ	S_a	S_b	S_c
(0...π/6)	sgn F_Ψ	sgn F_T	C
(π/6...π/3)	D	sgn F_M	– sgn F_Ψ
(π/3...π/2)	– sgn F_T	A	– sgn F_Ψ
(π/2...2π/3)	– sgn F_T	sgn F_Ψ	B
(2π/3...5π/6)	C	sgn F_Ψ	sgn F_T
(5π/6... π)	– sgn F_Ψ	D	sgn F_T
(π...7π/6)	– sgn F_Ψ	– sgn F_T	A
(7π/6...4π/3)	B	– sgn F_T	sgn F_Ψ
(4π/3...3π/2)	sgn F_T	C	sgn F_Ψ
(3π/3...5π/3)	sgn F_T	– sgn F_Ψ	D
(5π/3...11π/6)	A	– sgn F_Ψ	– sgn F_T
(11π/6...2π)	sgn F_Ψ	B	– sgn F_T

Table 3.

sgn F_Ψ	1	1	–1	–1
sgn F_T	1	–1	1	–1
A	1	0	0	–1
B	0	–1	1	0
C	–1	0	0	1
D	0	1	–1	0

This 3LVSI dc-link voltage value and control table guarantees that the system will – from initial condition selected in (12) and (13) – reach the sliding manifold (1), (6) in finite time, remain on it and will be robust against the load value, the selected uncertainty of the system parameters that have been selected on the first step of design by inequalities (12), (13).

It must be mentioned, that the IM drive is robust against the uncertainty of the 3LVSI dc-link voltage and the estimation of the stator-flux angle position, too. If condition (15) is satisfied, the sliding motion is guaranteed. But the dc voltage needs not to be constant; it may change and is bounded only to its lowest value. In this case the value of the dc-link capacitor and thus its size can be small.

The same remark can be made to the definition of the angle sectors table. If the dc-link voltage value is higher than the minimum value given by (15), the request upon the measuring angle sector table is lower.

As design result the SMC algorithms (6), (12), (13), (15) and Tables 2, 3 are obtained, that guarantee zero torque- and flux-modulus errors by variation of drive parameters, load and inverter dc-link voltage.

5. SIMULATION

To exemplify the behavior of the IM drive with sliding-mode controller, simulations were performed for IM and 3LVSI. The underlying IM characteristics are shown in Table 4.

Table 4. Characteristics of IM for Simulation

Parameter	Symbol	Value
Rated power (kW)		90
Rated voltage (V)		330
Rated current (A)		180
Rated speed (rad/s)		104
Rated torque (Nm)	M_n	580
Rated flux linkage (Wb)	Ψ	1.3
Stator resistance (mΩ)	R_s	25.9
Rotor resistance (mΩ)	R_r	18
Mutual inductance (mH)	L_μ	27.6
Leakage inductance (mH)	L_σ	1.3
Number of pole pairs	p	2

The dc-link voltage is U_d = 422 V, the control cycle time 200 µs and the average switching frequency 500 Hz. The 3LVSI state was determined by the sliding-mode controller that uses as input signals the error signs (10), (11) and information about the stator-flux position and produces the output signals, using the tables 2 and 3.

In a first step, the design of the sliding-mode controller uses only the full and intermediate voltage space-vectors. The flux and torque hysteresis bands were set to 7% and 3.5% of the rated value respectively. Speed was held constant at 104 rad/s, torque was set up to 30% of the break down torque, i.e. it is equal to the rated value. At t = 0 s, flux is commanded to its rated value, and at t = 0.03 s, torque is commanded to its rated value.

The simulation was carried out in the real physical variables, but they are presented in per unit (p.u.) system. Torque is normalized to break-down torque, time unit (horizontal scale) is s.

Fig. 3 shows the alpha/beta components of the stator-flux space vector and the torque. The torque at a speed of ~1000 rpm (104 rad/s) it is slightly erratic and has a ripple of 7.5% of rated torque. The torque behaviour is, as expected, similar to Direct Self Control.

The stator-flux and stator current hodographs and the voltage space-vectors can be seen in Fig. 4. The flux behaviour is due to the set hysteresis band. 18 switchings are used for torque control and 72 switchings to keep stator flux within the given hysteresis, so that there is a resultant pulse frequency of ~3000 Hz, which corresponds to a valve switching frequency of ~500 Hz in the 3LVSI.

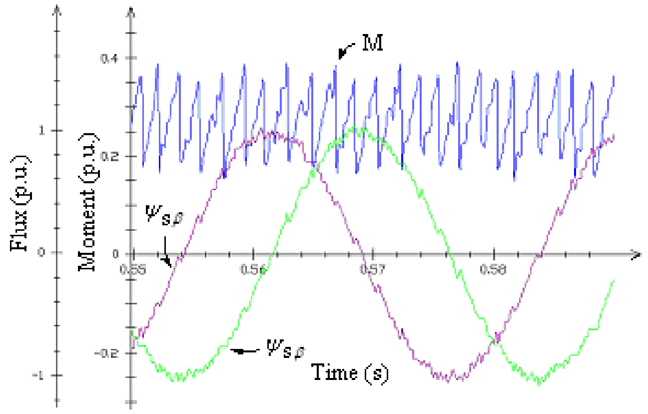

Fig. 3. Torque and alpha/beta components of the stator flux

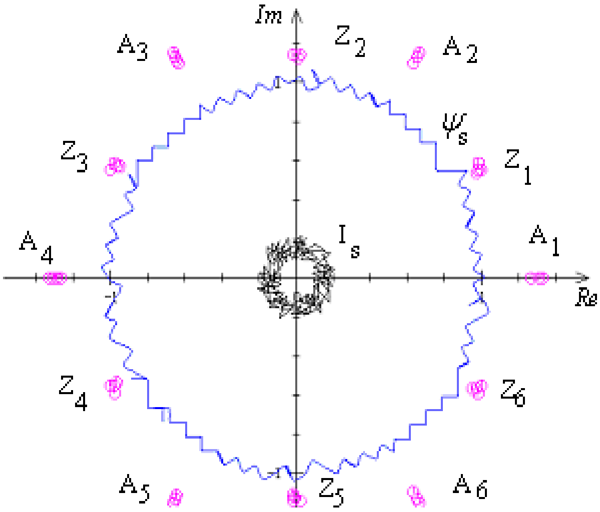

Fig. 4. Stator-flux, stator-current and voltage space-vectors

6. CONCLUSION

The application of the sliding-mode technique to the control design of an IM drive supplied by 3LVSIs with high-voltage power semiconductor switches is presented. The effective use of such a switched system as 3LVSI is discussed. The proposed new design technique allows solving the problem of redundancy of the discontinuous control. Using a two-step technique decomposes the control design task. The hierarchic procedure is described separately that allows using the nonlinearity of the IM and the switching character of the 3LVSI. In this case the control design is simpler and more graphical. The drive control that has been designed by using sliding-mode technique would be able to guarantee all advantageous characteristics of the control plant with such type of control as high dynamic, low sensitivity to disturbance of both the load and the input dc-link voltage and to plant parameter variations.

The next improvement of the torque control performance is to use the intermediate-voltage and zero-voltage space vectors by proper design of the controller, e.g. for the lower speed range. Such a solution will improve the control quality, but needs the development of the new design technique and the receiving the additional information about the position of the equivalent control.

ACKNOWLEDGEMENT

The kind sponsorship of the German Academic Exchange Service, Bonn, of the research visit of Prof. Sergey Ryvkin at the Institute for Electrical Power Engineering and Power Electronics of Ruhr-University Bochum is gratefully acknowledged

REFERENCES

Blaschke, F. (1972). The principle of field orientation as applied to the new Transvektor closed-loop control system for rotating-field machines. *Siemens Review*, **39**, pp. 217–220.

Baida, S.V. and Izosimov D.B. (1985). Vector method of design of sliding mode and simplex algorithms. *Automation and Remote Control,* **46**, pp. 830-837.

Buja, G. S. and. Kazmierkowski, M.P. (2004). Direct torque control of PWM inverter-fed AC motor – a survey. *IEEE Transactions on Industrial Electronics,* **51**, pp. 744–757.

Depenbrock, M. (1988). Direct self-control (DSC) of inverter-fed induction machine. *IEEE Transactions on Power Electronics*, **4**, 1988, pp. 420–429.

Depenbrock, M. and Steimel, A. (2004). Speed-sensorless stator-flux-oriented control of induction motor drives in traction. *Proceedings of German-Korean Symposium on Power Electronics and Electrical Drive.*

Heck, B. S. (1991). Sliding mode control for singularly perturbed systems. *International Journal of Control,* **53**, pp. 985–1001.

Krafft, E., Steimel, A. and Steinke, J. K. (1999). Three-level high-power inverters with IGCT and IGBT elements compared on the basis of measurements of the device loses. *Proceedings of the 8th European Conference on Power Electronics*.

Leonhard, W. (2001). *Control of electrical drive*, 3rd ed., Springer-Verlag, Berlin.

Nabae, A., Takahashi, I. and Akagi, H. (1981) A new neutral-point-clamped PWM inverter. *IEEE Transactions on Industrial Applications*, **17**, pp. 518–523.

Ryvkin, S. (2002). Sliding mode technique for AC drive. *Proceeding of the 10th International Power Electronics & Motion Control Conference, EPE – PEMC.*

Tiitinen, P., P. Pohjalainen and Lalu, J. (1995). The next generation motor control method: Direct torque control (DTC). *EPE Journal*, **5**, pp. 14–18.

Utkin, V.I., Güldner, J. and Shi, J. (1999). *Sliding mode control in electromechanical system.* Taylor & Francis, London, Philadelphia.

Vittek, J., Stulrajter, M., Makys, P., Skalka, I. and Mienkina, M. (2006). Microprocessor implementation of forced dynamics control of permanent magnet synchronous motor drives. *Proceedings of International Conference on Optimization of Electrical and Electronic Equipment, OPTIM 2006*, **III**, pp. 3-8.