Sensorless PM Motor Control for Washing Machines Applications

Master Thesis Abstract

Candidate: Giulia SCAGLIONE   **Supervisor:** Prof. Radu BOJOI   **Advisors:** Dr. Sandro RUBINO
InternshipTutor: Marco VALERIO

Abstract—This thesis focuses on the analysis and implementation of Permanent Magnet (PM) motor control strategies for washing machine applications. In particular, the application is a belt-driven horizontal axis washing machines using an interior PM (IPM) motor. This project has been developed in collaboration with Haier Group Europe, to develop an efficient sensorless motor control that exploit properly the motor selected for this application. The proposed solution is the Direct Flux Vector Control (DFVC) implemented with the integration of High Frequency Injection (HFI) method to detect initial rotor position and sensorless technique of active flux concept in Stator Flux Observer (SFO). After developing the C-code of motor control algorithm whose preliminary validation has been performed in Matlab/Simulink environment, experimental validation has been carried out on a washer made by Haier Group under the brand Candy.

I. Introduction

Washing Machine applications are slowly replacing the Induction Motors (IMs) with the use of Permanent Magnet Synchronous Motors (PMSMs) due to the high torque capability at starting, wider Constant Power Speed Ratio (CPSR) region and robustness at high speed. According to this, PMSM presents rotor anisotropy and electromagnetic model that can't be represented with linear relationships. Moreover, this kind of applications requires a sensorless motor control implementation. To put together these aspects, Magnetic Model Identification (MMI) procedures result to be necessary to exploit properly the motor in terms of performance. During the thesis activity, this preliminary procedure has been carried out, obtaining the direct and inverse flux maps, as well as the optimal maximum-torque per ampere (MTPA) and maximum-torque per volt (MTPV) trajectories. Sensorless motor control must exhibit high dynamic response and it must be robust for the entire speed range. DFVC with SFO satisfies these aspects properly; it refers to $d_s - q_s$ frame which is referring to stator flux vector (see Fig. 1). With this type of control, stator flux amplitude is directly controlled using d_s voltage while motor torque is controlled through the q_s torque current, i.e., acting on q_s voltage. DFVC needs MTPA regulation (torque-stator flux relationship) and MTPV limitation that becomes active at high speed when deep flux weakening occurs.

Furthermore, this control strategy is very sensitive to the dead-time error voltages and to the change of R_s value, so it is necessary to compensate dead-time error voltages and to estimate stator resistance R_s properly.

In the proposed control strategy, HFI is used for initial position detection. Pulses of high frequency voltage are injected on the d_s axis and the measured currents are filtered with moving average filters. High frequency current components are isolated, scaled by a demodulating function

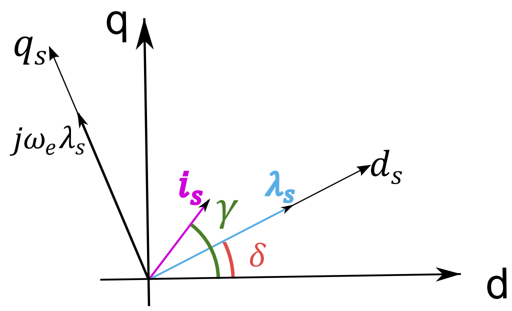

Fig. 1. View of *d*-*q* and d_s-q_s frames.

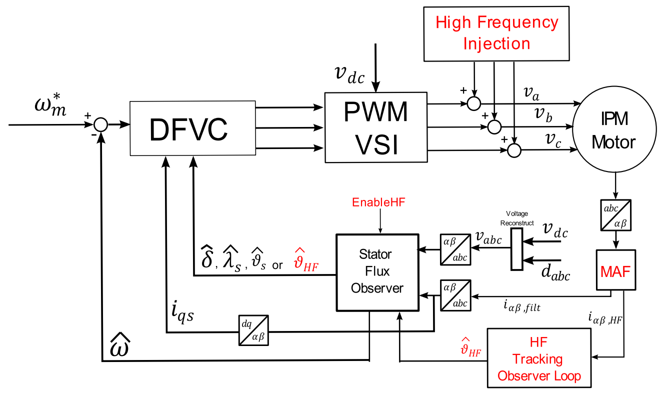

Fig. 2. Block diagram of the adopted solution.

to extract the information about the rotor position. This information is thus sent to a High Frequency Observer Tracking Loop (see Fig. 2).

The goal of my thesis is to develop the above-described strategy and demonstrate the good performance through simulation and experimental results.

II. Personal Contributions

My personal contributions in developing this master thesis are:

1) Studying and analyzing characterization of PM synchronous motors.
2) System modeling using Matlab/Simulink environment and simulate the operation at low- and high-speed ranges.
3) Work in Internship at Haier Group Europe in R&D Electrical Motor Laboratory. Some studies and techniques were also analyzed to improve performance of the current sensorless motor control algorithm.

Fig. 3. View of Candy Washing Machine: front (left), rear (right).

The simulation results show how essential is the estimation of stator resistance and how it gets worse if it is not used. The results also demonstrate how using HFI for initial rotor position detection and even at low speed until 300 rpm motor allow improving motor control performance significantly.

III. Experimental Results

The experimental validation of the washing machine application has been carried out on a 4 pole IPM for home appliances with maximum RMS current of 5 A, maximum torque of 3.3 Nm, and maximum speed of 18000 rpm.

Test rig

The motor under test is placed into the Haier Group - Candy washing machine having a capacity of 14 kg (see Fig. 3). The starting operation has been tested at full load with 11 kg of clothes, 35 l of water and 500 g of unbalance. Regarding the high-speed operation, preliminary validation in no-load conditions has been carried out. The frequency used for HFI is 500 Hz.

The power converter consists of a three-phase inverter module fed by a unidirectional dc source (bridge rectifier), while the digital controller is the dSPACE DS 1103 prototyping board. The control algorithm has been entirely developed in C-code. Switching and sampling frequencies have been set at 16 kHz (maximum motor fundamental frequency of 1200 Hz at 18000 rpm).

A. *Experimental results*

The following tests have been performed: 1) tumbling/washing operation, and 2) high-speed operation, focusing on the acceleration from 16000 to 18000 rpm.

The starting is the worst case for the motor control algorithm since it must provide the highest torque to overcome the drum's inertia. Also, the tumbling is considered a heavy operation since the motor must perform the following actions: starting, speed up to 400-500 rpm, stop and speed up again to 400-500 rpm in the opposite direction. The experimental results reported in the thesis refer to DFVC with HFI used only for initial rotor position detection, thus using SFO sensorless technique for the whole speed range.

Fig. 4 shows how the motor is able to follow the reference speed profile during washing machine starting without reporting any issue. At high-speed, the motor control algorithm performs the deep flux-weakening with MTPV properly, as shown Fig. 5 and Fig. 6, both focused on the acceleration from 16000 to 18000 rpm. The experimental results confirm the very good performance of the motor control algorithm although dc-link voltage reports significant oscillations (300 ± 10 V), and the ratio between sampling and fundamental frequencies is meaningful (16 kHz / 1.2 kHz).

IV. Conclusion

The goal of my thesis activity concerned the development of a high-performance sensorless motor control algorithm for IPM motors used in washing machine applications. The thesis activity has been performed in collaboration with Haier Group Europe through dedicated internship.

The developed control algorithm has been preliminarily validated by means of simulations performed in Matlab/Simulink environment. The preliminary experimental results confirmed the simulation ones, demonstrating the high performance of the proposed control solution in the whole speed range, especially at washing machine starting and spinning.

Future development of this thesis will consist of implementing the sensorless control algorithm in the facilities of Haier Group Europe.

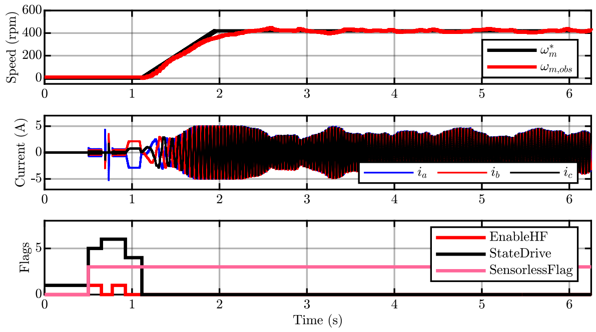

Fig. 4. Experimental results at washing machine starting. From top to bottom: reference and estimated rotor speed; motor phase currents; state-machine states.

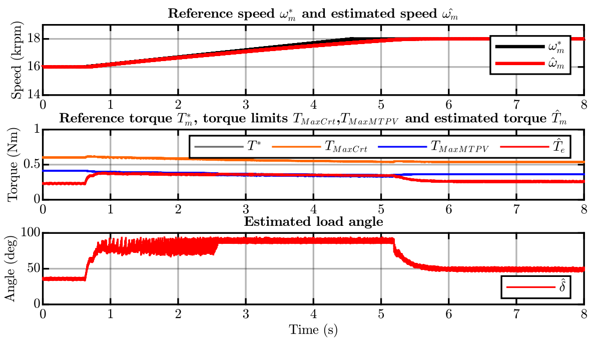

Fig. 5. Experimental results at washing machine spinning. From top to bottom: reference and estimated speed; reference-, maximum-, and estimated- torque; estimated load angle.

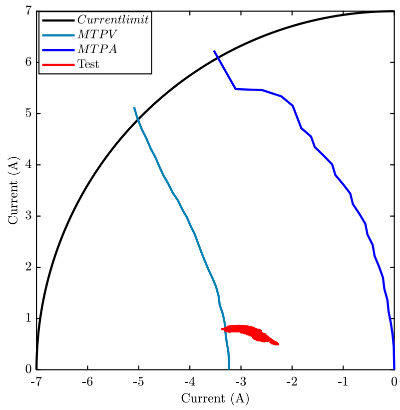

Fig. 6. Profiles of current limit, MTPA and MTPV plus experimental test points during washing machine spinning.