

# Cogging torque effect on motor start-up in a sensorless motor drive for permanent magnet synchronous motors

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**Abstract**— This paper deals with issues created by the cogging torque exhibited in permanent magnet synchronous motors in a motor drive with field oriented control. Experimental results are shown for both the start-up procedure and the steady-state operation of the used motor. The static and cogging torque are also measured at low speed to optimize the parameters of the start-up algorithm.

**Keywords**— *Electrical Drive, Cogging Torque, Field-Oriented Control, Sensorless, Vector Control, Permanent Magnet Synchronous Motor*

## I. INTRODUCTION

This paper discusses the effect of cogging torque and the instability it can cause in permanent magnet synchronous motors (PMSM) during the motor start-up procedure in sensorless field-oriented control (FOC) electrical drives for industrial fan applications. The sensorless method used in the application is based on a simple speed integral algorithm. While the benefit of using this algorithm is that it requires only a few motor parameters, it cannot be applied at zero or low speed. This requires that the motor is first started using some initial ramp-up in open loop and after that the control algorithm switches to FOC. The motor type used and its specific cogging torque play a major role in the dynamics and quality of the start-up procedure.

## II. MOTOR CONTROL SYSTEM

The system consists of a fan mounted on a PMSM. The motor is driven by a programmable three-phase inverter that can adapt several different sensorless control techniques and is integrated inside the motor. The main purpose of the implementation of this control system is to replace the induction motor previously used with a PMSM drive. This leads to an increase in the overall efficiency of the entire system by about 10% [1]. The motor used for this application is with exterior mounted magnets on the rotor for technological reasons in manufacturing. While this reduces manufacturing cost it creates a significant problem in motor start-up due to the increased cogging torque exhibited by this type of motors. The parameters required for the start-up procedure are usually manually selected for each motor type and application. This paper describes an approach to assess the effect of cogging torque on the start-up procedure which would help in proper parameter selection.

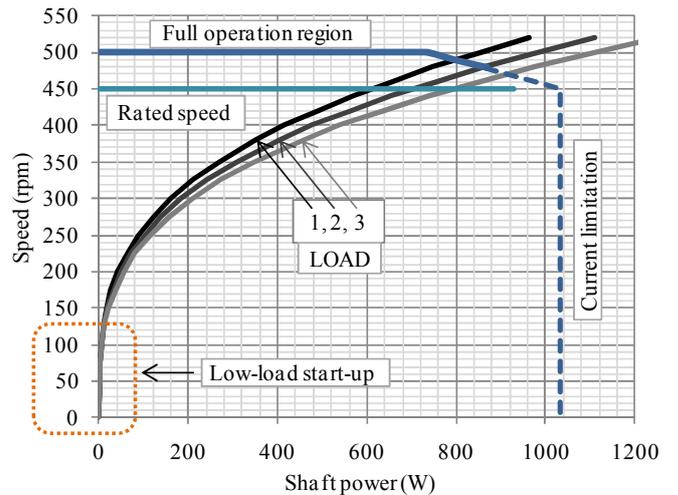


Fig. 1 Load curves and drive operation region

### A. Load curves and drive operation region

Fig. 1 shows typical static load curves for this application in different mechanical load conditions. Curve “1” represents the rated load of the fan without any external load (under-pressure). Overload of up to 30% is allowed in this specific application which is shown with “3”. The rated speed of the drive is 450RPM at 600W mechanical power. The control algorithm regulates speed using a proportional – integral (PI) regulator.

The full operation region allows a maximum speed of 500RPM and a maximum power of up to 1100W. It can be seen that at very low speeds (under 100RPM) the load from the fan is insignificant. In this operation region the torque produced by the motor is mainly to counteract the cogging torque.

### B. Field-oriented control and speed integral algorithm

The control algorithm is based on sensorless field oriented control that uses a speed integral algorithm to obtain rotor position. The rotor position is estimated by controlling the direct-axis current  $I_d$  being zero. There are four steps to this process Fig. 2. First the three phase currents ( $I_a, I_b, I_c$ ) of the motor are measured. After that the phase currents are transformed into two-phase currents ( $I_d$  and  $I_q$ ) using the Clarke and Park transformation [2][3].

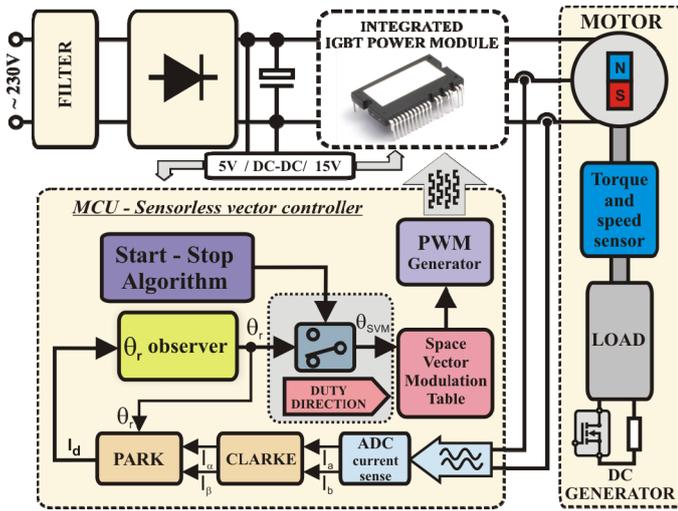


Fig. 2 Block diagram of the motor control system and a test bench

Afterwards the  $I_d$  component of the current vector is controlled to produce a speed command from a PI controller. That is the controller used to correct the current error between the actual  $I_d$  current and the reference current  $I_{d\_ref}$  which is zero. Finally the speed command is integrated to provide rotor angle information  $\theta_r$  to be used in pulse-width modulation (PWM) signal generation.

### C. Start-up procedure

The control algorithm is divided into two main modes of operation – start-up procedure and sensorless FOC Fig. 2.

The start-up algorithm requires several parameters to be selected which include duty cycle command at zero speed, duty cycle target command (at which point the algorithm switches to FOC) and acceleration rate. In most cases these parameters are determined through a manual trial and error process.

At zero speed the required duty cycle must be high enough to supply sufficient voltage to the motor to compensate for the active resistive voltage drop in the winding, the breakaway torque and the cogging torque. Winding resistance can easily be measured while measuring cogging torque can present a challenge [4].

At high speed the effect of cogging torque is greatly reduced due to the natural filtering that occurs from the shaft inertia. Cogging torque is strongly exhibited mostly at speed that is less than 20% of the rated speed. Since the speed integral algorithm cannot be applied at zero or low speed, duty cycle target must be selected to allow for a smooth transition between the start-up and FOC modes.

Acceleration rate is a parameter that determines the time it takes to reach the duty cycle target. If the acceleration time is not properly set the cogging torque ripple [5] might corrupt the speed integral algorithm angle estimation and cause it to fail.

## III. COGGING TORQUE AND EFFECTS ON MOTOR START-UP

Fig. 3 shows four start-ups with different parameters. An optimal start-up is shown where the parameters used for it allow for proper compensation of the cogging torque.

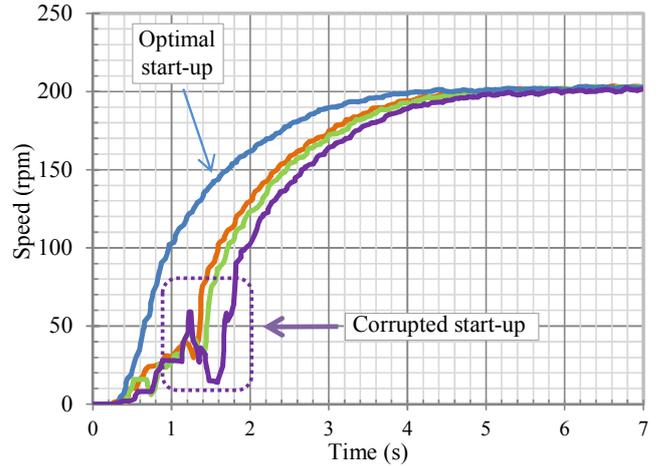


Fig. 3 Different start-ups with different parameters

In this case the FOC algorithm has adequate rotor angle information and the motor ramps up without issue. All other curves show a corrupted start-up while one of them brings a case where the motor almost fails to start.

The cogging torque in permanent magnet motors is due to the interaction between the magnetic flux from the rotor-mounted magnets and the stator teeth. It is a generally undesired effect as it produces torque ripple, audible noise, vibration and instability during motor start-up which can lead to loss of synchronism and failure to start the motor at all.

For the motor used in this application, the cogging torque is mostly notable in the speed region up to 100RPM. The amplitude is greatest in the range from 0 to 20RPM and then slowly diminishes. The best result is achieved if the algorithm switches from the start-up procedure to field oriented control at speed higher than 20RPM and under 70RPM. The switching gets degraded if it occurs at speed lower than 20RPM due to the larger cogging torque which introduces large error in rotor angle estimation.

A cogging torque measurement was performed for the used motor. The methodology used is based on a previously used strategy [6]. The test bench consists of the motor under test mechanically coupled with a drive mechanism and a torque sensor. Using the drive mechanism the shaft of the motor is slowly turned in one direction, ranging from  $0^\circ$  to about  $120^\circ$  of one full revolution and then back in the other direction up to the starting position. The torque is sensed and recorded for the entire process and a sample of it is shown on Fig. 4. It can be seen that the recorded torque consists of two components, a static torque which is constant with amplitude of 0.64Nm and cogging torque, whose ripple has amplitude of about 0.3Nm. The total initial torque required to properly start the motor without issues during the start-up procedure must be greater than both the static and the cogging torque.

Fig. 5 shows the relationship between cogging torque and rotor angular position of one of the measured samples. The whole sample is for angular displacement of  $90^\circ$  spread into three  $30^\circ$  regions. The periodic nature is easily noticeable with a  $30^\circ$  period which is exactly the area covered by each pole in this 12 pole motor.

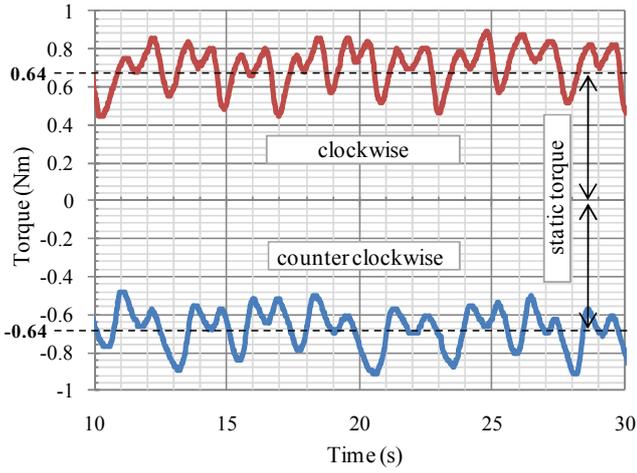


Fig. 4 Cogging and static torque sample

The shape of the curve is due to the stator slot geometry and the shape and position of the magnets. The used motor has 36 slots.

The selection of a proper start and end duty is based on knowledge of some parameters of the motor such as phase stator resistance  $R_s$ , number of pole pairs, rated mechanical torque  $M_n$  and phase current  $I_s$ .

The general equation for electromagnetic torque is:

$$M_e = (3/2) p (\Psi_f I_q + (L_d - L_q) I_d I_q) \quad (1)$$

Where:

$M_e$  – electromechanical torque,

$p$  – pole pairs,

$I_q$  – quadrature component of the current space vector  $I_s$ ,

$I_d$  – direct component of the current space vector  $I_s$ ,

$L_d, L_q$  – d and q axis inductances,

$\Psi_f$  - amplitude of the flux linkage induced by the permanent magnets of the rotor in the stator phases.

Since this is a permanent magnet motor with exterior mounted magnets it is non-salient and therefore  $L_d = L_q$  and the reluctance torque term in equation (1) vanishes.

The equation then becomes:

$$M_e = (3/2) p \Psi_f I_q \quad (2)$$

It's possible to determine the required start and end duty based on the rated current and torque.

First it's required to calculate the flux linkage of the permanent magnets  $\Psi_f$ :

$$\Psi_f = (2/3) M_e / (p I_q) \quad (3)$$

Having  $\Psi_f$  and knowing the amplitude of the static and cogging torque we can determine the required current at zero speed. The start duty parameter must be selected high enough to overcome the resistive voltage drop in the motor and to supply enough current so that the produced torque is sufficient to overcome the static and cogging torque.

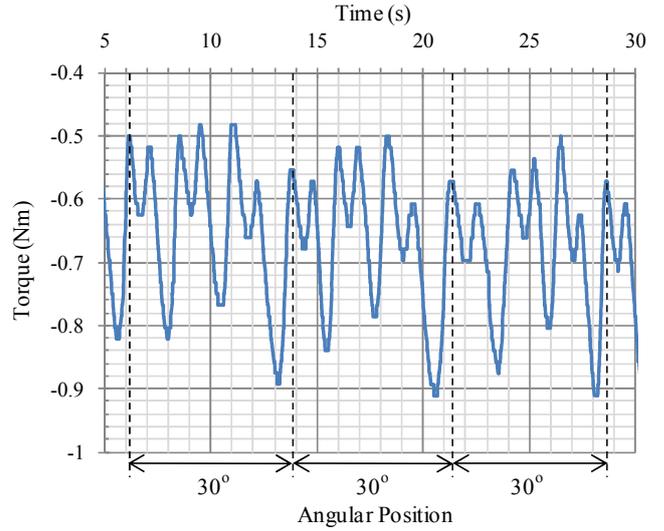


Fig. 5 Cogging and static torque in relation to angular position and time

At the same time this parameter shouldn't be selected too high above this value as it may cause the motor to fall out of synchronism while trying to ramp-up too fast. During the entire startup procedure the d-q reference frame is not yet properly aligned and the current vector contains some portion of the direct current component  $I_d$ . This must be taken into account when selecting the start and end duty to allow for enough reserve to compensate the  $I_d$  component as well. This is done by increasing the start duty by 1.1-1.5 times.

To set the end duty properly, the increased voltage requirement due to the back - EMF generated by the motor must be taken into account. The back - EMF is proportional to  $\omega \Psi_f$ . Since it is possible to calculate  $\Psi_f$  based on (3) we can determine the end duty by compensating the increased voltage requirement due to the back - EMF generated by the magnets. The relationship between the start and end duty increases linearly which corresponds to the linearly increasing back - EMF due to the increasing speed.

To further improve the proper orientation of the reference frame and because before the start-up procedure begins the rotor position is unknown, the motor is initially aligned to a specific position. This is done by injecting DC current in 2 of the phases while keeping the third one at 0V. The duty used during this process is the same as the start duty used in the start-up procedure.

To produce maximum torque it is required that the angle between the vector of the permanent magnet flux linkage and the stator flux linkage is kept 90°. In that case it can be seen that only the quadrature component  $I_q$  (2) of the current vector is necessary to produce torque and to achieve good efficiency the direct component  $I_d$  must be kept zero.

Fig. 6 shows two start-ups in relation to both speed and torque. The optimal start-up curve transitions between both modes smoothly while the moment of switching can be seen on the corrupted one at about 60RPM. The torque curve on the corrupted start clearly shows that the selected start and end duty of the start-up procedure were set too low. Therefore the torque produced by the motor was not enough to overcome the

static and cogging torque components which result in a very uncertain and noisy operation that may lead to complete start-up failure.

Unlike the characteristics shown on Fig. 3 where the motor is unloaded, Fig. 6 shows the start-up characteristics with the motor loaded. A permanent magnet DC generator is used to load the motor Fig. 2. A rated load at rated speed is set up in advance which is 10Nm at 500RPM for the motor used in this application. During the start-up the load torque increases relatively linear. This relates to harsher start-up conditions Fig. 6 in comparison to the real life application Fig.1 where the load is a fan and during the start-up procedure the largest part of the loading is the static and cogging torque.

Although the motor undergoes harsher start-up conditions on the test bench than those in the real life application the loading in the start-up region is still relatively low and does not cause issues even without changing the start-up parameters.

The proposed recommendations for start-up parameter selection yield good results which is obvious from the fact that the motor starts up reliably and smoothly both unloaded and loaded even in a harsher setup.

The overall efficiency of the drive is not affected by the start-up procedure. It can also be seen that even with sub-optimally chosen parameters the motor still operates properly after switching to the FOC algorithm.

The electronics used in this application Fig.7 are designed to be fit inside the motor, mounted on the rear bearing shield. An integrated power module is used instead of discrete semiconductors. The power module is mounted on the back side of the printed circuit board and the motor body is used for heat spreading. Due to safety requirements and protection from moisture, dust and other external influences the electronics is covered with a special electrically insulating and thermally conductive compound. There are two cables going through the back cover of the motor. One is used to connect to the power grid and the other is a signal cable used to send control signals for motor speed and direction. If the settings for motor speed and direction are fixed the signal cable can be eliminated.



Fig. 7 Electronics integrated inside the motor

#### IV. CONCLUSION

This paper presents an approach to evaluate cogging torque effect and properly select start-up parameters in sensorless FOC with the speed integral algorithm to avoid failure during motor start. The paper presents experimental results from both static and the cogging torque exhibited in the motor used in this application. The used approach for parameter selection can be adapted and used for different motors. Although this start-up procedure does not affect the motor operation once it ramps up it is key that it executes properly to allow for a stable transition to the FOC algorithm.

The drive with the selected control method and parameters performs well both in a controlled laboratory setting as well as in the real life application.

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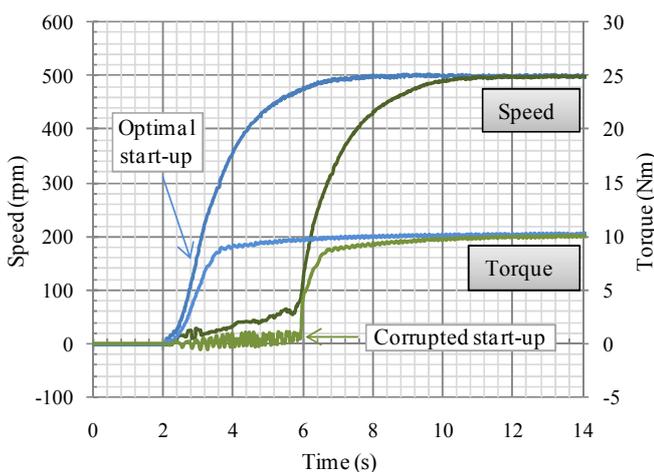


Fig. 6 Optimal and corrupted start-up procedure