AN APPROACH TO SOLVING RAMP START ISSUES IN SENSORLESS FIELD ORIENTED CONTROL WITH SLIDING MODE OBSERVER FOR PERMANENT MAGNET SYNCHRONOUS MOTORS

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***Abstract*— There are several issues in motor drive systems implementing sensorless field oriented control with a sliding mode observer (SMO) for permanent magnet synchronous motors (PMSM). One of those issues is stability during initial motor start-up when using a ramp. This is due to the fact that at low or zero speed there isn't a significant back-EMF signal to properly drive the observer into accurate angle tracking. Usually step commands are used to help with the transition from zero to the commanded speed as it allows for a very fast transition out of low speed operation. This paper discusses an approach to overcome issues when a ramp start is required by using an open loop control strategy for some portion of the start-up procedure.**

***Keywords*— Field oriented control, motor start-up, permanent magnet synchronous motor, sliding mode observer**

I. Introduction

The Sliding mode observer is one of the more robust and easy to implement angle tracking observers [1], used in sensorless field oriented control [2], as it only requires a few motor parameters to be known. There are however some issues to using this type of observer with PMSM, in addition to the cogging torque [3], stability at low speed is also a problem, since the observer is based on reconstruction of the back-EMF signal of the motor [4]. Since during startup the motor transitions from a standstill to the commanded speed, there is a range of operation where the back-EMF signal is either very small or nonexistent, therefore the observer cannot converge on the actual rotor angle and motor operation can be unstable. This introduces even more instability when a slow ramp command is used as it keeps the motor operating in the low speed range for a longer time. The proposed start-up procedure in this paper enables motor start with such ramp commands.

II. Motor Control

A. Field Oriented Control

The motor drive is based on a TMS320F28027 microcontroller from Texas Instruments C2000 series and a low voltage three phase inverter. Fig.1 shows a basic block diagram of the process used to verify and test the control strategy. The control algorithm is first realized in a Simulink simulation without using any special function embedded blocks. After that the model is adapted for the microcontroller using Simulink Embedded Coder Support Package for Texas Instruments C2000 Processors.

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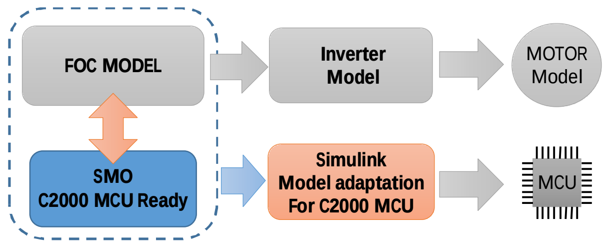

Fig. 1 Verification process of the proposed control strategy

The used motor is a PMSM with exterior mounted permanent magnets. The equation for electromechanical torque of this type of motor is:

$$M_e = \frac{3}{2}p(\Psi_f I_q + (L_d - L_q)I_d I_q) \tag{1}$$

Where:

M_e – electromechanical torque

I_d – direct component of the current vector I_s

I_q – quadrature component of the current vector I_s

L_d, L_q – direct and quadrature component of inductance

Ψ_f – rotor flux linkage

p – pole pairs

Since this is a non-salient PMSM and $L_d \approx L_q$ the equation gets reduced to:

$$M_e = \frac{3}{2}p\Psi_f I_q \tag{2}$$

As obtaining torque in this type of motors is only dependent on the quadrature component of the current I_q, to obtain maximum efficiency the direct component I_d is controlled to be $I_d = 0$

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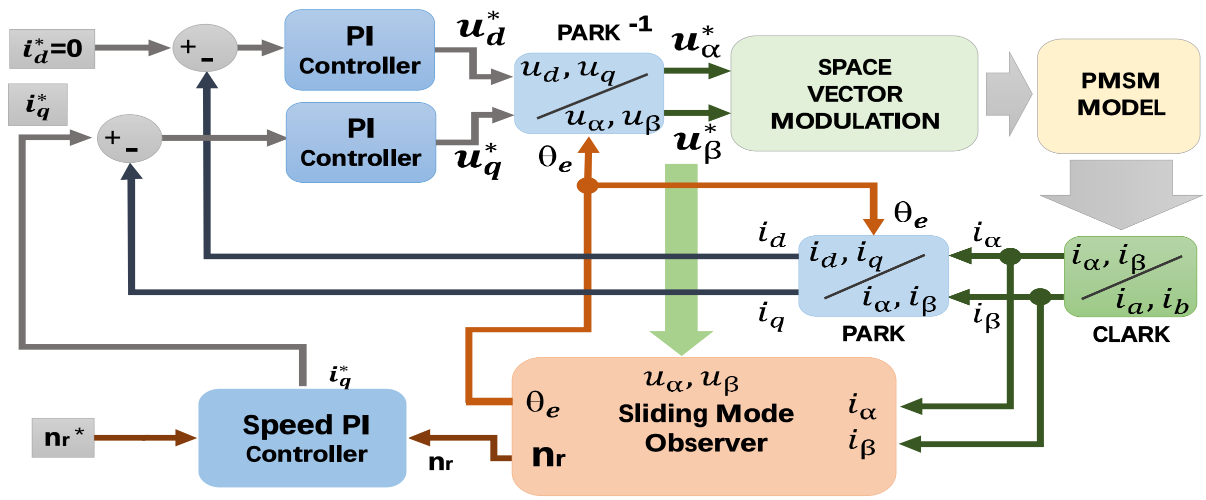

Fig.2 Block diagram of the field oriented control algorithm

To be able to do field oriented control, that is to control currents I_d and I_q, the system measures the stator phase currents I_a, I_b of the motor and converts them to I_d and I_q using the Clarke and Park framework transforms. The Clark transform (3) is used to calculate currents in the two-phase orthogonal stator frame I_α and I_β. This two-phase α-β frame is fed to the Park transform (4) where it's rotated over an angle θ to follow the d-q frame which is aligned to the rotor flux.

$$\begin{cases} i_\alpha = i_a \\ i_\beta = \frac{1}{\sqrt{3}} i_a + \frac{2}{\sqrt{3}} i_b \end{cases}, \tag{3}$$

where $i_a + i_b + i_c = 0$.

$$\begin{cases} i_d = i_\alpha \cos\theta + i_\beta \sin\theta \\ i_q = -i_\alpha \sin\theta + i_\beta \cos\theta \end{cases} \tag{4}$$

After that the currents are controlled using proportional-integral (PI) controllers to get a voltage vector, which is then recalculated back into the α-β frame using the inverse Park transform and fed to the space vector modulation block to set the inverter state.

Since this is a sensorless field oriented control implementation angle θ is not measured by means of a physical sensor, but instead it's calculated using a mathematical angle observer (Sliding mode observer) based on reconstruction of the back-EMF signal of the motor. Fig.2 shows a block diagram of the FOC part of the control system with the inclusion of a speed PI controller.

B. *Simulink Simulation*

Fig. 3 shows results from a simulated startup, as well as loading, with two different speed command profiles and no startup procedure. The first speed profile is a step command and the second one is a ramp. It can be seen that with proper parameter selection for both the observer and the current controllers the motor can start with a step command and the observer can converge on the rotor angle without a problem since the low speed region is quickly transitioned. However for the second profile, where a slower ramp is used, the observer fails to track the rotor angle at low speed and instability is observed. It should be noted that all PI controllers and the SMO parameters are kept unchanged for both startups and modifying those doesn't improve the ramp start in a significant and repeatable way.

The strategy implemented to overcome this issue is instead of initially using the observer angle feedback, to use preset ramps for both angle θ and the commanded current until the motor can spin up to a set point, where the SMO angle feedback can be reliably enabled. This in essence can be compared to open loop V/f control. Although the angle is fed into the system in open loop, the current still gets measured and converted to a d-q reference frame, based on the open loop angle and is controlled using PI controllers. Before the open loop startup the rotor is initially oriented by injecting a static current vector for a set period of time. After that the motor is ramped up until a set point where the SMO angle feedback is enabled. In the case of the used motor the observer can be enabled at about 20% of the rated speed. Fig.4 shows such a startup in simulation and the whole process can be broken down into 3 steps:

1. Injecting a static current vector - After injecting the static vector the current ramps up at a fixed rate and the rotor moves slightly to orient itself to the static field created by this vector.

2. Open loop ramp up - After a slight delay required for the rotor to settle, the motor is spun up in open loop using a predefined ramp for both angle and current.

3. Enabling the observer - Once the motor reaches a predefined speed threshold the system enables the SMO and takes angle feedback from the observer continuing to accelerate with the predefined speed ramp.

C. *Simulink model adapted for a microcontroller*

Fig. 5 shows the top level block diagram of the Simulink model of the control algorithm after it was adapted to run on a microcontroller. The adaptation consists of converting the entire model to discrete time as well as dimensioning all variables into a fixed-point format and then rescaling them. In addition to that all relevant peripherals used by the microcontroller are added to the model.

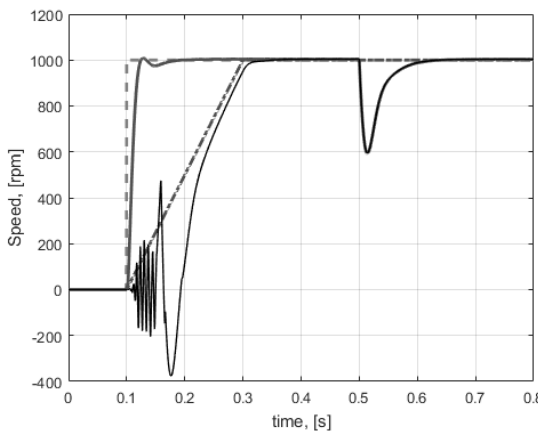

Fig. 3 Simulated step and ramp start-up without the procedure

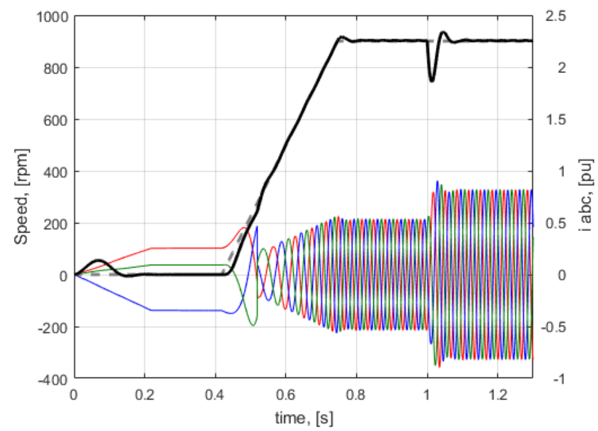

Fig. 4 Simulated ramp start-up with the procedure

The main subsystems of the model are the "FOC", "Speed Controller" and "Ramp Generation / Speed Command". In addition to that a few memory allocation blocks are used to reserve memory space for logging speed, angle and current signals as well as setting various parameters such as PI controller and SMO gains.

The FOC subsystem of the model consists of an analog-to-digital converter (ADC) sampling blocks used to sample the phase currents of the motor I_a and I_b, the SMO, PWM generation, the Clarke and Park coordinate transformations and I_d and I_q PI controllers. The FOC block is being asynchronously triggered by an interrupt generated from the PWM peripheral that runs at 20kHz. This interrupt triggers an ADC conversion and once the conversion is done the rest of the algorithm gets executed. Both the "Speed Controller" and the "Ramp Generation" blocks run significantly slower at a fixed rate of 100Hz. Fig. 5 also shows the dialog used to set the ramp parameters for current and speed as well as parameters for initial rotor orientation. While the speed is set in rpm it is later integrated to get an angle signal in rad/s for use with the d-q transformations inside the FOC block.

III. Experiment

After adapting the model and generating code for the microcontroller using Simulink's code generation tools the hardware board was programmed and several experiments were conducted. Scope captures of speed and current of two ramp startups with different current ramp parameters are shown on Fig.6 and Fig.7. The one on Fig.6 is a successful start where the parameters are experimentally optimized over the course of several startup iterations, while the one on Fig.7 is unstable since the initial current of the ramp isn't enough. Both too low and too high starting current can produce similar results and cause the startup to be unstable.

After the initial rotor orientation the open loop ramp speeds up the motor and when the speed command reaches the threshold set by the "SMO Enable" parameter, the algorithm sends a signal to enable the observer feedback, while still maintaining the speed ramp command as a reference. At the same time the current ramp is disabled. This is a critical part of the control strategy as it introduces a transient. This transient is due to the fact that there is always

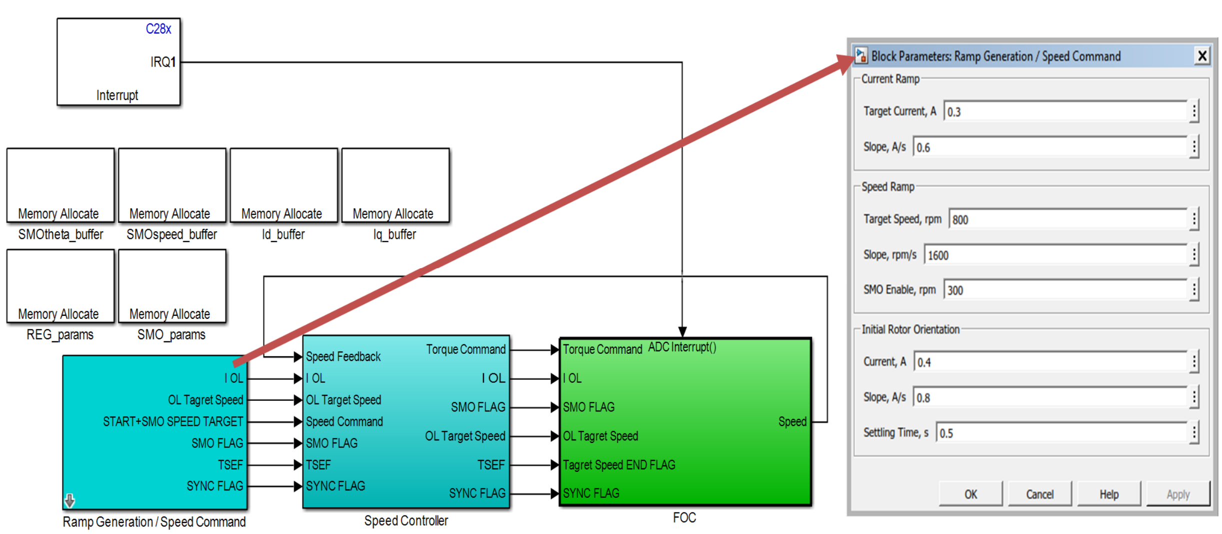

Fig. 5 Top level diagram of the adapted Simulink model ready to be programmed on a microcontroller.

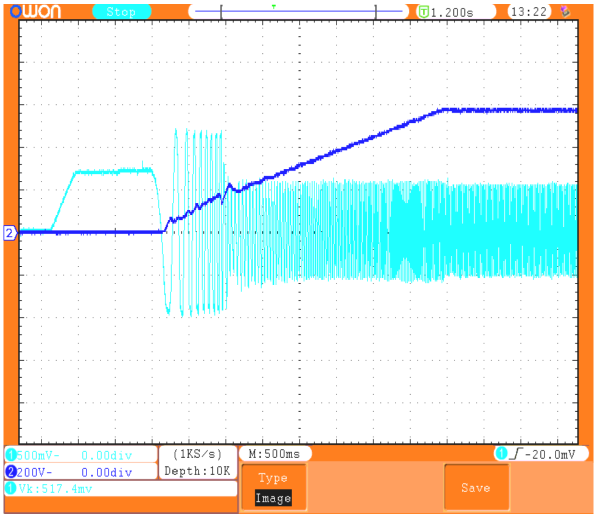

Fig. 6 Scope capture of a successful ramp start

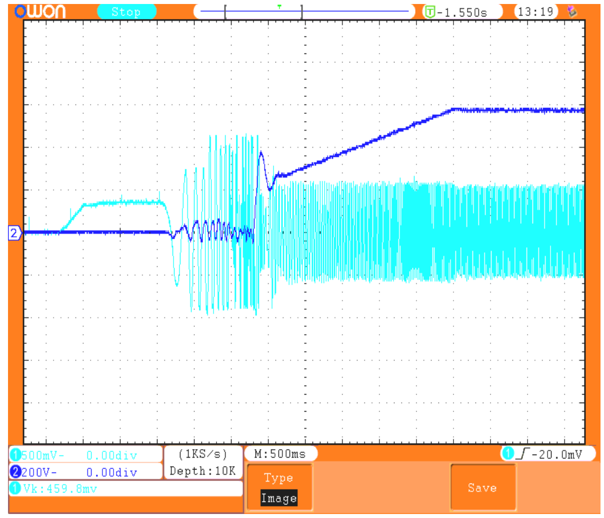

Fig. 7 Scope capture of an unstable ramp start

some phase misalignment between the open loop angle command and the angle from the observer. Due to this phase error once the system transitions to the SMO angle feedback the d-q framework is shifted rapidly causing a transient both in the speed and the current. Fig.6 also shows that after transitioning to the SMO feedback the current amplitude decreases quickly. Since before the transition the d-q reference frame is misaligned, there is some amount of excess current set by the current ramp that also includes an I_d component which is unnecessary. As the d-q frame gets aligned to the proper position the FOC can optimize the current vector, while also maintaining just enough I_q to achieve the torque demand. This results in reduction of the overall current consumption by the motor. Fig. 8 shows a zoomed in scope capture of this transient where the ramp parameters have been intentionally upset to better show the entire process.

Reducing this transient is currently done by experimentally adjusting the ramp parameters. A better way to manage this unwanted effect is basis for future work. One way to realize this is by using some adaptation mechanism such as an additional hysteresis controller with variable gain changing, based on the error between both angles. That way the open loop angle can be slowly corrected to converge on

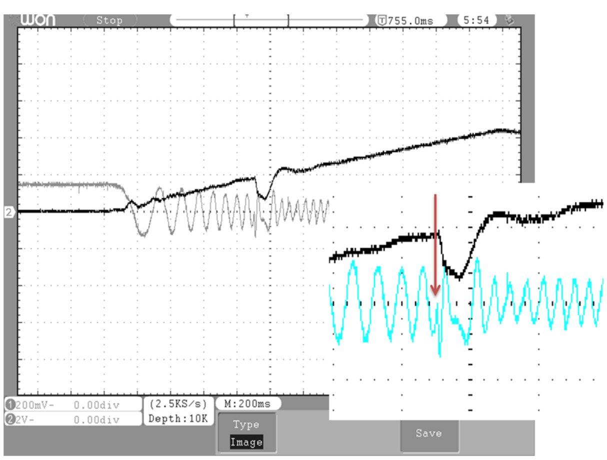

Fig. 8 Zoomed scope capture of the transient between open loop and SMO

the SMO angle before the transition between the two happens. In addition to that the open loop current ramp should also be controlled in a similar fashion. This in turn will make it so that the d-q reference frame will only have to shift a little or none at all. It should be noted that even with this transient present in the procedure, the system is still stable and successfully ramps the motor every time.

IV. Conclusion

This paper discusses an approach to enable ramp start in sensorless field-oriented control with a sliding-mode observer for PMSM. First the system is realized in simulation for verification after that the simulation model is adapted for a microcontroller. After successful implementation on hardware results from experiments are shown to prove the workability of the proposed procedure. The issues arising from this implementation such as unwanted transients and the need for manual selection of parameters over several experimental iterations are also mentioned as well as a method for possible future optimization of such systems.

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