Robust Online Stator Resistance Estimation of High-Speed Vector Controlled Induction Motor

Darko Marčetić, Marko Gecić Faculty of Technical Sciences University of Novi Sad Novi Sad, Serbia darmar@uns.ac.rs; gecicm@uns.ac.rs

Abstract— A technique for stator-resistance-based thermal monitoring suitable for low-cost vector controlled three phase induction motor (IM) drive is suggested in this paper. Estimated stator resistance can be used for motor thermal protection, or for compensation of parameter variations in control algorithm. The technique is specifically selected to provide robust temperature estimation while rotor is in high speed range. The suggested method is based on periodical injection of relatively small dc voltage offset, which results in technique that is noninvasive but accurate and does not depend on the rest of motor parameters or working conditions. The method is implemented in fixed point microprocessor and tested under various operations conditions. The achieved estimation results at high speeds are superior compared with any model based stator resistance techniques.

Keyword: induction motor, stator resistance, parameter estimation

I. INTRODUCTION

A technique for stator-resistance-based thermal monitoring suitable for high speed vector controlled drive is suggested in this paper. Most of induction motor (IM) shaft-sensorless control strategies are model based and for robust operation at low speeds require accurate knowledge of IM stator resistance (R_s) . That is why most of the online stator resistance estimation techniques are specifically designed and tested for low speed operations and address specific problems such are voltage error and open loop integration. However, at the same time the advantage of low speed operation for R_s estimation is relatively large voltage drop across the stator resistance that is comparable with back electromotive force (bemf). That is why IM model at low speeds is highly sensitive to the change in stator resistance and one can find different motor outputs and states that hold enough information about actual R_s change.

The situation is quite different at medium and high speeds, on which stator voltage drop at R_s is practically neglectable and masked by rotor bemf. That is also the reason why most of shaft-sensorless algorithms at high speeds do not require accurate knowledge of R_s for robust operation. However, high speed R_s estimation can still be attractive for losses optimization and for stator-resistance-based thermal monitoring and protection.

There are two important groups of online R_s estimation techniques: model based and test signal based techniques. Model based online R_s estimation techniques are usually Petar Matić Faculty of Electrical Engineering University of Banja Luka Banja Luka, Republic of Srpska petar.matic@etfbl.net

suggested as an upgrade of the shaft-sensorless IM drive control system which improves flux and speed estimation, especially at low speeds. Most of model based online R_s estimation methods are using MRAS (Model Reference Adaptive System) approach having two models estimating same IM state or output. One of two models is used as reference, and has output which is not sensitive to R_s parameter error. Output of the second model is sensitive to R_s error and MRAS feedback adapts R_s parameter until two outputs match. Different IM states or outputs are suggested in the literature for MRAS R_s estimation, such are active power [1], X-power [2] or rotor flux amplitude [3].

But, all the model based solutions suffer from sensitivity to an error in other IM parameter, and also to an error in voltage and speed estimates used in MRAS models. Additionally, as rotor speed increases the voltage drop at R_s becomes almost neglectable compared with rotor bemf and model information about the R_s value diminishes. As a result, the sensitivity of model based R_s estimation techniques to other model errors increases. Consequently, at high speeds model based R_s estimation solutions are not robust and therefore not acceptable, especially for R_s based thermal protection. That is especially the case for low cost shaft-sensorless IM drive with large excursions of other IM parameters and significant errors in both voltage and speed estimates.

The dc-signal-injection based techniques make second important group of online R_s estimation techniques. Advantage of those techniques is robustness to variation of other IM model parameters because dc signal does not pass the air gap and machine reaction can be easily separated from its reaction to ac signals. However, the drawback is that dc-signal-injection based methods produce unwanted torque pulsations and audible noise. Another drawback is that the dc voltage injection methods are applicable only for voltage fed IM, directly line connected [4] or scalar driven with voltage source inverter (VSI) [5]. Suggested dc injection techniques cannot be directly implemented in vector controlled IM with current regulated VSI (CRVSI) due to closed current loop which tends to cancel the injected dc test signal.

This paper proposes a robust estimation of IM R_s suitable to be implemented in shaft-sensorless vector controlled CRVSI fed IM drive with high rotor speed and different levels of loads. The suggested method is based on periodical injection of small dc voltage offset, which results in technique that is noninvasive but accurate and does not depend on rest of motor parameters or working conditions. The method is based on dc-injection method for scalar controlled drive but adapted to field oriented control (FOC) vector drive with closed current loop. The method is implemented in fixed point microprocessor and tested under various operations conditions. The method is also compared with selected model based R_s estimation techniques and has shown superior results.

II. BASICS OF DC SIGNAL BASED RS ESTIMATION IN VOLTAGE FED IM DRIVES

The dc-signal-injection based techniques for online R_s estimation is easy to implement in voltage fed scalar controlled IM drives [4]–[5]. One possible implementation is to use space vector module (SVPWM) with two voltage vector components in stationary reference frame as inputs, Fig.1.



Figure 1. Voltage source inverter with external dc signal injection in stationary reference frame

$$v_{\alpha s} = |V| \cos(\omega_{dq} t) + V_{DC}^{OFFSET} , \qquad (1)$$

$$v_{\beta s} = |V| \sin(\omega_{dq} t) , \qquad (2)$$

where |V| is amplitude and ω_{dq} frequency of ac voltage. With voltage vector coordinates in stator stationary reference frame defined with (1) – (2) one gets following IM phase voltages:

$$v_{as}^{DC} = V_{DC}^{OFFSET}, v_{bs}^{DC} = -\frac{1}{2} V_{DC}^{OFFSET}, v_{cs}^{DC} = -\frac{1}{2} V_{DC}^{OFFSET}$$
(3)

Selected stator dc voltages will inject dc current in all three stator windings, providing dc current offset to be only in the α axis, while β current will be unaffected.

In order to provide mean value of stator current (dc component), during the time period of the dc voltage injection phase A current $i_{as}(t)$ is measured and summed. If the current summation is done for exact number of ac periods, which could be determinate by β voltage zero crossing detection, the filtering of current ac component is not needed. In that case only dc current component remains and R_s can be calculated as:

$$R_s^{est} = \frac{V_{DC}^{OFFSET}}{\sum_k^N I_{as}(k)} , \qquad (4)$$

III. IMPLEMENTATION CONSIDIRATIONS FOR DC SIGNAL BASED RS ESTIMATION METHOD IN FOC IM DRIVES

This chapter describes the implementation of the dc-signalinjection based techniques for online R_s estimation in FOC IM drive with inner current vector control loop. In FOC drive current vector is usually regulated by CRVSI using two independent current loops operating in synchronous rotating dqreference frame. Each loop controls one dq coordinate of current vector by regulating corresponding dq coordinate of voltage vector. The major drawback of this scheme, regarding dc signal injection based R_s estimation, is that while controlling current vector reference the inner current loops also tend to cancel the injected dc signal since this offset is seen as disturbance to the control loops.



Figure 2. Current control loops in dq reference frame with extra dc signal injection in α stationary voltage component

The problem is that injected dc voltage component in stationary reference frame becomes unwanted sinusoidal voltage component in both *dq* reference frame axis:

$$v_{ds} = v_{ds}^* + V_{DC}^{OFFSET} \cos(\omega_{dq} t), \qquad (5)$$

$$v_{qs} = v_{qs}^* - V_{DC}^{OFFSET} \sin(\omega_{dq}t).$$
(6)

Those parasitic ac voltage components in the dq frame are seen as disturbance by current controllers. If their frequency (ω_{dq}) is low enough to fall in closed loop bandwidth the current regulators react and try to cancel the injected ac components by adjusting v_{ds}^* and v_{qs}^* . Thus, the additional dc component gets created in stationary $\alpha\beta$ frame and reduces actually injected dc voltage signal. The resulting attenuation of the dc test signal depends on current regulator bandwidth and on the rotor speed, which defines the injected voltage frequency in the dq reference frame. As a conclusion, during the dc-injection based R_s estimation current regulators should be suspended or configured to operate with reduced closed loop bandwidth.

IV. PROPOSED IMPLEMENTATION OF DC SIGNAL BASED RS ESTIMATION METHOD IN FOC IM DRIVES

Simple implementation of the dc signal based R_s estimation in FOC drive with current control is proposed and discussed in this section. Due to the large temperature constant R_s estimation process is called in 1 minute intervals, with the approximate duration of 300ms. In that case the R_s estimation doesn't produce significant speed or torque ripple, and noise disturbance is minimal. Moreover, in order to avoid the influence of current loop dynamics on the injected dc voltage offset and consequently on the R_s result the current loop is suspended during the signal injection phase, as shown on Fig. 3. Thus, the last value of ac voltage amplitude is memorized and during the next 300ms drive switches to voltage control with the added dc voltage signal. Ones estimation is done current loops are enabled and the dc signal canceled.

Online R_s estimation function is called every PWM period and is designed as the state machine, Fig. 4. In zero state ($Rs_estimator_state=0$) the state machine is non active. Outside process ones in 1 minute sets the state to 1 and triggers the start of the dc injection process and R_s estimation. Flag *FLAG_estimate_Rs* is set to 1 and control loop temporary switches from current control to voltage control with constant ac voltage amplitude. Also, while this flag is set the dc signal is added to α component of stator voltage, as shown on Fig. 3. State 1 is further designed as a wait period which allows dc current response to settle. After 200ms function switches to state number 2. In that state software waits for next voltage zero crossing moment, in order to synchronize current samples collection with full ac voltage periods. In state 3 phase A current is sampled and added in the current samples sum. The duration of state 3 is exactly N ac voltage periods, which results in cancelation of ac current component in total sum. At the end of state 3 the R_s is estimated by using (4).



Figure 3. Block diagram of control loop during the dc-signal-injection for Rs estimation



Figure 4. Software block diagram of dc-signal-injection based technique for online Rs estimation

V. EXPERIMENTAL RESULTS

The performance of suggested R_s estimation technique is validated experimentally. The R_s estimation function is incorporated in shaft-sensorless FOC drive with three phase IM (1 kW, 195 V, $R_s = 3.26 \Omega$, $R_r = 1 \Omega$, $L_m = 71$ mH, $L_s = L_r = 74$ mH, $L_{\sigma} = 5.7$ mH, J = 0.001 kg·m2, and four poles). The function is called every PWM period (50µs) and triggered (state set to 1) every 10 sec, to have more R_s results.



Figure 5. Rs estimation results. Injected 5V dc. Different speeds, no load.



Figure 6. Rs estimation results. Injected 2.5V dc. Different speeds, no load.

In the first experiment (Fig. 5) dc voltage of 5V is injected in the $v_{\alpha s}$ phase reference every 10s. During the injection and dc current measurement the dq current loops were suspended. Estimated R_s value is kept constant in the period between two dc injections. Different rotor speeds are commanded to test robustness of the method. In the second experiment (Fig. 6) twice smaller dc voltage (2.5V) is injected. This test is designed to test robustness of the dead time compensation and voltage estimator which cancel inverter nonlinearities. Both tests are performed promptly, with cooled no-load IM. Thus, actual R_s value did not change notably, which was confirmed with phase resistance measurement before and after the test. Figures show practically constant R_s estimation results, for speeds in the range 500 rpm to 5000 rpm. There is reasonable fluctuation of R_s result, but without noticeable influence of rotor speed, ac voltage level or test dc voltage level. Figures also show sudden jump in R_s estimation results, for speeds higher than 5000 rpm. This also corresponds with VSI output voltage saturation. Additional tests showed that VSI in voltage limit continues to compensate dc voltage drop in positive ac voltage half periods, but not in negative. This could be the source of additional dc offset in phase A voltage, which adds to injected dc voltage and affects R_s estimation.

VI. CONCLUSION

An online stator resistance estimation scheme has been proposed for the thermal protection of FOC controlled CRVSI fed induction motors. In order to have comparable results in low, medium and high speed range dc-signal-injection based method is selected. DC signal was intermittently injected into the motor using a modified SVPWM pattern and resulting dc current is measured. It was found that successful R_s estimation can be performed with signal injection period less than 300ms. With injection period that short, speed and torque ripple and noise problems are avoided.

Online R_s estimation method showed minimal sensitivity to rotor speed change. One complete R_s estimation duration is reasonably short, and although dc-signal injected based, showed no significant problems with speed, torque or noise. The only problem noted during the experiments is operation in inverter output voltage limit. In that regime dc-signal-injection based estimated R_s value slightly increases, which is the effect that will be investigated further. The level of torque pulsations during the measuring should be investigated also.

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