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Stator-Flux-Oriented Based Encoderless Direct Torque Control for Synchronous Reluctance Machines Using Sliding Mode Approach

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***Abstract*—**In this paper a sliding-mode torque and flux control is designed for encoderless synchronous reluctance motor drive. The sliding-mode plus PI controllers are designed in the stator-flux field oriented reference frame which is able to track the mentioned reference signals with a minimum pulsations in the state condition. In addition, with these controllers a fast dynamic response is also achieved for the drive system. The proposed control scheme is robust subject to parameters variation except to stator resistance. To solve this problem a simple estimator is used for on-line detecting of this parameter. Moreover, the rotor position and speed are estimated by on-line obtaining of the stator-flux-space vector. The effectiveness and capability of the proposed control approach is verified by both the simulation and experimental results.

***Keywords*—**Synchronous Reluctance Motor, Direct Torque and Flux Control, Sliding Mode, Field-Oriented Frame, Encoderless.

I. Introduction

THE SynRM is one of the oldest and simplest types of electric motors. In recent years, it has been shown that SynRM can be competitive with other ac motors [1]-[3]. A SynRM is advantaged on induction motor by the absence of rotor copper losses, on brushless motors by inexpensive rotor structure and on switched reluctance motor by a much lower torque ripple and low noise. A multitude of solutions for control of SynRM drives have been proposed [1]–[7]. Among them, the direct torque and stator flux control for SynRM drives has been developed as direct torque control (DTC) [4]-[7]. The DTC strategy was an induction motor control technique [8] that has been successful because it explicitly considers the variable structure nature of the voltage source inverter and uses few machine parameters, while being more robust to parameter uncertainty than field-oriented control (FOC) [9]. The DTC features fast responses, structural simplicity and robustness to modeling uncertainty and disturbances. Compared to the conventional FOC, the advantages include the elimination of current controllers operated in rotor reference frame, associated coordinate transformation, continuous rotor position requirement and separate voltage pulse-width modulator. However, it still has some disadvantages that can be summarized in the following points: high torque, flux and current ripples; variable switching frequency behavior and difficulty to control torque and flux at very low speed. To overcome the above drawbacks, some researchers have tried to propose some different DTC space vector modulation (SVM) techniques or to improve switching state patterns [6, 7]. In [6], a predictive direct torque control has been presented for encoderless SynRM which is able to operate at low speed. At low speed operation, the rotor angular position is estimated by injecting test voltage signals (TVSs) to detect the spatial orientations of existing position-dependent rotor anisotropies. However, the TVSs deteriorate the performance of the predictive algorithm, and they create some audible noise. The method of [6] is complicated and for each motor chosen it is required to obtain the motor inductances by off-line parameter identification methods. In [7], a nonlinear method capable of high dynamic torque regulation and efficiency optimization of SynRM has been described based on input-output feedback linearization (IOFL) DTC-SVM. In [7], the SynRM efficiency is optimized by using Lagrange’s theorem [10]. Then, the efficiency optimization criterion and the motor torque are chosen as output variables. IOFL technique however, requires the full knowledge of the motor parameters with sufficient accuracy. In addition, two PI controllers employed in [7] that its coefficients should be properly adjusted.

Variable structure control (VSC) or sliding mode control (SMC) is an effective, high frequency switching control for nonlinear systems with uncertainties [11]. It features simple implementation, disturbance rejection, strong robustness and fast responses. Since power converters for ac drives are, by their nature, switching devices, it is worth considering VSC as a solution for generating discontinuous control laws. In fact, the classical DTC is a VSC scheme, excellently designed to match the eight-state, discrete nature of the voltage source inverter. Recently, several solutions that integrate the VSC and DTC principles (VS-DTC) within high performance drives have been proposed [12], [13]. A VS-DTC IPMSM drive was presented in stationary reference frame [12]. Although the proposed controller assure the tracking of the torque and stator flux of IPMSM but, the fast switching may generate unexpected chattering. So, authors of [12] have

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suggested using saturation function instead of sign type. This function reduces chattering phenomenon, however produces steady-state error and drops transient system behavior. A VS-DTC for induction machine was proposed with stator flux oriented [13]. It employs a switching component and a linear PI regulator for torque and flux control respectively. This flexible DTC scheme takes advantage of the best features of linear control, smooth operation, and of VSC, robustness to perturbations. In the transients, the linear component is dominant, and the PI gains are selected so as the linear control realizes the desired dynamic response. In the steady-state, the VSC component is prevailing and the gains are selected to obtain the desired performance in terms of steady-state robustness and chattering. Therefore, the DTC transient merits and its robustness are preserved while the steady-state behavior is much improved.

In this paper, a novel VSC-DTC for Encoderless SynRM drives is suggested. Two sliding mode-plus-PI controllers are designed in the stator-flux field oriented reference frame. Each of these combined controllers employs a switching component and a linear one so that has dual behavior. This flexible DTC scheme takes advantage of the best features of linear control, smooth operation, and of VSC, robustness to perturbations (LVSC). In the transients, the linear component is dominant, and the PI gains are selected so as the linear control realizes the desired dynamic response. In the steady-state, the VSC component is prevailing and the gains are selected to obtain the desired performance in terms of steady-state robustness and chattering. Therefore, the DTC transient and robustness merits are preserved while the steady-state behavior is much improved. One may notice that proposed system drive don't need position sensor due to using stator flux reference frame instead of rotor reference frame.

II. VS-DTC of Sensorless SynRM Drives

The DTC for ac drives is a strategy exclusively based on stator voltage control. The consecutive voltage vectors applied to the motor are directly selected on the basis of torque and flux errors. In this way, fast response and robust torque and flux control are obtained, without intermediate current control. The classic DTC uses bang-bang torque and flux controllers, without decoupling [7]. A simple switching logic (switching table) employs the output signals of these controllers to select the most appropriate voltage vector, i.e., the one which rapidly reduces the torque and flux errors. Due to the fact that the voltage vector is maintained for the whole duration of the control period, the classic approach causes large torque, flux and current ripple, accompanied by acoustical noise. The switching frequency of the power devices is variable and uncontrollable. One way to decrease the ripple is to significantly shorten the duration of the control period. This requires powerful/expensive digital signal processors (DSPs), and the switching frequency remains variable.

Another approach is to increase the control resolution. The torque ripple was reduced, in [14], when the control period was divided into three subintervals and a sequence of three voltage vectors was applied in this time. This refinement can be further continued, the control resolution will continue to

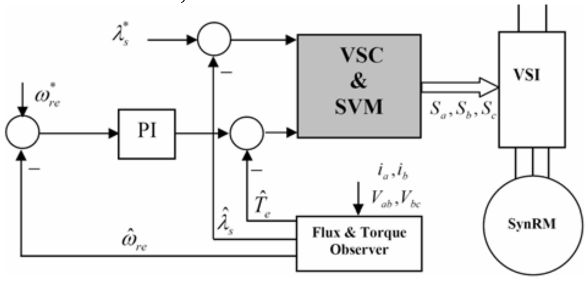


Fig. 1 Proposed VS-DTC of Encoderless SynRM Drive

increase and the ripple will decrease. Asymptotical, ripple-free behavior was realized with linear PI torque and flux controllers and SVM, in [15]; smooth operation was obtained in the steady-state, but the robustness is low due to the linear controller.

To preserve DTC transient and robustness merits, a sliding mode-plus-PI controller is designed for torque and flux control respectively. In fact, based on classic DTC concept, a variable structure controller for direct torque and stator flux regulation is exploited. The implementation is simple. Block diagram of the proposed VSC-DTC sensorless SynRM drive is shown in Fig. 1. This drive is stator-flux oriented and stator-flux controlled. Control quantities are the torque T_e and the stator flux magnitude λ_s. Torque reference T_e^* is produced by an outer speed control loop, with a PI speed controller. The inner loop includes VS-DTC controller which calculates the most appropriate stator voltage vectors to drive the torque and flux to track their corresponding references. The stator voltage control signals have been limited before proceeding to SVM block, providing a solution for high resolution control and constant inverter switching frequency. The flux estimator block is implemented by integrating the stator-induced voltage and then estimated torque is calculated. Stator flux and torque control can be achieved taking into account the SynRM stator equation in stator flux reference frame

$$\overline{V}_s = R_s \bar{i}_s + \frac{d}{dt}\overline{\lambda}_s + j\hat{\omega}_{\lambda s}\overline{\lambda}_s \tag{1}$$

Where $\overline{V}_s$ and $\bar{i}_s$ are the stator voltage and current, $\hat{R}_s$ is the estimated stator resistance, and $\hat{\omega}_{\lambda s}$ is the estimated stator flux angular speed. The direct and quadrature components of (1) are

$$V_{sx} = \hat{R}_s\, i_{sx} + \frac{d}{dt}\lambda_s \tag{2-1}$$

$$V_{sy} = \hat{R}_s\, i_{sy} + \hat{\omega}_{\lambda s}\lambda_s \tag{2-2}$$

Under the assumed orientation, the develop torque is

$$T_e = 1.5P\,\lambda_s\, i_{sy} \tag{3}$$

Combining (2-2) and (3)

$$V_{sy} = \frac{2R_s}{3P\,\lambda_s}T_e + \hat{\omega}_{\lambda s}\,\lambda_s \tag{4}$$

The estimated electrical angular speed of the stator flux vector can be obtained by

$$\hat{\omega}_{\lambda s} = \frac{d}{dt}\left(\tan^{-1}\frac{\lambda_{Qs}}{\lambda_{Ds}}\right) = \frac{\left(\lambda_{Ds} * \dot{\lambda}_{Qs} - \lambda_{Qs} * \dot{\lambda}_{Ds}\right)}{\lambda_s^2} = \frac{\left(\lambda_{Ds} * \left(v_{Qs} - \hat{R}_s i_{Qs}\right) - \lambda_{Qs} * \left(v_{Ds} - \hat{R}_s i_{Ds}\right)\right)}{\lambda_s^2} \quad (5)$$

where λ_{Ds} and λ_{Qs} are two-axis stator fluxes in the stationary reference frame. The precision of the calculation is not so important, since a PI regulator is present on the torque channel. It corrects the torque even if the last term in (4) is erroneously estimated. The flux control is accomplished by modifying the real component V_{sx}, the flux component of the voltage vector. For each sampling period T_{samp}, one can approximate the V_{sx} voltage as

$$V_{sx} = \hat{R}_s \, i_{sx} + \Delta\lambda_s / T_{samp} \quad (6)$$

At high rotor speed, the $\hat{R}_s \, i_{sx}$ voltage drop can be neglected and voltage becomes proportional with the flux change $\Delta\lambda_s$ and the switching frequency $1/T_{samp}$. At low speed, the $\hat{R}_s \, i_{sx}$ term is not negligible. The simplest way is to add the $\hat{R}_s \, i_{sx}$ term at the output of the flux regulator in same manner as the speed dependent term was added to the torque controller output. However, the computation of the voltage drop term requires a time-consuming stator flux coordinate transformation. Instead of it, a PI controller was used on the flux channel.

The VS-DTC solution integrates VSC and SVM within a robust high-performance drive. The symmetrical SVM applies six voltage vectors within a control period, and the duration of each vector is determined with high time resolution. The switching frequency of the power devices is constant and controllable.

The block diagram of the torque and flux controller is shown in Fig. 2 and is called "linear and variable structure control" (LVSC). It consists of a sliding-mode controller that is combined with a conventional PI controller. The combined controllers are a generalized and flexible scheme which takes advantage of the best features of linear control, smooth operation, and of VSC, robustness to perturbations and modeling uncertainties.

The sliding surface of $S = S_{\lambda s} + jS_{Te}$ is selected so as to impose sliding-mode operation with first-order dynamics

$$S = e_{\lambda s} + c_{\lambda s}\, se_{\lambda s} + j\left(e_{Te} + c_{Te}\, se_{Te}\right) \quad (7)$$

where $s = d/dt, e_{\lambda s} = \lambda_s^* - \hat{\lambda}_s$, and $e_{Te} = T_e^* - \hat{T}_e$ are the flux and torque errors, and "^" denotes estimated quantities. Design constants $c_{\lambda s}$ and c_{Te} are selected so as to impose the desired linear first-order behavior of the system during sliding modes, i.e., when $S = 0$.

The controllers of (8) and (9) produce the reference voltage vector $V_s^* = V_{sx}^* + jV_{sy}^*$ in the stator flux reference frame so that

$$V_{sx}^* = \left(K_{P\lambda s} + K_{I\lambda s}/s\right)\left(e_{\lambda s} + K_{VSC\lambda s}\,\mathrm{sgn}\left(S_{\lambda s}\right)\right) \quad (8)$$

$$V_{sy}^* = \left(K_{PTe} + K_{ITe}/s\right)\left(e_{Te} + K_{VSCTe}\,\mathrm{sgn}\left(S_{Te}\right)\right) + \hat{\omega}_{\lambda s}\,\hat{\lambda}_s \quad (9)$$

where $K_{P\lambda s}$, $K_{I\lambda s}$, K_{PTe} and K_{ITe} are the PI controller gains and $K_{VSC\lambda s}$, K_{VSCTe} are the VSC gains. An SVM block that generates the inverter switching signals is the output stage.

The LVSC employs a nonlinear switching component and a linear component. During transients $e_\chi > K_{VSC\chi}\,\mathrm{sgn}\left(S_\chi\right)$, where χ is T_e or λ_s, and the linear (PI specific) behavior is dominant. In the steady-state, errors are very small and the switching (VSC specific) behavior prevails and the ripple magnitude depends on the K_{VSC} gains. Adequate balance between linear and switching behavior is easily achieved by proper gain selection. PI gains are chosen so that the linear control provides the desired dynamic response, while the VSC gains determine the robustness in steady-state operation. The VSC design procedure [7] requires the gain to be large enough in order to compensate for modeling uncertainties and perturbations. In this case, the K_{VSC} gains are selected as large as needed to obtain the desired performance in terms of robustness and chattering.

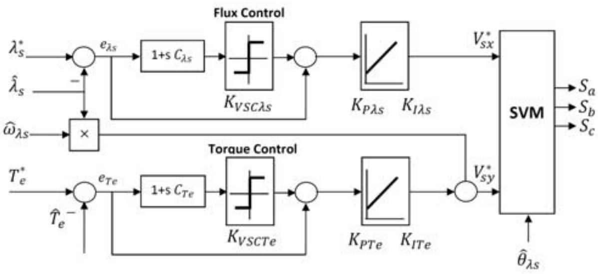


Fig. 2 Linear and Variable Structure Control (LVSC)

III. Stator Resistance Estimation

The variation of the stator resistance is a thermal process and therefore is not only determined by the machine losses but also the time [16]. Among the machine variables, the stator flux vector is highly affected by the resistance changes particularly at low speed. In addition, the IOFL controller can be made more reliable if the stator resistance is estimated online during operation of machine. In this paper, a PI estimator is employed based on comparing the actual current and the reference current to predict the stator resistance [16, 17]. As shown in Fig. 4, the error in the stator current is used as an input to the PI estimator. The technique is based on the principle that the error between the actual stator current and the reference current is proportional to the stator resistance change [16]. The PI resistance estimator is described by

$$\Delta R_s = \left(K_P + \frac{K_I}{s}\right)\Delta I_s \quad (10)$$

Where s is Laplace operator and K_P and K_I are the proportional and integral gains of PI estimator. The error between the actual stator current and its reference is passed through a low pass filter with a very low cutoff frequency in order to attenuate high frequency component contained in the estimated stator current. Then the signal is passed through a PI estimator. The output of the PI estimator is the required change of resistance ΔR_s due to change in temperature or frequency. The change of stator resistance ΔR_s is continuously added to the previously estimated stator resistance $R_{s(k-1)}$. This updated stator resistance can be used directly in the controller.

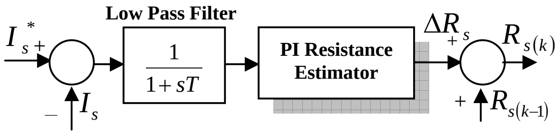
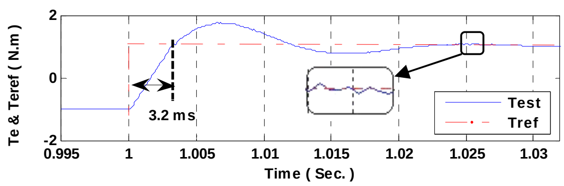


Fig. 3 PI Resistance Estimator of SynRM Drive System

IV. Simulation Results

Some simulations are performed to show that the proposed VS-DTC drive is able to operate with reduced torque and flux ripple, without compromising the fast dynamic response and robustness of torque and flux control, of the classic DTC [8]. The VS-DTC and DTC strategies are simulated for a 0.37 Kw four-pole three-phase SynRM drive, at 5 KHz sampling frequency, and representative results are illustrated in Figs. 4 and 5. In both cases, at the instant 1 sec, the torque command is changed from -1 N.m to +1 N.m, with the stator flux maintained at the rated level, while the motor was running at -200 Rpm. The torque transients and stator flux magnitude in the VS-DTC drive are shown in Fig. 4, while Fig.5 shows similar quantities in the DTC drive. Although the DTC was fine tuned to produce low torque ripple, the VS-DTC exhibits much lower ripple, while its dynamic response is approximately the same. Torque response in Fig.4 illustrates well the characteristic behavior of the VS-DTC controller: it has linear behavior during transients, and switching behavior is apparent in the steady-state. Increasing the VSC gains strengthens the VSC component, increases the ripple, and makes the VS-DTC behavior approach that of DTC. The VS-DTC flux control is superior to DTC flux control, it has low ripple, and is equally robust with respect to torque transients.



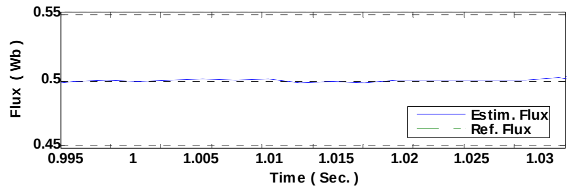
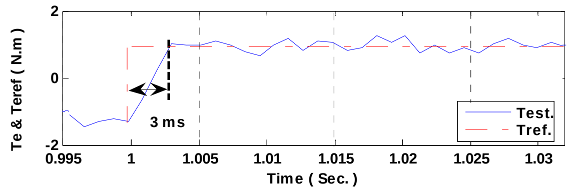


Fig. 4 Torque Transients and Stator Flux magnitude in the VS-DTC drive



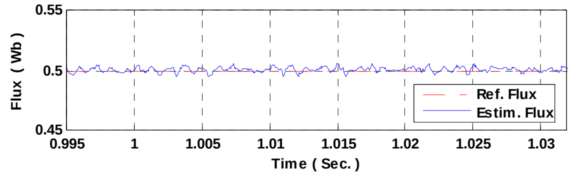


Fig. 5 Torque Transients and Stator Flux magnitude in the Classical DTC drive

V. Exprimental Setup and Results

For practical evaluation of the actual system performance, a PC-based prototype system was built and tested. The experimental setup corresponding to overall system block diagram shown in Fig. 6 is depicted in Fig. 7 consists of the following sections: A 0.37kW three-phase SynRM and a 1.1kW DC generator as its load; Three-phase voltage source inverter and its isolation board; Voltage and current sensors board; 96 bit Advantech digital Input-Output card; 32-channel Advantech A/D converter card; CPLD board and a personal computer (PC) for calculating required signals and viewing the registered waveforms. The SynRM parameters are reported in TABLE I.

The SynRM is supplied by a three-phase inverter with a symmetrical two level space vector modulation. A Xilinx XC95288xl CPLD has been selected for real time implementation of switching patterns using a switching frequency of 5 kHz. The CPLD board communicates with PC via the digital Advantech PCI-1753 I/O board. CPLD in experimental setup realizes the following tasks: Switching pattern generation of IGBT switches based on SVM technique, providing a useful dead time in the so-called switching patterns of power switches, generation of the synchronizing signal for data transmission between PC and hardware and shutting down the inverter in the case of emergency conditions such as over current or PC hanging states.

The inverter has been designed & implemented specifically for this experiment using SKM75 GD 124 D SEMIKRON module. The required drive board has been designed by HCPL 316J which is fast and intelligent IGBT driver and guarantees a reliable isolation between the high voltage and control boards. The DC link voltage and stator phase currents and

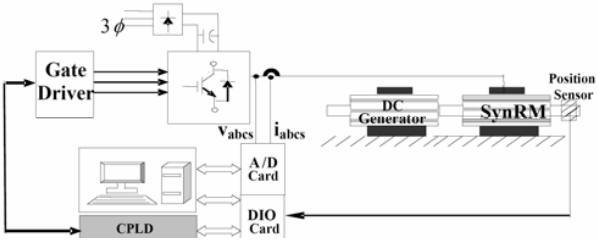


Fig. 6 Laboratory Implementation Block Diagram

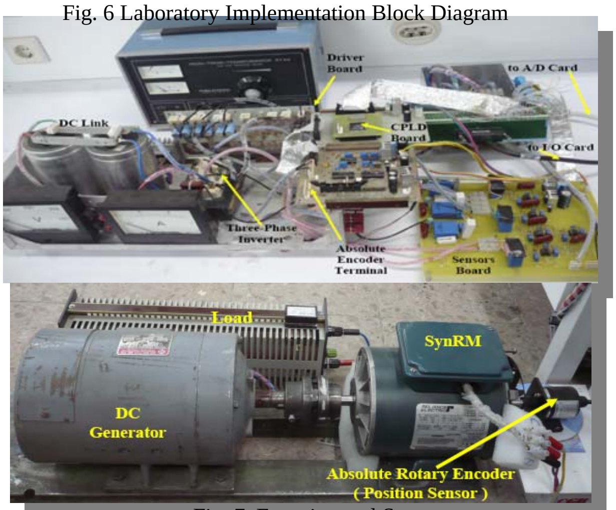


Fig. 7 Experimental Setup

TABLE I. SPECIFICATIONS AND PARAMETERS OF THREE-PHASE SYNRM

$P_n = 370W$	$V_n = 230$	$I_n = 2.8A$
$L_{md,unSat} = 232mH$	$L_{md,Sat} = 178mH$	$L_{mq} = 118mH$
$R_s = 2.95\Omega$	$f_n = 60$ Hz	$No.\ of\ Poles = 4$
$T_{en} = 1.9\ N.m$	$J_m = .015\ \mathrm{Kg.m^2}$	$B_m = .003$ Nm/rad/sec

voltages are measured by Hall-type LEM sensors. All measured electrical signals are filtered using the separate analogue second order low pass filters and then converted to digital signals using an A/D card with 10µs conversion time. In order to evaluate the accuracy of rotor speed estimation, the actual rotor position is obtained from an absolute encoder with 1024 pulses per revolution.

A. Dynamics Performance

The torque and stator flux dynamic responses to command changes are presented in Fig. 8. The rise time for proposed VS-DTC is 3.5 ms and in terms of settling time, estimated torque signal reaches steady-state within 10 ms. As shown in Fig. 8, the torque overshoot is acceptable.

B. Steady-State Performance

The steady-states of speed, torque and flux at 1400 rpm with 50% full load under proposed VS-DTC are shown in Fig. 9. From this figure, it can be seen the ripples in speed and torque are reduced significantly.

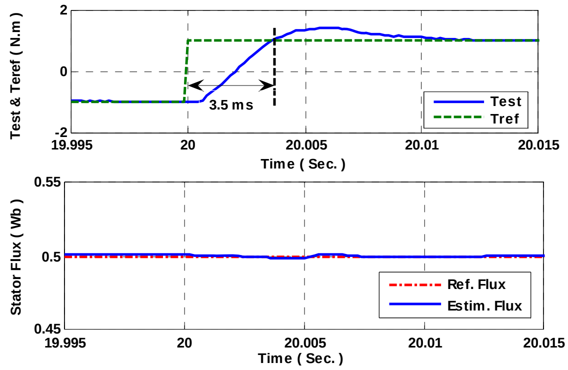


Fig. 8 Dynamic Performance of VS-DTC. The motor was running at -200 Rpm with -1N.m Load before the Torque Changed to 1N.m

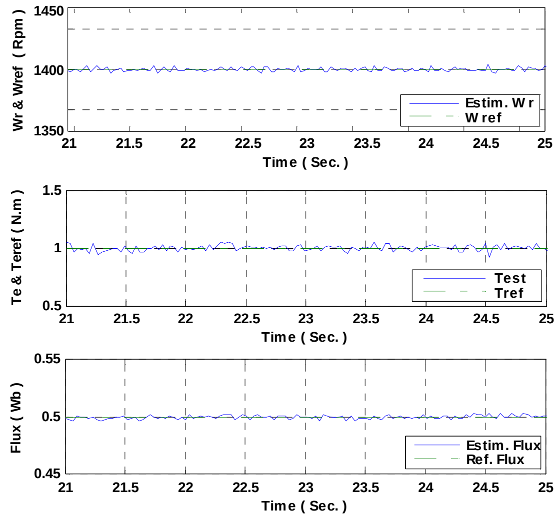
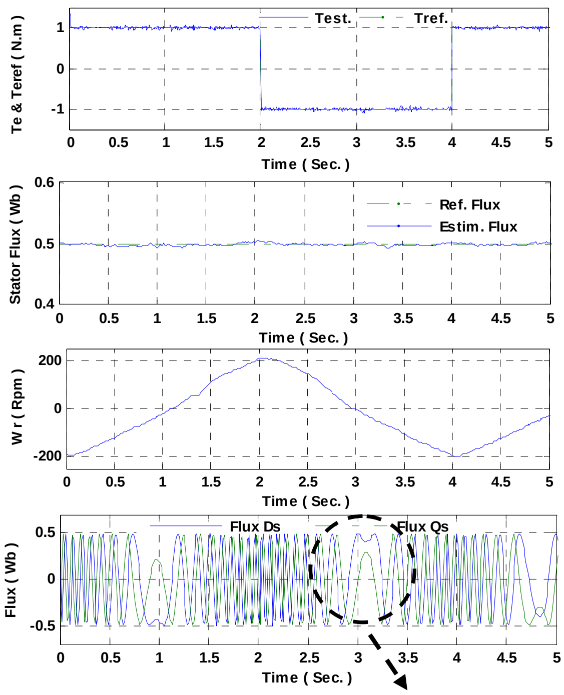


Fig. 9 Steady-State Performance of VS-DTC, Speed, Torque and Flux at 1400 Rpm with 50% Full Load



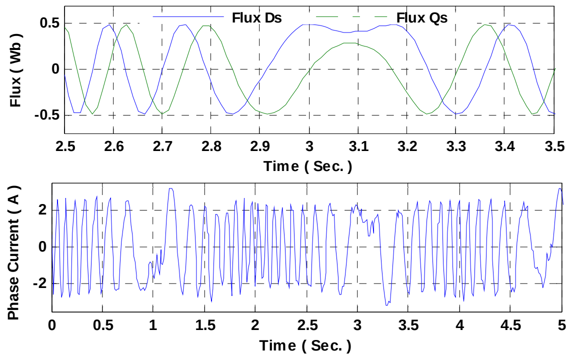


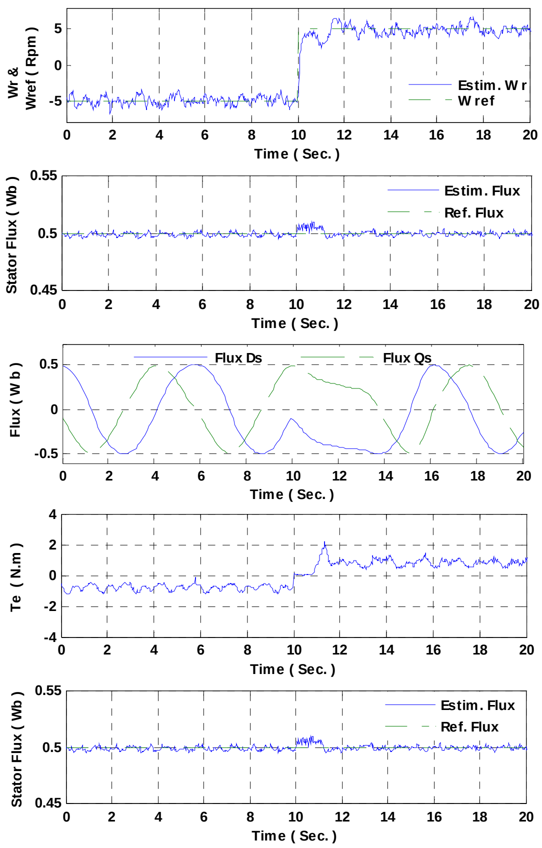
Fig. 10 Chattering Free Responses of SynRM Drive System under Proposed VS-DTC, when Torque Reverses.

C. Chattering Free Responses

The chattering free torque and flux dynamics are illustrated in Fig. 10 when the torque command reverses between ±1 N.m. the corresponding trajectories of estimated rotor speed, flux and phase current are in this figure.

D. Very Low Speed Operation

The performance of the proposed rotor speed estimation method at very low speed has been shown in Fig. 11. The speed reference is reserved from -5 rpm to +5 rpm at t =10 Sec. under 50% full load. It is seen that the speed reference command is perfectly tracked and the torque and speed are smooth enough and flux hodograph is almost circle.



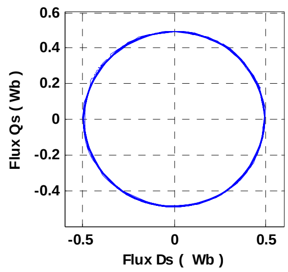


Fig. 11 Performance of the proposed method in very low speed

VI. Conclusion

In this paper, a variable structure controller has been proposed for direct torque and stator flux control of an encoderless SynRM drive in stator flux reference frame. Combining the principles of the Sliding Mode, DTC, and space-vector modulation yields a simple but robust sensorless drive system. In particular, the sliding mode control contributes to robustness of the drive, the DTC results in a fast dynamic response, and the SVM improves the torque, flux and current steady-state waveforms by ripple reduction. The proposed VS-DTC has minimum number of dependent-parameter (only stator resistance). Based on this control approach, the rotor low speed estimation has been achieved by using a simple technique for online estimation of the stator resistance.

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