Reducing the transient in switching from scalar to field oriented control for smooth ramp start of a permanent magnet synchronous motor

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***Abstract*— An important practical issue in sensorless field oriented control is smooth ramp start of the motor. The most common observers used to determine rotor position and speed are based on an error calculation between measured and calculated currents. Using this error the back-EMF of the motor can be determined and from there the rotor position can be calculated. The main issue in this type of rotor position observers is that at zero speed the back-EMF of the motor is zero and at low speed the ability to measure current and calculate back-EMF can be limited depending on hardware and software. When using step commands low speed operation is quickly transitioned and the position observer is able to track the rotor properly. However during a slower start due to a high inertia load or a ramp start the transitioning through the critical speed region can be a problem. This paper proposes an approach to allow reliable ramp start of a PMSM motor with a sensorless field oriented control drive using a sliding mode observer to track rotor position.**

Keywords—permanent magnet synchronous motor, field oriented control, sliding mode observer, ramp start, transient

I. Introduction

In many applications that do not require high dynamics of the drive such as pumps, compressors and ventilation [1] simple sensorless field control algorithms can be implemented with great success. However abrupt motor start is not recommended and speed ramp profiles with parameters depending on the application are used. Ramp start provides several advantages – reduced inrush current, reduced mechanical transients, reduced energy consumption in applications that require frequent on-off cycles.

One of the most popular methods of calculating rotor position in sensorless field oriented control is by implementing a sliding mode observer(SMO). This type of electrical drives provide great characteristics for speeds above 10-20% of the rated motor speed. At low speed however a different solution is required. Depending on the required dynamics several techniques can be applied. In the case of motor control for pumps, compressors and ventilation the method used starts the motor in scalar, open-loop control and switches to field oriented control once the motor ramps up to a predefined speed. Usually the predefined speed is about 10-20% of the rated motor speed and depends on hardware and software specifics. This hybrid, scalar – field oriented control strategy is published in [1]. The current paper addresses issues related to the transition between the two modes of operation proposing an approach to adaptively synchronize the two. Currently the algorithm is experimentally implemented and future work is planned to expand the capabilities of this method for drives with higher dynamics requirement and greater loads at low speed.

II. Step response and ramp start in sensorless field oriented control

A. Ramp start with SMO

Sensorless field oriented control with SMO provides an excellent opportunity to implement a control system with speed feedback when low speed or precise position is not required. In a wide range of motor control applications a smooth start as well as speed regulation and high energy efficiency is required making the use of field oriented control with a PMSM very convenient. Direct step command and a ramp command when using FOC with SMO is demonstrated on the scope captures in Fig.1 and Fig.2. It should be noted that all parameters of the control algorithm are kept the same in both cases. Initial rotor orientation (IRO) is shown on Fig.2 following it is a ramp start with the speed feedback form the SMO enabled. Initially the rotor is oscillating out of control and at some point in time the observer finally manages to converge on the proper rotor position. It's important to note that this process is not repeatable and while some of the starts

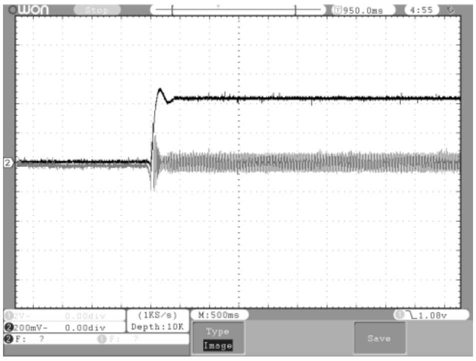

Fig.1 Current and speed in a step command start

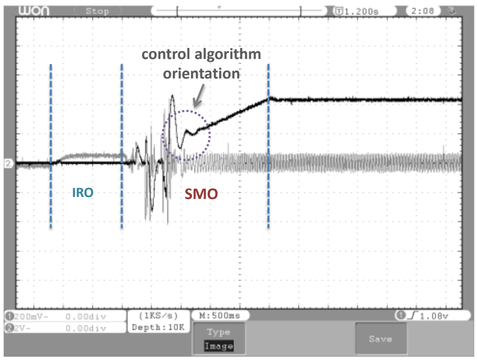

Fig.2 Current and speed in a ramp command start

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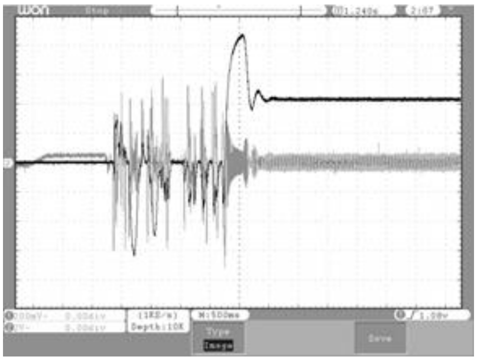

Fig.3 Current and speed in an unsuccessful ramp start

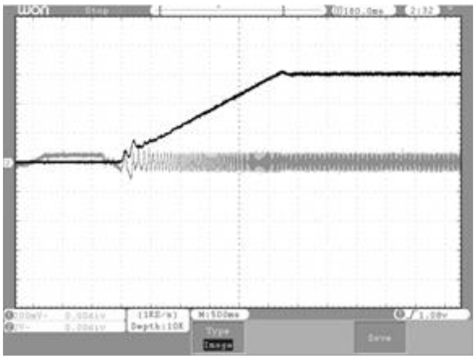

Fig.4 Current and speed in a rare case of a successful

successfully manage to enter convergence often the ramp up start fails altogether.

Fig.3 and Fig.4 show such extreme cases where one of the ramp commands is highly unstable and fails to start the motor smoothly and the other one is seemingly stable.

B. Sensorless field oriented control and low speed issues

To better explain the need of special measures for low speed operation one has to look at a simplified permanent magnet synchronous motor Fig.5. If we consider zero torque operation at zero speed as a starting position it can be said that the stator flux is static. In this case the rotor orients itself to this magnetic flux and it becomes fixed to it – hence no torque is produced. On Fig.5 the stator of the motor is represented as a permanent magnet. If a mechanical torque is applied to the rotor to move it (and its flux vector) at an angle exactly 90° in respect to the stator flux the motor would resist with a maximum electromagnetic torque. It can be said that in field oriented control the concept starts from the position of the motor at which the angle of the rotor flux with respect to the stator is always 90° as to produce the maximum torque possible.

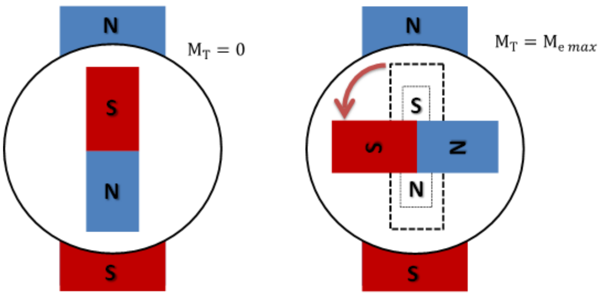

Fig.5 Simplified permanent magnet synchronous motor

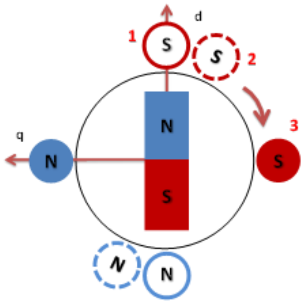

Fig.6 Simplified field oriented control concept

Let's assume that the stator field is rotating instead of being static. In a general field oriented control application the stator flux is controlled in such a way as to not magnetize (loss of energy as the rotor is already a permanent magnet one) or demagnetize (also known as field weakening) the rotor, meaning perpendicular at exactly 90° in relation to the rotor flux Fig.6.

It's no coincidence that field oriented control can produce maximum torque at zero speed. Since the rotor is static the induced back-EMF in the stator coils is zero. This allows the use of the entire voltage supply which makes it possible to inject the maximum allowed current through the stator windings. As this current is controlled to be entirely torque producing the maximum torque is produced. As the speed of the rotor increases the voltage differential between the supply and the back-EMF gets smaller and the maximum possible current drawn by the motor decreases.

This concept clarifies the main problem of sensorless control at low or zero speed. In order to maintain zero position the rotor position must be exactly known. One of the approaches to determine rotor position is based on current measurements and calculation of back-EMF in the stator windings. This of course poses a problem at low or zero speed as there isn't a significant back-EMF to be calculated.

Various solutions to this problem exist, one of which is to work with scalar control (open loop without speed or angle feedback similar to V/f control) near zero speed, especially when the exact rotor position is irrelevant for the application, and rather, it is important to have stable low speed transition until useful feedback from the observer can be obtained. Once meaningful angle information can be obtained from the observer the algorithm can switch to field-oriented control.

Applying such a hybrid switching algorithm however has one fundamental issue which is shown on Fig.7, Fig.8 and Fig.9.

The startup procedure begins with the application of a static stator field in order to initially orient the rotor. This is

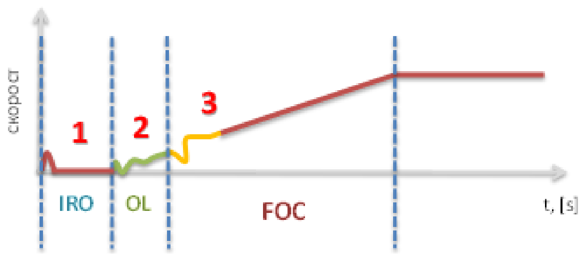

Fig.7 Switching between scalar and field oriented control during a ramp start

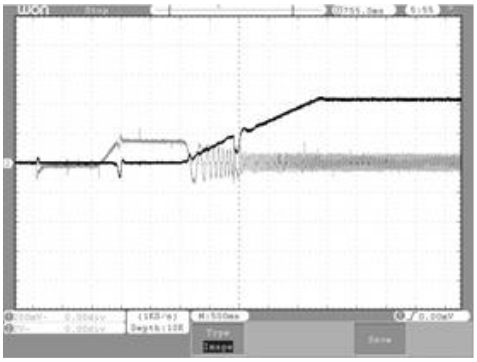

Fig.8 Scope capture of the transient in speed and current

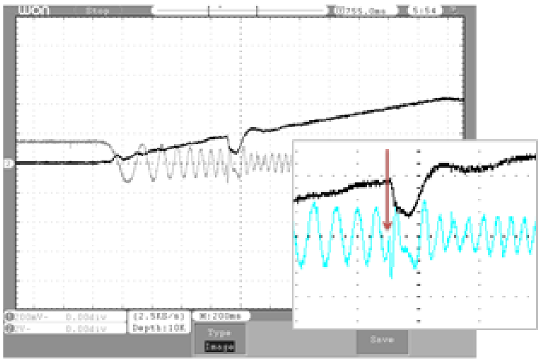

Fig.9 Scope capture of the transient in speed and current for a another startup

position "1" designated as IRO (initial rotor orientation). After applying an increasing angle and current commands in open loop the drive starts ramping the motor and depending on the static torque, cogging torque [2][3], inertia of the load and the current ramp setting, variations of the speed can be observed – position "2" OL (open loop).

The main contribution to this oscillation is from the cogging torque as for applications such as pumps, fans and compressors the initial load at low speed is negligible.

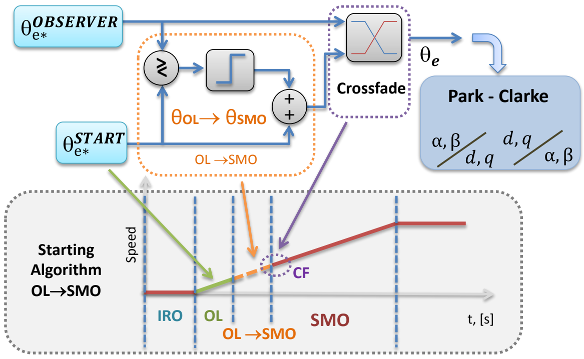

Fig.11 Rotor angle synchronization

Once the rotor reaches a predetermined speed at which the observer can give adequate position signal the algorithm switches from scalar (OL) to sensorless field oriented control (with SMO) .This instant switching between the two modes of operation causes the issue and the transient observed on Fig.8 and Fig.9 as it corresponds to rapid transition from position "2" to position "3" as shown on Fig.6. In practice the transient is somewhat random and changing filters, PI controller parameters or SMO parameters doesn't improve it.

For certain applications this transient may have little impact and practice has shown [1] that the method is applicable. The present work however raises the question of eliminating it in order to start the motor smoothly. The approach proposed is based on gradual synchronization of current and angle commands between both control methods such as to only switch to field oriented control once the error between the two is small enough which in turn removes the transient.

III. Synchronization between Scalar and Field Oriented Control during the Ramp Start Procedure

The block diagram of the proposed control system is shown on Fig.10. The diagram is based on the one reported in [1] and the additional synchronization procedure was added.

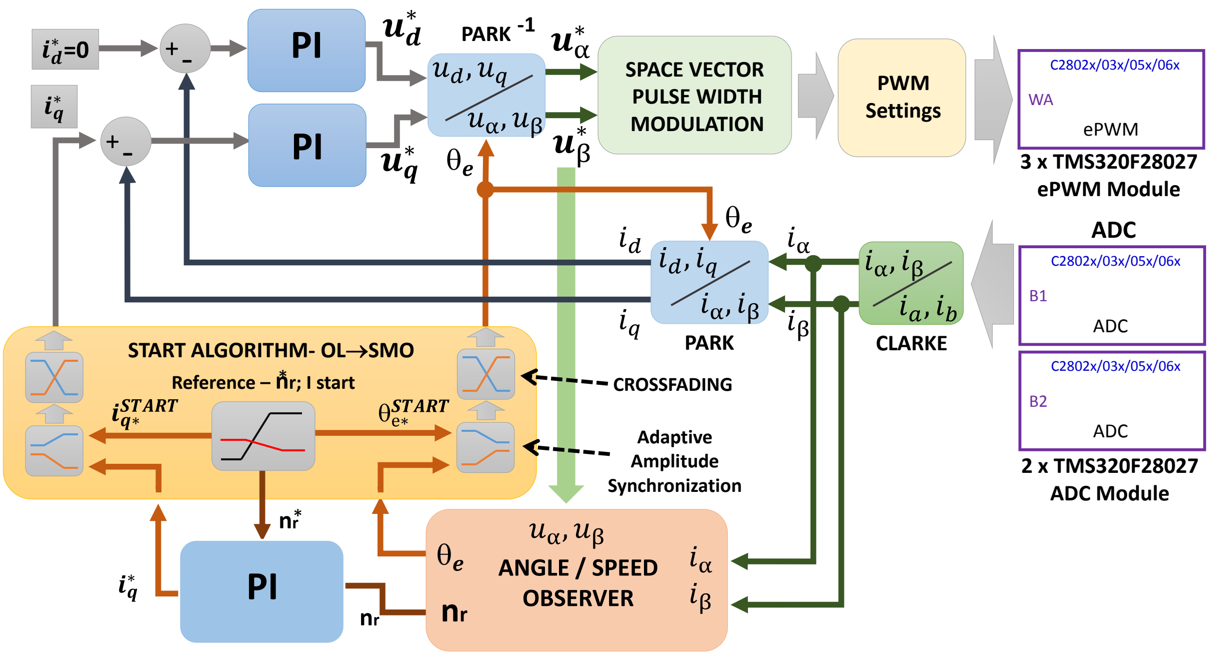

Fig.10 Block diagram of the control algorithm

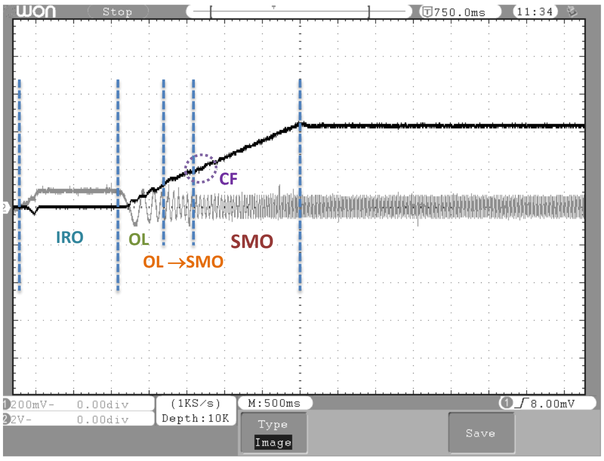

Fig.12 Scope capture of a ramp start with the procedure

The synchronization is designated as OL -> SMO on the diagram and is shown more in depth on Fig.11

There are two criteria determining the switching timing:

- Amplitude synchronization of the current set by the start procedure and the current obtained from the speed controller output based on the observer, which is operating outside of the control loop.

- Phase synchronization of the angle set by the start procedure and the angle obtained from the observer.

This additional synchronization logic produces a smooth transition from scalar to field oriented control and is confirmed to work well both in simulation and in practice

The algorithm shown on Fig.11 is implemented a second time for the current command. It should be noted that only the torque producing current I_q is being synchronized and I_d is kept zero at all times.

The whole synchronization logic is added inside the startup procedure as an additional algorithm. It's shown as OL->SMO (open loop to sliding mode observer) on Fig.9. The algorithm simultaneously adapts the angle and the current between both modes of operation using a hysteresis controller with variable gain. Once the error is small enough an additional "crossfade" operation is performed to reduce the error even further.

Fig.11 shows experimental scope capture of ramp start with the proposed synchronization.

Comparing Fig.8 and Fig.9 to Fig.12 the positive effect of implementing this synchronization mechanism in the start-up procedure is obvious.

Currently the ramp startup procedure works successfully and the startup current is set depending on the initial loading torque requirement. Basis for future work is the optimization of this algorithm as to achieve more stable operation in the open loop region. Instability in this region is mainly due to the cogging torque present in this type of motors (surface mounted magnets). Previous research on cogging torque [4][5] show that the effect is strongly exhibited at speeds about 5-10% of the rated speed. Eliminating the stability issues in the OL zone would require a start up with larger current to counteract the cogging torque easier. Higher current startup however keeps the rotor close to position "1" shown on Fig.6. This puts an additional requirement for a more precise adaptation of the algorithm to transition the rotor flux to position "3".

IV. Conclusions

This paper discusses an improvement to the start-up procedure proposed in [1] for permanent magnet synchronous motors with surface mounted magnets. The transient due to switching between the two modes of operation (scalar and field oriented control) was removed by implementing an additional synchronization algorithm based on hysteresis controllers that adapt both current and angle before the actual switching is done. The experimental results show that this method is usable in applications where the starting load is low and the focus of future work is improving the open loop performance to allow operation with higher inertia loads.

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