The paper presents the sliding-mode observer-based sensorless control of an AC adjustable speed drive with induction motor, voltage-source inverter (DC/AC converter) and reversible AC/DC line-side converter. The sensorless control is applied to both the AC/DC and DC/AC converter confining the number of the used transducers and eliminating the rotor speed direct acquisition. The virtual grid flux vector estimated in the sliding-mode observer yields robustness against the line voltage distortions. The observer of rotor flux and speed of induction motor provides the insensitiveness to certain extent of the fluctuations of the motor parameters. The proposed sensorless control of the double-sided converter provides four-quadrant operation of the induction motor drive at the acceptable computational effort and thus at inexpensive costs of its hardware realization.

1. INTRODUCTION

The modern frequency converters are often equipped with the AC/DC line-side converter in the form of PWM rectifiers, that interfaces the grid with the inverter-fed induction motor. The PWM rectifiers usually have the same topology as the voltage-source inverters. Hence their control techniques can be based on known methods of vector control elaborated for the induction motors [3, 4, 6].

The paper presents the description of the AC/DC/AC control system for the four-quadrant operation of induction motor with the minimized number of sensors. In this system the rotor flux and speed of induction motor, as well as the virtual grid flux are estimated using the sliding-mode observers.

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2. VECTOR CONTROL OF GRID AND MOTOR CONVERTER

The basic control principles of grid and induction motor converter with field-orientation approach is presented on Fig. 1. The field-oriented control of induction motor with frequency converter is based on the decomposition of the stator current vector \( i_s \) into two rectangular components \( i_{sd} \) and \( i_{sq} \) in the rectangular coordinates frame d-q oriented with the rotating rotor flux vector \( \psi_r \) (Fig.1a). The amplitude of the rotor flux vector \( \psi_r \) is proportional to the \( i_{sd} \) component while the motor torque is controlled by the \( i_{sq} \) component of the stator current \( i_s \).

The application of the vector control to the grid converter is based on the assumption that the supply line can be considered as a virtual induction machine. The issue of the virtual grid flux-oriented control for the AC/DC line-side converter is based on the decomposition of the grid current vector \( i_g \) into two rectangular components \( i_{gd} \) and \( i_{gq} \) in the d-q coordinates frame oriented with the rotating virtual grid flux vector \( \psi_g \) (Fig.1b). The grid current vector component \( i_{gq} \) is proportional to the active power while the component \( i_{gd} \) is proportional to the reactive power. Thus the active power and reactive power can be controlled independently. The unity power factor condition is met when the grid current vector \( i_g \) is situated perpendicular to the grid virtual flux vector \( \psi_g \).

![Fig. 1. Decomposition of current vector in field-oriented control: a) for stator current vector \( i_s \) of induction motor and rotor flux vector \( \psi_r \), b) for grid current vector \( i_g \) and virtual grid flux vector \( \psi_g \)](image)

The development trends in industrial electrical drives indicate the tendency of an application of sensorless control. The sensorless control in adjustable speed drives has evolved from the simple solutions based on the state simulators (estimators) up to the advanced state observers using numerous different approaches. The state observers are the adjustable reference system models tuned by the feedback signals coming from the controlled plant, so that the output estimates follow their real counterparts.
The existence of the feedback standard signal provides better robustness of the observer against the inaccuracies of the system parameter identification.

The paper presents a sliding-mode approach to design the robust control system of the induction motor converter and the grid converter. In order to estimate the rotor flux vector and rotor speed the sliding-mode observers will be designed. The sliding-mode methodology will also be used to design the virtual grid flux vector for the AC/DC line-side converter.

3. SLIDING-MODE-BASED DESIGN OF ASYMPTOTIC OBSERVERS

3.1. SLIDING-MODE ROTOR FLUX VECTOR AND ROTOR SPEED OBSERVER

The sliding-mode rotor flux vector and rotor speed observer (1) is strictly based on the model of the induction motor described in ($\alpha$-$\beta$) coordinate frame [1, 2, 3, 5, 7]:

\[
\begin{align*}
\frac{di_{\alpha}}{dt} &= \beta \eta \psi_{ra} + \beta \dot{\omega} \psi_{r\beta} - \dot{\psi}_{s\alpha} + \frac{1}{\sigma L_s} u_{s\alpha} \\
\frac{di_{\beta}}{dt} &= \beta \eta \psi_{r\beta} - \beta \dot{\omega} \psi_{ra} - \dot{\psi}_{s\beta} + \frac{1}{\sigma L_s} u_{s\beta} \\
\frac{d\psi_{ra}}{dt} &= -\eta \dot{\psi}_{s\alpha} - \dot{\omega} \psi_{r\beta} + \eta L_{m} i_{sa} \\
\frac{d\psi_{r\beta}}{dt} &= -\eta \dot{\psi}_{s\beta} + \dot{\omega} \psi_{ra} + \eta L_{m} i_{sb} \\
\eta &= \frac{R_s}{L_s}, \quad \rho = 1 - \frac{L_m^2}{L_s L_r}, \quad \beta = \frac{L_m}{\sigma L_s L_r}, \quad \gamma = \frac{1}{\sigma L_m} \left( R_r + \frac{L_m^2}{L_r} R_s \right).
\end{align*}
\]

where $R_s, L_s$ – stator resistance and inductance; $R_r, L_r$ – rotor resistance and inductance; $L_m$ – magnetizing inductance; $u_{s\alpha}, u_{s\beta}$ – stator voltages in ($\alpha$-$\beta$) coordinates frame; $i_{sa}, i_{sb}$ – the estimated components of stator currents and $\psi_{ra}, \psi_{r\beta}$ – the estimated components of rotor flux in ($\alpha$-$\beta$) coordinates frame in sliding-mode.

The estimate of the electrical rotor speed $\dot{\omega}_e$ will be replaced by the high-gain discontinuous term to realize the sliding motion (2):

\[
\dot{\omega}_e = \omega_0 \text{sign}(s_n)
\]
where \( \omega_0 \) is a positive control gain. The switching surface \( s_n \) is designed so that the estimates in (1) converge to their real counterparts in the sliding-mode (3):

\[
s_n = (i_{\beta} - i_{\beta})\dot{\psi}_{\alpha} - (i_{\alpha} - i_{\alpha})\dot{\psi}_{\beta} = 0
\]

When \( \omega_0 \) is appropriately selected, the sliding-mode is reached when \( s_n = 0 \). Since the estimated electrical rotor speed is a discontinuous signal it should be low-pass filtered and divided by the number of pole pairs in order to achieve an equivalent continuous signal of the expected rotor speed [7].

### 3.2. SLIDING-MODE VIRTUAL GRID FLUX OBSERVER

The starting-point of the design procedure of the sliding-mode virtual grid flux observer [3,7] is based on the three-phase model of the AC/DC line-side converter (4):

\[
\frac{d\hat{i}_{gA}}{dt} = -\frac{R_g}{L_g} \hat{i}_{gA} - \frac{u_{dc}}{3} (2K_{1a} - K_{1b} - K_{1c}) + \frac{1}{L_g} \hat{e}_{gA}
\]

where \( \hat{i}_{gA}, \hat{e}_{gA} \) are the estimated grid current and grid source voltage in phase A respectively. The estimate of the phase grid source voltage \( \hat{e}_{gA} \) will be replaced with the high-gain switching term (5):

\[
\hat{e}_{gA} = e_{g0} sign(s_g)
\]

where \( e_{g0} \) is a positive control gain. The switching line \( s_g \) is selected so that the estimates in (4) converge to their real values in the sliding-mode (6):

\[
s_g = i_{gA} - \hat{i}_{gA} = 0
\]

By \( e_{g0} \) large enough the condition \( s_g = 0 \) is fulfilled and sliding-mode is reached. In order to achieve the virtual grid flux, the discontinuous term (5) should be directly integrated without the previous low-pass filtering (7):

\[
\dot{\psi}_{gA} = e_{g0} \int sign(\hat{i}_{gA} - \hat{i}_{gA})
\]

The flux estimates for phases B and C may be achieved in similar manner [7].
The developed control structure of AC/DC/AC converter-fed induction motor based on sliding-mode observers is presented in Fig.2.

The presented sensorless current control of AC/DC/AC converter-fed induction motor based on sliding-mode observers has been validated through the numerous simulations. The selected simulation results presented in the separate paper [4] have proven the good flexibility of the considered control system.

5. CONCLUSIONS

The paper presented the sliding-mode control in approach to design of the robust asymptotic observers in sensorless control system of the AC/DC/AC converter-fed induction motor. The purpose was the minimization of the number of the voltage and current sensors and the elimination of the rotor speed transducer in order to reduce the
hardware equipment. The presented sensorless current control of AC/DC/AC converter-fed induction motor based on sliding-mode observers has the good flexibility and provides the robustness against the changes of system parameters.

REFERENCES


STEROWANIE BEZCZUJNIKOWE SILNIKIEM INDUKCYJNYM Z PRZEKSZTAŁNIKIEM AC/DC/AC Z ZASTOSOWANIEM OBSERWATORÓW ŚLIZGOWYCH

W artykule przedstawiono bezczujnikowy układ sterowania częstotliwościowego silnika indukcyjnego klatkowego z przekształtnikiem dwustronnym AC/DC/AC. Opisano zasady sterowania wektorowym silnikiem indukcyjnym i przekształtnikiem sieciowym. Do sterowania wektorowym przekształtnikiem sieciowym wykorzystano wirtualny wektor strumienia sieci oparty na analogii obwodów sieci zasilającej i silnika indukcyjnego. Zasada bezczujnikowego sterowania została oparta na zastosowaniu obserwatorów ślizgowych. Wprowadzono estymację zmiennych stanu po stronie przekształtnika sieciowego i przekształtnika silnikowego w celu zminimalizowania liczby niezbędnych czujników pomiarowych oraz wyeliminowania przetwornika prędkości kątowej wału. Przedstawiono opis matematyczny ślizgowego obserwatora wirtualnego wektoru strumienia sieci oraz ślizgowego obserwatora strumienia wirnika i prędkości kątowej silnika indukcyjnego.