Sensorless PMSM Control for H-axis Washing Machine Drive

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Abstract — **In this paper a position and speed estimation method without position transducer is presented. This method is applied for horizontal axis washing machines with Permanent Magnet Synchronous Motor (PMSM). By integrating methods, i.e. using a speed reference for zero speed startup and low speed acceleration, and back-EMF for mid-high speed operation, the rotor position can be estimated and controlled over the full speed range. In order to achieve correct operation from zero speed, the two techniques are combined with a crossover function based on the speed reference. The proposed method can be used in applications with significant and unpredictable variation in loads, such as horizontal axis washing machines. Moreover, the proposed method can be applied on drives with surface mounted PMSM or motors with low or distorted saliency signature. To verify the functionality of the proposed method, experimental validation was conducted using horizontal axis washing machine.**

I. Introduction

Recent world-wide interest towards the environmental friendliness, water consumption, and energy saving particularly impinges to home appliance area. Employing variable speed motor drives with PMSM yield an opportunity to increase overall energy efficiency, power density and intelligent control consequently outperforms conventional uncontrolled drives [1]. Particularly in PMSM achieving the variable speed drive requires determination of the optimal motor speed and position by using a shaft position sensor to successfully perform the field oriented control (FOC) of the PM motor. Therefore the aim is not to use this mechanical sensor to measure the position directly but employ some indirect technique to estimate the rotor position instead.

The variable speed motor drives are used in modern belt-driven washing machines, where the driving motor works at lower speeds and higher torque levels during tumble-wash cycle and high speed during spin-dry cycle. Proposed position estimation techniques are very well suited for such application enabling better washing performance. An electronically controlled three phase interior PM motor provides a unique feature set with the higher efficiency and power density. A variable speed operation with optimum performance of the interior PM motor can only be achieved when its excitation is precisely synchronized with the instantaneous rotor position.

In order to be able to use FOC, the position of rotor flux has to be known prior to any control action is executed. Therefore detection algorithm based on injection of pulsating HF signal in synchronous frame is used to estimate the rotor position of rotor at start-up. This technique avoids generation of unwanted rotor movements, which is common when conventional alignment process is employed. The enhanced back EMF observer detects the voltages induced by the PM flux on the stator windings. These signals are used to calculate the rotor position and speed needed for control. As the observed variables are not available at low angular speed, an open loop starting procedure is implemented. The resulting control structure has been fully analyzed by experiments, in order to test the performance both in steady-state and transient operations.

The application software was implemented on a 16-bit fixed point DSC56F8025 digital signal controller. Performance of the sensorless drive over a wide range of operating conditions within washing machine is demonstrated. It is illustrated that even such demanding control technique can be realized using the 16-bit digital signal controller, which combines both MCU's and DSP's capabilities.

II. Proposed Approach

The first stage of the proposed overall control structure is detection algorithm of rotor PM to determine accurate initial position. This allows applying a full start-up torque to the motor of the washing machine. In the second stage, the field oriented control is in open-loop mode, in order to move the motor up to a speed value where the observer provides sufficiently accurate speed and position estimations. As soon as the observer provides appropriate estimates the rotor speed and position calculation is based on the estimation of a back EMF in the stationary reference frame using a Luenberger type of observer.

A. *Initial Position Detection*

The field oriented control of PM motor is based on controlling the stator current vector to be perpendicular to the rotor flux vector, which enables full torque utilization of the machine. The rotor flux vector position has to be known at any time during the machine operation [2]. To successfully achieve a start up procedure, the rotor initial position has to be determined. Detection algorithm based on injection of pulsating HF signal in synchronous frame is used to estimate the rotor position of rotor at start-up. This sensorless approach is physically based on property of d and q axes flux being decoupled [3][4]. The block diagram of designed method is depicted in Fig. 1.

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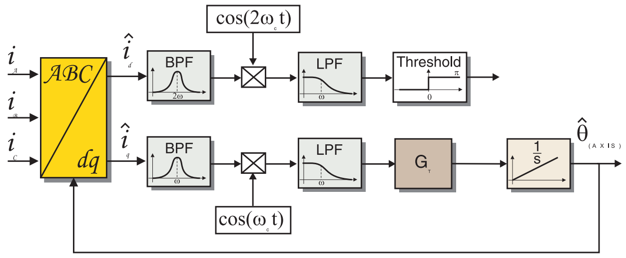

Figure 1. Block diagram of proposed PLL scheme for initial position estimation and PM polarity detection.

Therefore if an estimated reference frame is defined and not precisely aligned with a real rotor reference frame, then by applying flux vector at known carrier frequency in the estimated 'd' axis, current at carrier frequency can be observed in the estimated 'q' axis. This current is directly proportional to the misalignment angle of the estimated and rotor reference frame expressed in (1). Therefore changing the position of estimated frame such that this axis current is zero or minimal, will allow for tracking of real rotor i.e. saliency position.

Considering the high frequency signals, the quadrature axis motor model in synchronous frame is rewritten into the estimated reference frame. In this HF model, the voltage drop across the stator resistance and back-EMF components are neglected. Applying high frequency signal $u_{HF} = U_M \sin(\omega_{HF} t)$ in d-axis of HF model will result in high frequency current, given as follows:

$$\begin{bmatrix} \hat{i}_d \\ \hat{i}_q \end{bmatrix} = \frac{U_M \Delta L}{\omega_{HF} L_d L_q} \cos(\omega_{HF} t) \begin{bmatrix} L_0 - \Delta L \cos(2\theta_{error}) \\ \Delta L \sin(2\theta_{error}) \end{bmatrix} \quad (1)$$

It can be noted from (1), that the q-axis current is amplitude modulated HF current with modulation frequency proportional to the position difference between real rotor and estimated synchronous reference frame. Since the HF coupling impedance spatial modulation in PMSM repeats twice per one electrical revolution, the estimated position can be displaced by π from the actual rotor position. Therefore the magnet polarity has to be identified once the PM axis is identified in the equilibrium point. The PM polarity detection method is based on the stator core saturation phenomenon.

B. Open Loop Startup

Upon completion of identifying the initial rotor position, the field oriented control is used in open-loop mode. The current set-point is determined by the speed controller, which generates the torque reference current i_Q^{ref} and the proportional integral controller of speed control loop is initialized to maximum allowable current. The angular speed feedback ω_{FBCK} is kept at zero level during the open loop operation and the vector transformations are fed by a time varying reference position signal derived by integrating the speed ramp reference. This strategy moves the motor up to the speed values where the observer provides sufficiently accurate speed and position estimates.

In order to correctly switch on the sensorless PMSM control, the open-loop estimates and high speed sensorless algorithm have to be evaluated and merged. Merging algorithm based on a cross-over function is designed to assure smooth transition to close the position and speed feedbacks.

The merge function with weighting coefficient a_M is used to determine the speed and position feedback signals based on speed ramp command. The weighting function is divide into three subsequent regions named as open-loop state, merge state, and closed loop state respectively. The weighting coefficient a_M is kept at zero level during open loop state. The merge state is determined between respective lower and upper speed limits ω_{M1}, ω_{M2} where weighting coefficient a_M increases up to reaching closed loop state. The weighting function is shown in Fig. 2.

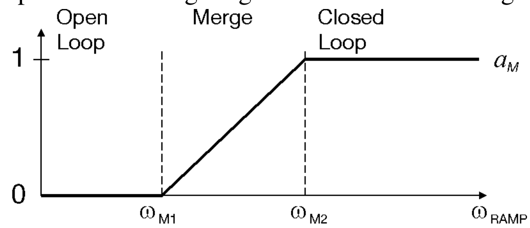

Figure 2. Crossover function with a_M weight coefficient

The upper and lower speed limits of the crossover function ω_{M1}, ω_{M2} are found from the estimation accuracy limits by experiments.

Angular speed feedback ω_{FBCK} is determined by following formula

$$\omega_{FBCK} = a_M \cdot \omega_{OBSRV} \quad (2)$$

where estimated speed ω_{OBSRV} is multiplied by weighting coefficient a_M.

The vector transformations are fed by position feedback signal θ_{FBCK}, which is determined by combination of open-loop position signal θ_{OL} and position calculated by back-EMF observer θ_{OBSRV}. The resulting feedback position signal θ_{FBCK} is calculated using crossover function (3) with weighting coefficient a_M

$$\theta_{FBCK} = \theta_{OL} \cdot a_M + (1 - a_M) \cdot \theta_{OBSRV} \quad (3)$$

where weighting coefficient a_M is multiplied by both the estimated position θ_{OBSRV} and open-loop position θ_{OL} signals. Then the products are added to form the feedback position signal θ_{FBCK}.

The open loop position θ_{OL} is a time varying reference signal derived by integrating the speed ramp reference. This ramp of the reference speed command is carefully chosen in order to assure a safe starting with minimum oscillation up to the maximum torque. Speed reference ramp is chosen such that the start-up torque is greater than the one required by the washing machine. Therefore the actual rotor position advances the 'forced' open loop position θ_{START}.

By initializing the integrator part of the speed controller to maximum allowable current value and simultaneously knowing the correct rotor position at beginning, allows delivering the full start-up torque. This accelerates the washing machine at the rate equal to the angular speed output of the back-EMF observer. Once the upper speed limit ω_{M2} is attained, the back-EMF observer is switched on-line and the closed-loop speed control is achieved.

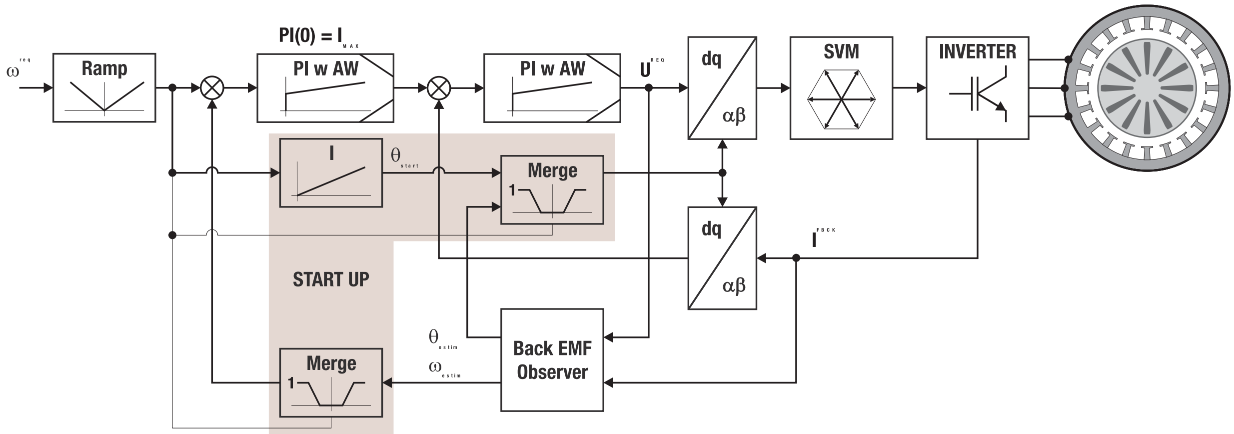

Figure 3. Sensorless speed control with open loop startup and back-EMF observer

C. Back EMF Observer

When the minimum operating speed is reached a measurable level of back EMF is generated by the rotor permanent magnets. The back EMF observer is then gradually transition into the closed-loop mode. The feedback loops are then controlled by the estimated angle and estimated speed signals from the back EMF observer.

This estimation method for the position and angular speed is based on the motor mathematical model with an extended electro-motive force function [4][5]. This extended back-EMF model includes both position information from the conventionally defined back-EMF and the stator inductance as well. This allows to extracts the rotor position and velocity information by estimating the extended back EMF only.

$$\begin{bmatrix}u_\alpha\\ u_\beta\end{bmatrix} = R\begin{bmatrix}i_\alpha\\ i_\beta\end{bmatrix} + \begin{bmatrix}pL_d & (L_d-L_q)\omega_e\\ -(L_d-L_q)\omega_e & pL_d\end{bmatrix}\begin{bmatrix}i_\alpha\\ i_\beta\end{bmatrix} + \{(L_d-L_q)(\omega_e i_d - i'_q)+k_e\omega_e\}\begin{bmatrix}-\sin(\theta_e)\\ \cos(\theta_e)\end{bmatrix} \quad (3)$$

where

R – stator resistance

L_d, L_q – d-axis and q-axis inductance

k_e – back-EMF constant

ω_e – angular electrical speed

u_α, u_β – α, β stator voltages

i_α, i_β – α, β stator currents

p – operator of derivative

i'_q – first derivative of i_q current

The observer is applied to PMSM motor with an estimator model excluding the extended back-EMF term. Then extended back-EMF term can be estimated using the observer as depicted in Fig. 4, which utilizes a simple observer of PMSM motor stator current. Here presented back-EMF observer is realized within stationary reference frame (αβ). The estimator of α-axis consists of the stator current observer based on RL motor circuit with estimated motor parameters $\hat{R}_s, \hat{L}_d, \hat{L}_q$. This current observer is fed by the sum of the actual applied motor voltage, cross-coupled rotational term, which corresponds to the motor saliency *(L_d-L_q)* and compensator corrective output. The observer provides back-EMF signals as disturbance because back-EMF is not included in observer model.

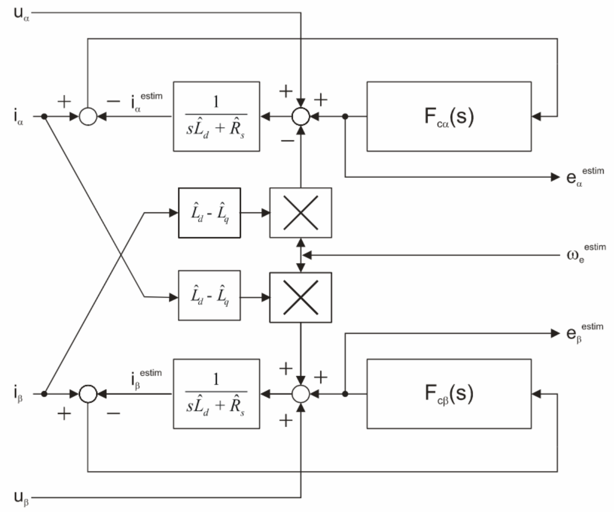

Figure 4. Diagram of extended back-EMF and angle tracking observer

The angle tracking observer [6] is used for the estimation of the rotor angle and its speed. By employing the tracking observer, noise on the position estimate can be filtered out without adding lag to the estimate within its bandwidth. This filtering is achieved by the integrator and PI controller, which are connected in series and closed by a unit feedback loop. The feedback loops are controlled by the estimated angle and estimated speed signals from the back EMF observer [4].

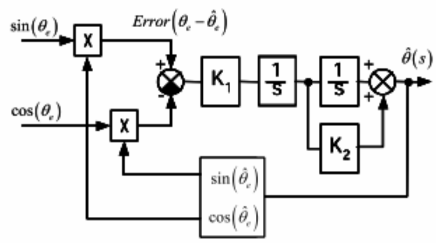

Figure 5. Block diagram of angle tracking observer

III. Experimental Results

All results presented in this section have been obtained in sensorless operation. In order to test the accuracy of the position and speed estimation, the motor has been equipped with an incremental encoder giving the exact rotor position. All algorithms initial position detection, stat up sequence, and back-EMF state observer has been implemented using 16-bit fixed point digital signal controller Freescale MC56F8025. Motor phase currents were measured at the shunt resistors placed in each of the inverter leg and each phase current is reconstructed according to [7].

A. *Start-up Performance*

Finding the initial position was evaluated such that the rotor was manually turned while the position tracking loop was disabled. Then the position tracking loop was switched on and the HF carrier signal voltage was applied along the estimated d-axis. Position of the estimated dq reference frame is set to zero every time the position tracking loop is reset. Initial position is found as soon as the position tracking loop stabilizes in one of the equilibriums. Duration of this transient depends on the position tracking loop bandwidth but will be prolonged, if the initial estimated position error is bigger than $\pm\pi/4$. In that case, having the initial estimated position set to zero, the position tracking loop can be considered to be placed in the unstable region, which prolongs the transient duration. The experimental results of initial sensorless position estimation with magnet polarity detection are shown in Figure 6.

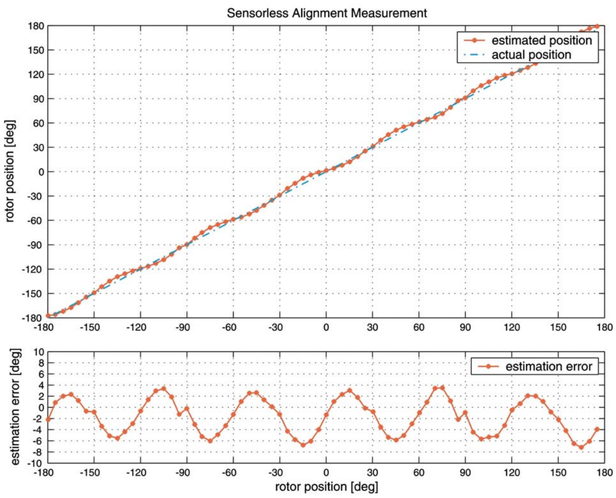

Figure 6. Initial position alignment with PM polarity detection for full electrical revolution.

It can be seen from Fig. 6, that the rotor position was correctly identified even if the initial position error was larger than $\pi/2$. Therefore, considering the magnet polarity detection, the steady state initial position estimation error of ±3° electrical was achieved.

The experiments were carried out with PM axis detection loop bandwidth was set to 50[Hz]. Such bandwidth ensured the stabilization time to be less than 50[ms] even if the initial estimation error was close to p/2. To account for the filters initial transient, the duration of the magnet polarity detection routine was set to 350[ms]. Thus the duration of the whole sensorless alignment process was 400[ms]. The estimation error varies rather periodically with period of 60[°el.]. This is caused by the stator slotting, which was found to be significant in the used PMSM motor.

After identifying the initial rotor position, the field oriented control is started in open-loop mode. The current set-point is determined by the speed controller, which generates the torque reference current i_q^{REF}. Moreover a certain amount of i_d^{REF} current is generated, which improves torque producing capability of the motor by adding a reluctance torque.

Fig. 7 shows experimental results of startup sequence where the time profile of the reference open loop position θ_{OL} and the reference currents i_q^{REF}, i_d^{REF} are displayed. This sequence is accurately chosen in order to assure safe starting with minimum oscillation up to the maximum torque. The weighting function parameters for the lower limit ω_{M1} was set to 100[rpm] and the upper limit ω_{M2} was set to 200[rpm] respectively.

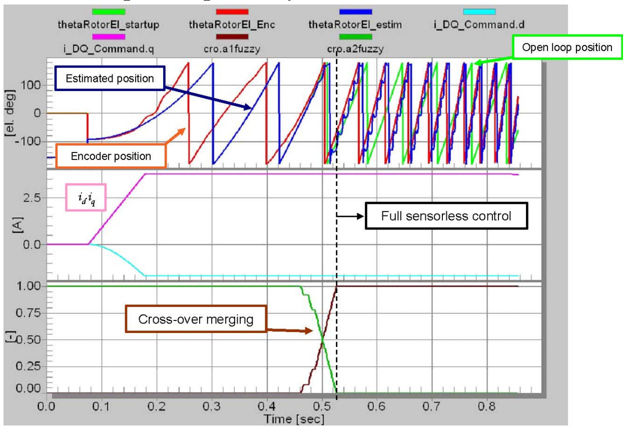

Figure 7. Experimental results of startup sequence

Motor phase currents during start-up sequence consist of initial position detection, open-loop startup and transition to sensorless closed loop operation are depicted on Fig. 8.

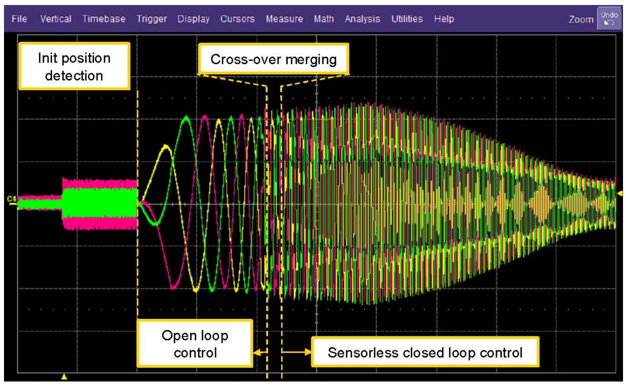

Figure 8. Phase currents measured on the oscilloscope from zero speed up to wash cycle operation, 2A/div.

B. *Washing Cycle Performance*

During wash cycle operation motor runs at relatively low speed (300 up to 1000[rpm]) and it might generate high torque (up to 2.5[Nm]) depending on loading condition, which are given by weigh of clothes, wash program, amount of the water etc... Fig. 9 shows sensorless operation at constant 300[rpm] where speed/torque ripple can be identified under load condition. The torque ripples were caused by unbalanced load.

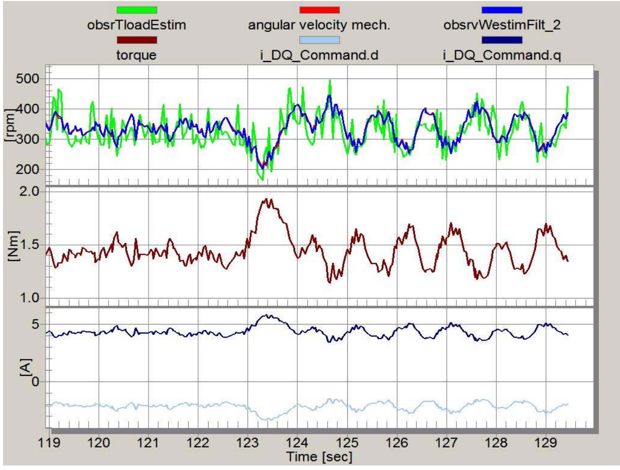

Figure 9. Sensorless operation during steady state spin at 300[rpm].

Fig. 10 shows speed profile diagram where initially the motor runs at 300[rpm] with fully loaded washing machine. The torque variation visible in Fig. 10 is caused by agitation of heavily soaked clothes. The wash program commands acceleration to 750[rpm] speed level, then there is a certain time interval of constant spin at 750[rpm].

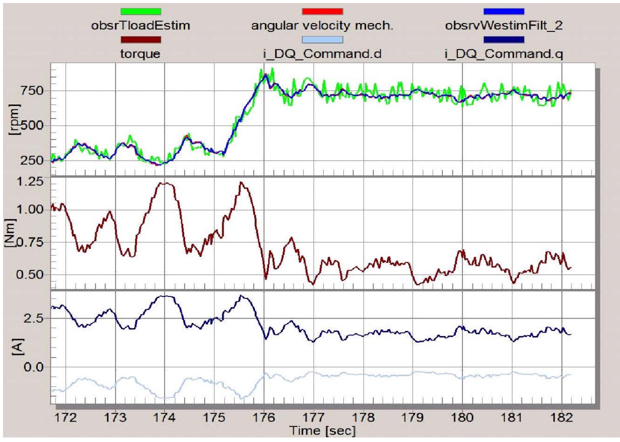

Figure 10. Speed operation during wash cycle with acceleration.

Motor phase currents of sensorless speed control during wash cycle operation when motor accelerates from 300[rpm] to 750[rpm] are depicted on Fig. 11.

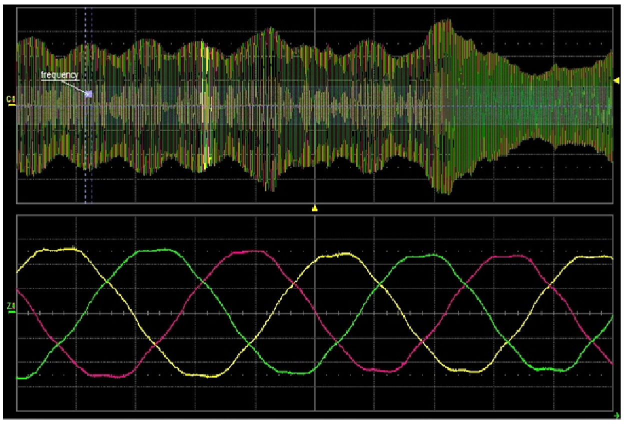

Figure 11. Phase currents measured on the oscilloscope during acceleration, 1A/div.

C. *Spin Cycle Performance*

Upon completion of the wash cycle, the washing machine starts operation in spin-dry cycle as illustrated in Fig. 12. The estimated torque was used to detect out-of-balance in the wash load before entering the spin cycle. The washing machine accelerates to pre-defined high speed level to 11000[rpm] for a spin dry where it remains for a short time. Next the washtub is demanded to decelerate down to 9000[rpm] and next deceleration proceeds to low speed level. This cycle might be repeated several times depending on a chosen wash program.

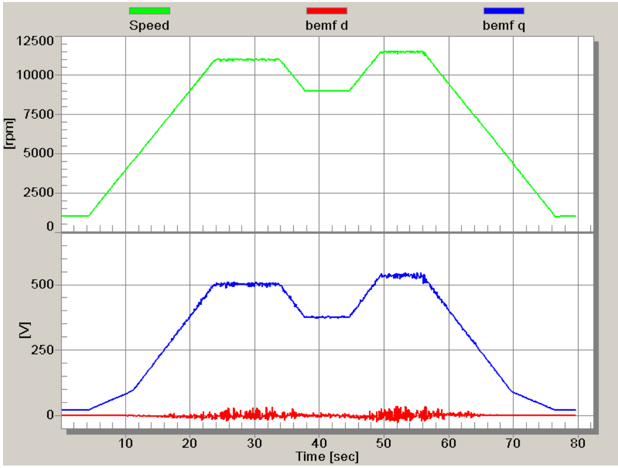

Figure 12. Sensorless operation during spin cycle

On of the most important characteristic of the electric motor for washing machine drives, is the motor mechanical characteristic. This characteristic shows the motor torque generation capability across the operational speed range. Knowing the shape of the motor mechanical characteristic, allows the designer of the application to select the correct motor drive. Hence in order to validate the proposed sensorless algorithm, the motor mechanical characteristic was measured in both sensored and full sensorless mode, Fig. 13. As can be seen from the results, the torque generation capability of the motor in sensorless mode is almost the same as when the motor is operated in sensored mode. The measured torque error is less than 0.02Nm, across the measured range.

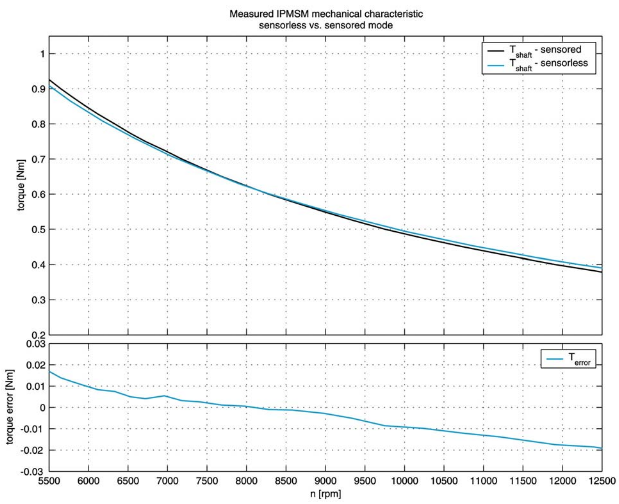

Figure 13. Mechanical characteristic of used PM synchronous motor measured in sensored and sensorless control mode.

IV. Conclusion

A sensorless speed control of a permanent magnet synchronous motor using a back-EMF mode observer with angle tracking observer have been developed. The experimental results showing the performance of proposed algorithm implemented on a DSP controller MC56F8025 were presented. The proposed sensorless algorithm was applied to the horizontal belted drive washer and its driving performance for washing and spinning was verified by experiments. It has been proved that proposed algorithm is suitable for this type of the washing mach

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