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Controlling the Relative Orientation between the Two Magnetic Fields of a Synchronous Motor

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Abstract

A simple and reliable method for controlling the relative orientation between the two magnetic fields of a permanent magnet synchronous motor is presented. Finding the initial (at motor powering-up time) value of this relative location is essential for the proper operation of the motor. The utilized feedback control loop finds this initial relative orientation quickly. Further, using the proposed method allows considerable cost saving, as a transducer that is usually used for this purpose can be eliminated. The cost saving is most obvious in the case of linear motors and angle motors with large diameters. The way the problem is posed is an essential part of this work and it is the reason behind the apparent simplicity of the solution. The method relied upon a single sensor, and it has been tested when a relative encoder was used.

Keywords
Permanent Magnet Synchronous Motors, Motor Control, Linear Motors, Commutation Parameter, Torque Angle, Motor Coordinates, Feedback control.

1 Introduction

As the name suggests, a Permanent Magnet Synchronous Motor (PMSM) has one of its two interacting magnetic fields produced from a permanent magnet. This magnet is usually the rotor, and it is a long strip of consecutive poles on the machine bed in case of linear motor. The other magnetic field of the motor is produced from three phase coils.

One needs to know the relative orientation between the two magnetic fields of the motor. This is the problem to be solved in the current work. Further, one would need to position them with respect to each other in a way that would realize some criterion (usually maximum torque per coil Ampere). A hall-effect (pole-position) sensor is usually used to realize this task. This sensor, however, is expensive (it costs about $1000 in case of linear motor), temperature sensitive (which limits the operation of the motor to below 75°C [1]) and obviously needs extra space and its own special mechanical arrangement. Using an absolute encoder is also an expensive option especially in the case of linear motor.

A number of software solutions have been proposed to find this initial relative orientation. A Kalman filter has been used to estimate this relative orientation as part of the state after measuring current and voltage [2, 3, 4]. Philips Company has also developed and patented a method for finding this relative orientation when a relative encoder is used together with current sensing [5]. One can see that all of these solutions are based on a comprehensive dynamic model of one part or another of the motor. In most of the cases these models are derived based on analyzing the physics of the motor and in other cases it is based on identification techniques [6].

After testing these solutions, we believe that the one presented here is by far the simplest and most reliable one. Reliability here is critical, as failure of the solution means instability of the machine, which can cause destructive damage. The simplicity of the proposed method stems from the adoption of system input-output point of view rather than involvement in the physics of the motor. This initial relative location under scope (or a scaled version of it) is expressed eventually using a parameter, which is usually known as the commutation parameters. The solution presented here is also extremely intuitive.

2 PMSM as a System

Usually motors are controlled after analyzing and maybe modelling their physics. In this work a system approach is adopted. That is, the motor is viewed as a black box, the independent inputs, state variables and outputs of that box are specified and then dynamics are correlated using system identification approach after defining the constraints involved. This allows minimum involvement with the motor physics.

The system approach is commonly used in conjunction with motor identification. In this work, however, we emphasise the conceptual level of the system approach rather than the mathematical correlation between the inputs and outputs, and we...
also emphasise the subsequent degrees of freedom of the control. This will highlight the essence of the proposed solution.

Figure 1 shows the fundamental inputs to the PMSM System. These are amplitude, phase and frequency of the armature voltage. Theoretically, this should allow controlling three independent outputs of the PMSM. The state variables that are usually of interest are; torque, rotor (or translator in case of linear motor) position, armature current, armature voltage, flux, power factor angle and their time derivatives. Other state variables are local to different blocks of the figure.

In motion control, these local state variables are usually out of concern. It is not possible to control all these variables dynamically and independently though (even if they are all measured) because of the dynamic dependence among some of them. Notice that dynamic control of a certain output exclusively means control of the time derivative of that output. The main dynamic dependence is between position and torque. That is, for a certain torque-time profile, there is a certain position-time profile. Therefore, one cannot dynamically control both position and torque (or their derivatives) independently. Further, the amplitude together with the phase of that voltage are together mainly responsible for torque value, whereas the frequency of the armature voltage is mainly responsible for the dynamics of the position. Therefore, in motion control one cannot choose amplitude, frequency and phase of the armature voltage in an independent way. The frequency is usually selected to be the dependent input. This leads to the least amount of coupling between the inputs and the outputs of the PMSM. If the motor position is sensed it will be easy to derive the needed input frequency from the measured position (or actually its time-rate of change). In sensorless control a dynamic model is needed to cater for the dependence. Thus, for motion control purposes the PMSM system has only two independent inputs. It is important also to note that the dependence is between the armature current from one-side and the motor torque and flux from the other side. For a given armature amplitude and orientation the torque and the flux are completely specified.

This leads us to Figure 2. Notice that the new added loop is an artificial one, whereas the one in Figure 1 is an in-built/physical one. In fact, Figure 3 is actually the system we care about in motion control of PMSM, with the measured state variables depicted. In some cases armature voltage is measured with or instead of the armature current. Notice that if the motor’s current is regulated the commanded armature current orientation (phase) become the two independent inputs.

3  PMSM System Coordinates

This section helps us to realise the concepts discussed in the previous section. The fundamental system variables (i.e. independent/control inputs, state variables or outputs) and parameters can be expressed in terms of different coordinates. Naturally, the number of independent system inputs does not change by changing the coordinates. These inputs (as discussed in the previous section) are always two. Physically in real PMSMs they are two voltages to any of the three phases. The value of the voltage to the 3rd phase is a dependent variable. These two inputs can be defined in terms of other quantities depending on the coordinates selected.

The important quantities here are the two interacting magnetic fields. Each of them is displaced and is related to a certain rigid body. These rigid bodies are the permanent magnet and the armature coils. Therefore, for a start, the coordinates-sets selected will be fixed to either the armature coils or to the permanent magnet. Further, practically the voltages to the armature three phases are usually sinusoidal (or in rare cases other periodic) signals that have same amplitude and are equally distributed (i.e. 120 electrical degrees) in space and time. This distribution allows space rotation of the resulting volt and its consequent magnetic field. The rotation speed of the field is the same as the frequency of the sinusoids. It might be clear by now that the coil phases directions represent one relevant coordinates-set that is fixed to the armature coils. The input phase-volts mentioned above produce the rotating coil’s magnetic field. The direction of this field together with the direction perpendicular to it forms the 2nd coordinates-set. This 2nd coordinates-set rotates at the speed of the coil’s field. On the other hand, the magnetic field direction of the permanent magnet (also called the D or Direct axis) and the direction perpendicular to it (also called the Q or Quadrature axis) together form our 3rd-coordinates-set of interest. This coordinates-set is fixed to the permanent magnet.

Changing the 1st input of Figure 3 means changing the angle between the 2nd and the 3rd-coordinates-sets, or equivalently changing the angle between the 1st coordinates-set and the initial location of the 3rd coordinate-set. The transformation between any two of these coordinates and also the phasor diagrams (which provides further insight into this transformation) can be found in any book about the PMSM theory, e.g. Dubey 1990.
4 The Solution

The solution proposed is based on a number of simple first principles. These are:
- To obtain motoring effect (i.e., produce torque/torque) from two magnetic fields one needs to have an angle between the two vectors representing the direction of these two fields.

The relation between this angle and the torque is sinusoidal. That is, the maximum torque (force) generated from the interaction of the two magnetic field is realized when these fields are perpendicular to each other and no force is generated if the fields are vectorially aligned or opposing each other.
• The two relative orientations that provide zero torque (the two singularities) are different in nature. Although both represent equilibrium points. The earlier point provides a stable equilibrium and the latter provides an unstable equilibrium [7,8,9].

• If one could drive the motor to the stable point where force generated is zero, then the problem under scope is solved. At this point one would know that the two fields are aligned. Similarly, the problem is solved if one could drive the motor to the point where maximum force/Ampere is generated. At this point we know that the two fields are perpendicular.

• A search for the point of zero force is preferred, as the other point has the potential to generate more motion. This initial motion can be prohibited in some applications. For example, the machine is booted while a cutter is inside the metal, motion then will at least break the cutter.

• If one assumes that the magnetic field produced by the permanent magnet is stationary in direction, then moving the magnetic field produced by the coils should help us realize the zero force/torque situation.

• A torque (force) indicator (sensor) would ideally be helpful to close a force loop. The output of the force controller would then feed the 1st input of Figure 3 above, which will drive the system till the targeted zero force point is reached.

• As force sensors are rarely used in normal motor applications, a relative-position (or velocity) sensor can substitute the mentioned force indicator. This is a slower force indicator though, which means slower search for the sought angle. Acceleration sensor would provide a faster search, a loop with a higher bandwidth.

• The 2nd input of the system (ie the armature voltage amplitude) is to be kept at a constant value.

• On should consider the case where the system is exactly at one of the equilibrium points. The system should be excited in that case, which is to be achieved by superimposing a ramp on the 1st control signal. This ramp is to be disconnected once force/motion is detected.

• The search loop needs to have at least one integrator (type I system). This will maintain the search as long as there is a force/motion.

• When the control signal settles at a value, then the search is finished and the 2nd input is effectively injected to the D-direction discussed above.

A block diagram of the proposed scheme is shown in Figure 4. The PMSM System block is the one detailed in Figure 3.

More details need to be considered to realise a practically efficient solution. These are:

• Velocity is the feedback variable selected in this work higher order differentiation of position was noisy enough to prohibit using higher order controller.

• The 2nd input of the system is ramped rather than being kept fixed to avoid sudden motion.

• The selected control is PI. This is acceptable as the system to be controlled is not a type 2 system. These type 2 systems need higher order controllers that introduces some phase lead action [7].

• Using a state estimator and using a higher order controller can significantly reduce the amount of resulting displacement and eliminate the need for position sensor [10].

It is important to note that in case of PMSM this initial relative orientation does not need to be changed and thus the control loop proposed does not need to be activated during the normal operation of the motor. It is only active at power-up stage.

5 Experimental Validation

The afore-mentioned basic ideas could now be experimentally tested and validated. The experiments have been conducted on a linear PMSM. The motor used is from SIEMENS with model number “IFN1 124-5 F71”. This motor can provide a thrust of up to 500Kg at 100m/min, and it was actually loaded with 450 Kg. A Raineshaw linear encoder is used to measure the position of the translator of the linear motor. The distance between two gratings of the linear strip is 20µm. This means that every a displacement of 20µm the encoder head delivers two analog sinusoidal signals that are 90 electrical degrees phase shifted from each other. Therefore, the scale value (resolution) of position sensing can be 20µm, and can also be increased as much as the sampling rate, speed of motion and computation allow. The effective encoder resolution in our case was 0.5 µm.

The time for the search for the sought orientation is set to 8 second. In most cases the time needed is smaller than that, as seen form the time scale of the figures to follow. The effective search time depends on the actual initial relative orientation at the power-up time and the stiction level. Stiction level is a parameter because the search-loop is only active when motion happens. The situation is different if a force sensor is used.
Figure 5 shows the armature current during the test. The armature voltage amplitude (2nd system input) is changed from 0 to a value that would produce torque well above the stiction level. Ramping the voltage from 0 to half the supply value (600 volt in our setting) should be a generic setting. Notice that at the end of the test about 300 volts are injected while no motion is produced, so this volt must be in the D-direction.

Figure 6 shows the total displacement of the armature field (in electrical degrees) at the power-up stage during the search period. This corresponds to about 40 μm displacement (46 mm pole-pitch). The voltage orientation (1st system input) is ramped from 0 to 180 electrical degrees during the test period.

Notice that at the end of the search the injected voltage will be a D-axis voltage, and therefore, one should not leave the motor at this state for excessively long period as this produced current can cause heating. Further, Figure 7 shows the rotor (translator) displacement. This displacement is small. However, it is sudden. Figure 8 shows the velocity plot during the search period. Tuning the PI controller reduces the peak velocity and smoothes it.
6 Conclusions

The method proposed allows finding the relative orientation between the rotor (translator) field and the armature field. The method is very simple. After establishing the fact that the PMSM has only two independent inputs (which is irrelevant to many readers), one can see that the solution is very brief. The method is also very accurate, as a PI velocity controller is used.

A controller with an integrator means that zero velocity error is achieved even with given high current injected in the coils, and consequently the directions defining D and Q must be exact. The resulted motion is dependent on the resolution of the position measurement. By proper controller tuning, the total motion associated does not exceed 100 microns. In many practical applications, the resulting position motion would be satisfactory. Less motion can be obtained by using a higher order controller or a state estimator that would allow higher order derivative controller and consequently higher closed loop bandwidth. The fundamental idea is presented here though. Also, the method can be equally used with current-controlled motors. The method presented is load-independent, hence for a certain motor the tuning of the controller can happen before installing the motor within the rest of the system as long as the friction level is roughly known. Lack of knowledge of that level will merely result in less satisfactory dynamic behavior during the search period.

References

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