

Sensorless Sinusoidal PMSM Gas Compressor on MC56F80xx

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1 Introduction

The gas compressors play a unique role in the history of refrigeration. They are important in the type of refrigeration systems which uses Reverse Carnot Cycle. Historically, various kinds of motors have been used to drive gas compressors. This application note deals with an implementation of the gas compressors using the permanent magnet synchronous motors (PMSM) in field oriented control (FOC). To reach high speed of the compressor the application uses special field weakening technique patented by Freescale.

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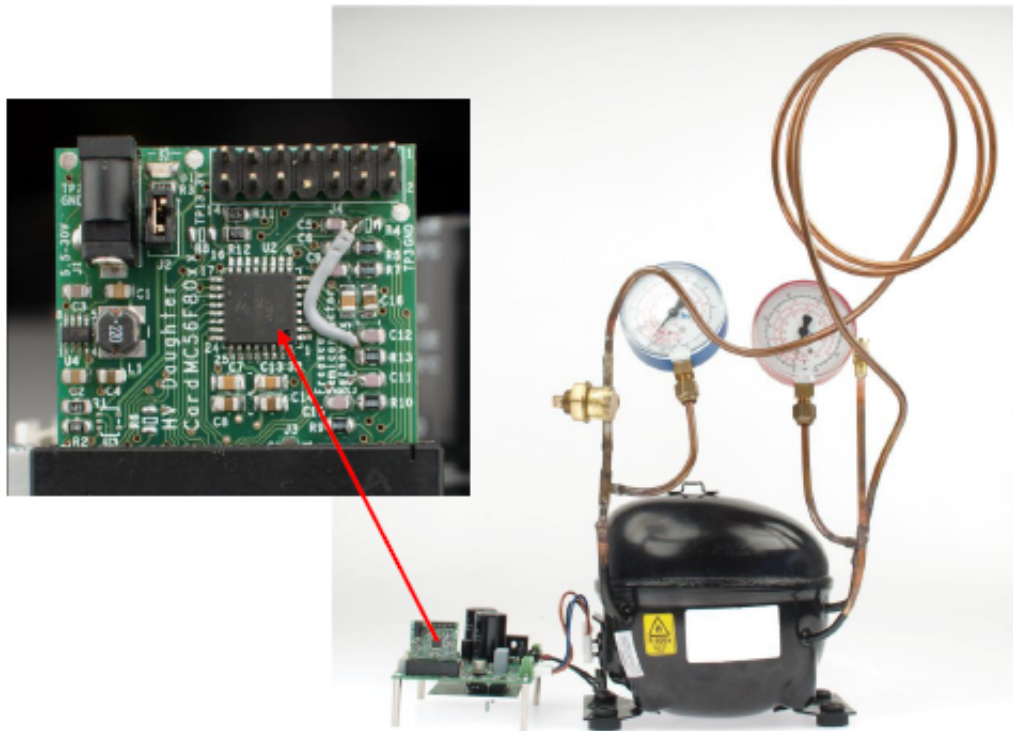


Figure 1. Freescale solution for Compressor Drive

Choosing the Freescale solution saves time as it has the chip, hardware and software.

2 Refrigeration

2.1 Principle

There are several types of refrigeration principle, this application note deals with the one which benefits from Reverse Carnot Cycle.

Reverse Carnot Cycle consists of four components:

1. Compressor – compresses gas from low pressure to higher pressure. During the compression process the gas gets hot.
2. Condenser – emits the heat from the hot compressed gas to the environment. During this process the hot gas turns into liquid of environmental temperature.
3. Expansion Valve – throttles the expansion of the liquid and keeps low pressure after the valve where the liquid expands and gets low temperature.
4. Evaporator – cold medley of liquid and gas absorbs the refrigerator heat and evaporates. As such the gas is pumped back into the compressor.

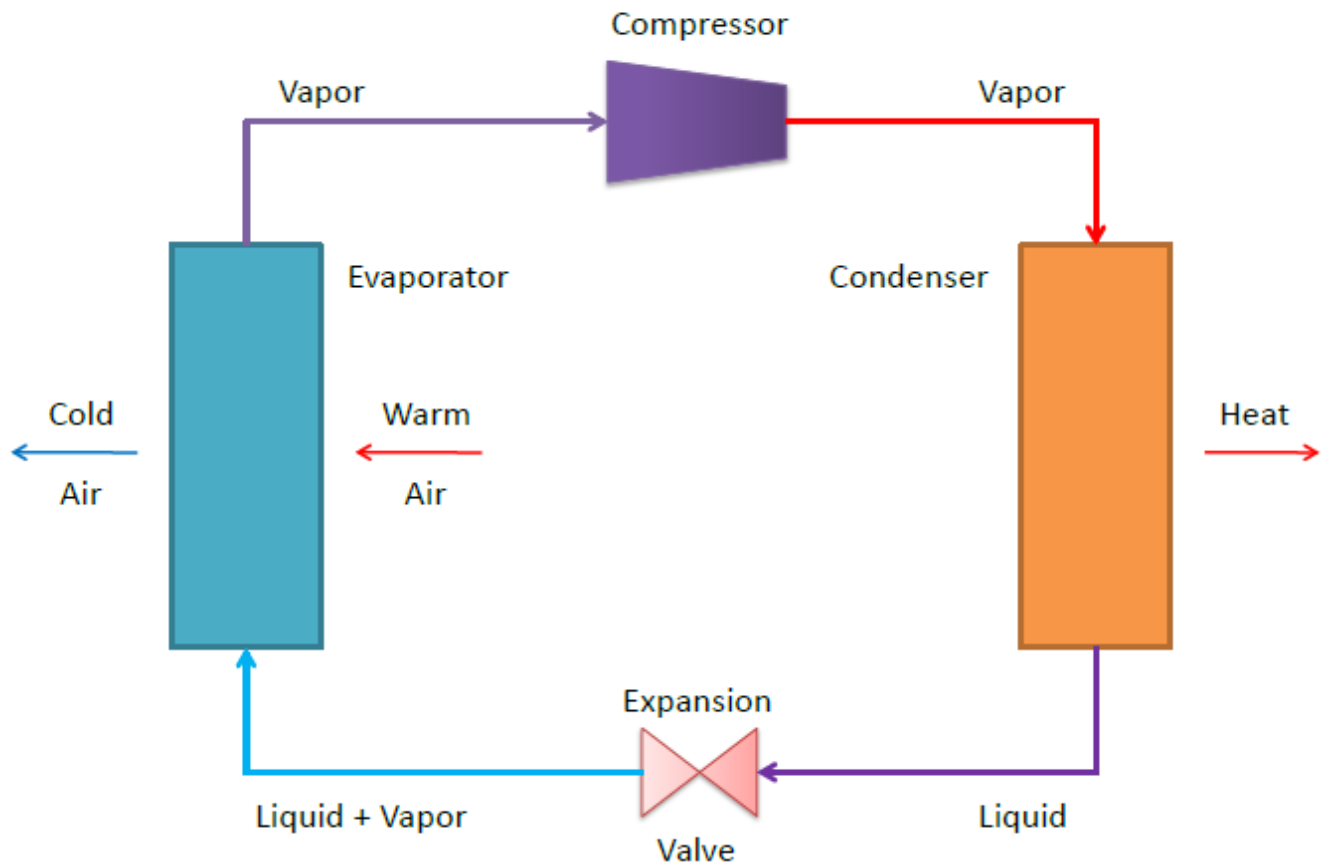


Figure 2. Reverse Carnot cycle

2.2 Compressor

The compressors are electrical motors which must pump the gas against strong load. Therefore such motors must be able to start up and work although the load torque is high. Following is a summary of the advantages and disadvantages of different types of motors used for the compression drive:

Single-phase induction motor – is a motor of winding on the stator and heavy metal so called “squirrel cage” rotor. So the cost of this motor metal will be a significant factor. The motor is connected directly to an outlet phase, so it is a very simple solution because it does not need complicated control. This point was taken in consideration for long time. Nevertheless, one phase can only create pulsing field which does not offer good starting conditions. More specifically, this field only generates torque at a certain speed, therefore no torque is generated when the motor is stopped. Another problem is that the pulsing field does not determine the direction of rotation. So to cope with this limitation it is necessary to create a starting phase which is derived from the main phase connected via a capacitor. Such phase is then shifted by 90 degrees against the main phase. Another point which can be considered as negative is the efficiency of small induction motor which is not good.

Three-phase induction motor – is from the construction point of view no different to the single phase induction motor. The only detail is that it contains three phases of winding thus it is necessary to connect it to three phase outlet. As the three phase outlet is not generally installed in the home environments, this solution is not applicable. So it is obvious that a three phase inverter is required to do the job. The existence and cost of such an inverter has avoided this kind of compressor drive for long and this motor started to be in consideration in the recent history. Finally, the field of the motor is rotating so the motor generates nice torque from zero speed until the required speed. As the previous motor, the efficiency of small induction motor is not great.

Three-phase brushless DC motor (BLDC) – is a motor of three phases of winding on the stator with permanent magnets on the rotor. In comparison to the induction motors this motor does not require much metal, that is, the motor is cheaper from this point of view. As the previous motor it also has three phases to be fed. But only two phases at a time are fed with DC voltage. The connection of the phases is altered during the spinning. Thus a three phase inverter is inevitable as well as a logic to control the motor commutation. The commutation time depends on the rotor position. But a sensor to read the rotor position can significantly screw up the cost of the system.

Simply said, to be able to go to the market with this solution, a sensorless commutation technique must have been developed. An advantage of this kind of motor is that all the time there is one phase unconnected where the BEMF can be observed. What is yet more fascinating is that we can just watch a point where the BEMF crosses a logical voltage level. Such control is easy to implement on not very powerful controllers.

As mentioned above, this motor is fed with DC voltage, that is the current is not sinusoidal and the torque is not as nice as with the three phase induction motor. Moreover, the commutation and torque ripples will generate some noise. Finally the missing position sensor reduces the start-up possibilities of the motor to only known load torque. If the start-up load torque differs too much the motor start-up fails and it is necessary for the moment when the pressure gets lower. In the other hand this motor's efficiency is far better than the induction motors. They comply with the "Go Green" initiatives as well.

Three-phase permanent magnets motor (PMS) – is a motor of similar construction to the BLDC motors. Their difference consists in the rotor magnets magnetization. The BLDC motors are magnetized to have trapezoidal BEMF while the PMS motors generate the sinusoidal BEMF. As the name says, the motor has three phases to be fed with sinusoidal voltage. But as the motor has permanent magnets it is necessary to precisely read the rotor position, that is, it is not controlled as easily as the induction motor. As with the BLDC motor, to be able to go to the market it is necessary to avoid the position sensor cost. This is not as simple as the technique used with the BLDC motors. To estimate the position of the PMS motor it is necessary to have better calculation power of the controller because the application requires calculation of the BEMF observer and the field orient control algorithms too. This factor has avoided this solution until now. One positive factor in comparison to the BLDC motor is that the motor has nice stable torque and no commutation ripples. Therefore the compressor is quiet and has yet higher efficiency. Nevertheless the start-up brings similar limitations as the BLDC motor with the difference that the PMS motors have better torque.

3 PMS Motor Compressor Drive – Sensorless Sinusoidal Vector Control

The following section focuses on the implementation of the gas compressor by means of a PMS motor drive. As mentioned above this kind of motor drive is getting into foreground in the recent times due to the decreasing tendencies of its production cost and due to the great and cost effective offer of calculation power of the controllers. So assuming these reasons and the fact the application of this motor reduces energy consumption it is an excellent choice for the "Go Green" initiatives.

3.1 Typical requirements

Let us summarize the requirements for this control:

- Sensorless FOC of a sine PMS motor – to achieve this, a powerful digital signal controller must be chosen
- Speed 3000 - 10000 RPM electrical (1500 - 5000 RPM mechanical) – the sensorless algorithm must estimate position and speed within this speed range
- Start-up torque 1Nm, running torque 0.2 – 0.5 Nm – the torque at the start-up can be high but when running it gets lower.
- Hard alignment – unknown piston position and pressure conditions. Sometimes it is necessary to wait until the pressure gets low.
- PWM frequency 10kHz – this is a compromise among switching losses, audible noise and enough samples for the sensorless control, where the ADC is synchronized to the PWM.

It is clear that a very important point is the selection of the right DSC to control such an application. Freescale offers a lot of digital signal controllers with various features. So at the first sight it can be a difficult task to choose a right controller. Following is a list of what is mandatory for such an application in terms of motor control:

- PWM – the module should offer center-aligned mode, complementary switching capability with the deadtime insertion, three-phase oriented and somehow synchronize with the ADC.
- ADC – the ADC will measure two currents at one instant, so the ADC should have two channels working in the parallel mode. It is required to measure the dc bus voltage and maybe other quantities like temperature etc.
- Timer – the timer is necessary for the PWM-to-ADC synchronization control. This peripheral should measure the time from the PWM reload (timer start) to the instant where the current is measured (ADC start). This peripheral must be able to connect to the PWM and ADC.
- SCI – this is necessary for the communication with FreeMASTER to be able to debug the application when it is developed.
- Interrupt controller – the interrupt controller must be priority-controlled to be able to avoid disintegrity of the control technique. The interrupt latency should be short.
- Core – the core must have great computation potential in terms of mathematical operations like multiply and accumulate, division, rotation, parallel instructions etc.

So, as mentioned in this list, the controller does not need to be a big die. To control this application one can start the look-up from the small controller like 56F80xx. It is necessary to keep in mind if there are additional requirements on top of the motor control applications.

Figure 3 shows an overview of the 56F8023 controller. It is observed that the controller contains all the mentioned peripherals and a powerful core for this kind of application. The memory has enough space to fit this application.

By choosing the Freescale DSC the user does not only gets the controller, the user benefits from the following options too:

- Free-of-cost online support by expert of the technical information center.
- Free-of-cost FreeMASTER real-time debugger tool download – number one tool at the application development and tuning.
- Free-of-cost Freescale Embedded Software Libraries download – a lot of math, motor control and filter algorithms which facilitate and speed up the application development.
- Free-of-cost access to reference designs, application notes, videos, and other material which is useful for the development.

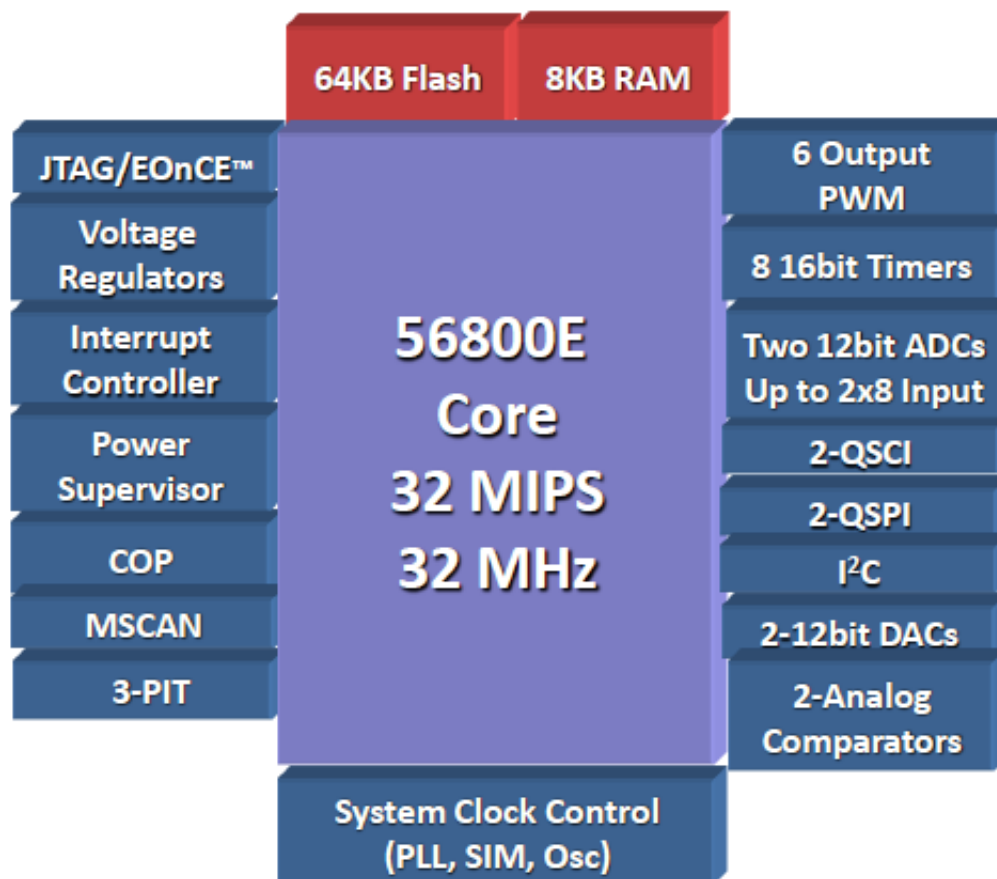


Figure 3. DSC 56F8023

3.2 Control Board

To drive the PMS motors it is necessary to have a three-phase inverter. Such an inverter has six switches (MOSFET's, IGBT's) which are controlled from the controller. The controller produces the PWM signals to modulate the desired three-phase sinusoidal voltage. This signal is amplified by gate drivers and finally led to the switches.

To drive the motor the controller needs to measure the motor current. So the board must be equipped with each phase current measurement. Simple current measurement can be made using shunt resistors at the lower switches. It is also necessary to monitor the DC bus voltage to generate correct duty cycles by the PWM.

The board must have the over-current and over-voltage protection. The protection turns off the controller's PWM outputs and protects the system and the motor against surge.

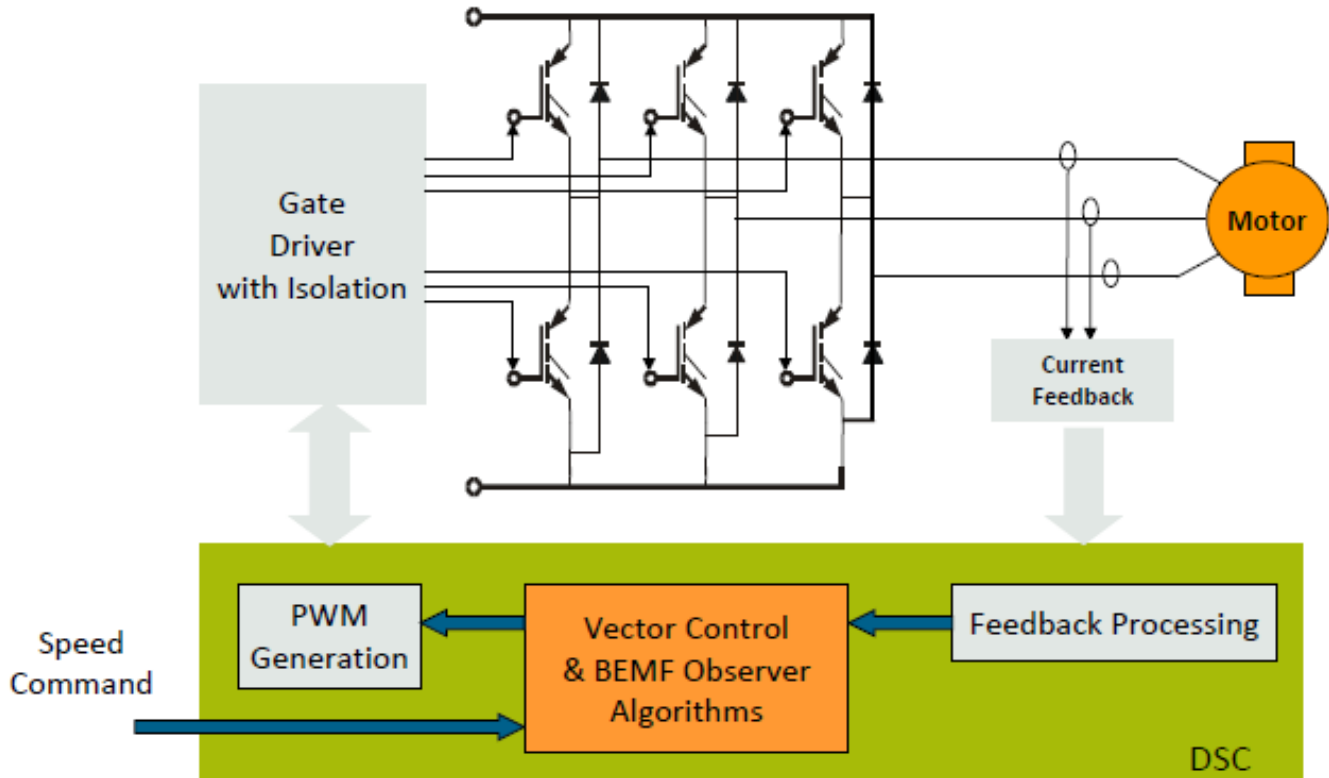


Figure 4. Motor control topology

3.3 Motor Control – Sinusoidal Vector Control

The PMS motor rotates when its three phases are supplied by sinusoidal current. The phase of each sine must be aligned to the position of the rotor to create appropriate torque. The torque is then proportional to the supplied current. But it is very time consuming to control three sinusoidal wave forms. That is why these three components are re-calculated into two components aligned to the rotor position. Then we reach two components where one controls the magnetization and the other one controls the torque, as given in Figure 5.

Finally we use PI controllers to control these two currents. The torque current desired value is given by the output of the speed PI controller. The magnetization current is kept zero until a moment when we need to reduce the strength of the field. In this case this current is reduced to negative levels, as given in Figure 5. This moment occurs when the speed is high and the induced BEMF is at the level of the DC bus voltage. In this case it will not be possible to reach higher speed, therefore reducing the strength of field, lower level of BEMF is induced. In this case the DC bus voltage has a reserve to be applied on the motor and current can be increased in the motor. Then higher speed is reached. This method of field weakening has been developed and later patented by Freescale (WO/2009/138821).

As mentioned above, the three-phase signals must be converted into the two-phase signals. To do this, a certain kind of the controller with great peripherals and computation power is required. Such good controllers are present in the family of the Freescale DSC's 56800E. These DSC's have excellent ADC which is synchronized to the PWM modulation and correct current signals are measured. Then these currents are converted by means of algorithms which are part of the Freescale Embedded Software Libraries (FSLESL) as well as the PI controllers, back transformation into the three-phase components, space vector modulation algorithms, and ramp generators and so on.

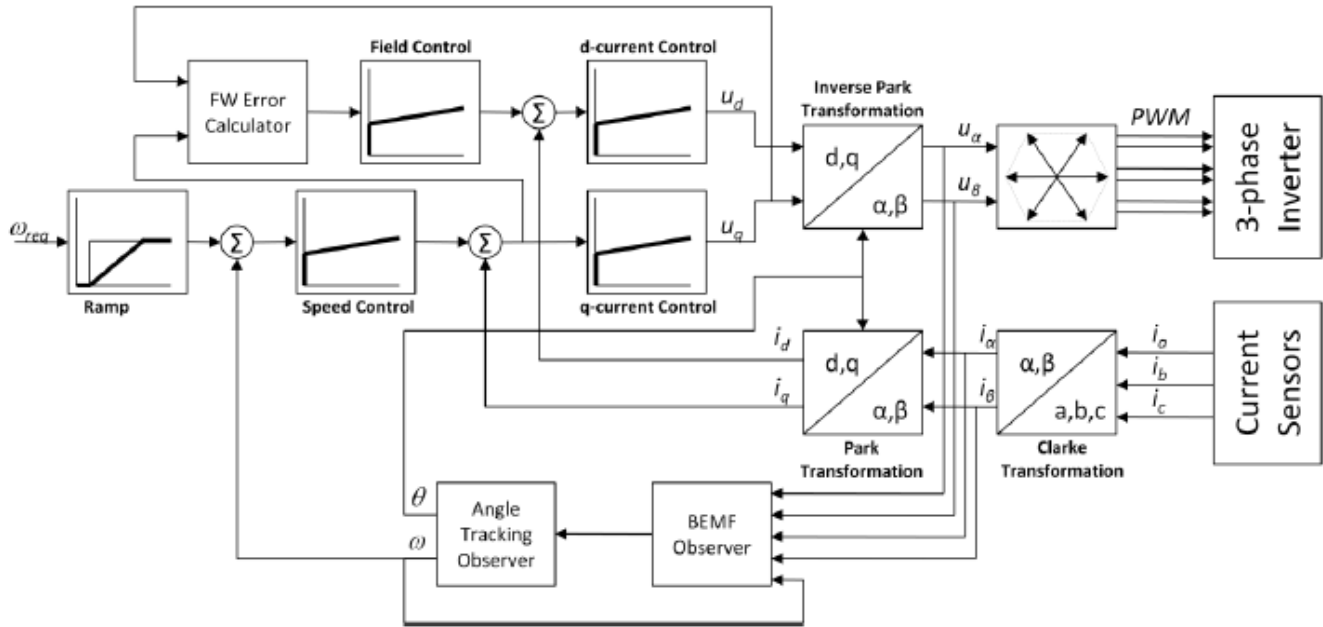


Figure 5. Sensorless Sinusoidal Vector Control

3.4 Motor Position and Speed – Sensorless Driving

The application requires a position and speed sensing to be able to spin the motor. One possible way can be a sensor. But such an application is not cheap and it will be difficult to go to the market. Therefore it is necessary to get the position and speed without the need of additional physical position sensor.

To read the speed and position, it is necessary to know the motor parameters well to calculate its model observer. The parameters are programmed into the algorithm called BEMF Observer, see Figure 7. This observer's function is to calculate the position of the BEMF, which is needed to drive the motor. The position is then passed through Angle Tracking Observer to be filtered and as a side product of this, the actual speed is as displayed in Figure 6. Its inputs are the measured current, applied voltages and speed. At this point we see that this solution requires a powerful controller which is the DSC 56800E family. The BEMF Observer as well as the Angle Tracking Observer are in the FSLESL which is supplied for free.

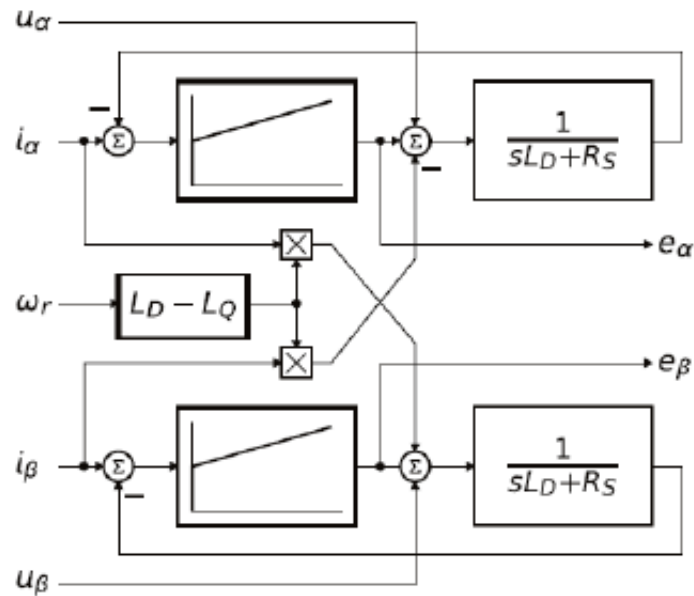


Figure 6. BEMF observer

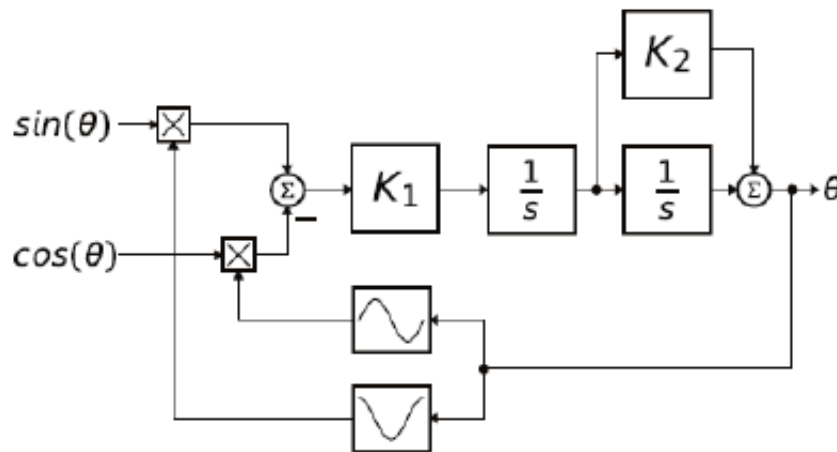


Figure 7. Angle Tracking Observer

What is more complicated is the position detection of the motor at the start-up. The BEMF observer gives the correct position from the certain level of speed. In this case it is necessary to start turning a motor with a defined torque (current) and constant ramp after the rotor alignment. When certain ramped speed is reached the speed is compared to the observer speed. If they are close to each other the system is switched into the sensorless closed-loop mode.

So to sum it up, the user can easily make a PMS motor sensorless application on the DSC 56800E family with just downloading FSLESL which already contains the necessary algorithms. Nevertheless setting up of the parameters requires knowledge in the area of electrical motors and fractional arithmetic.

3.5 Advantages of the PMS Motor

In comparison to the compressors with the induction motor where it is not necessary to recognize the position of the rotor, it seems to be more complicated to have the PMS motor instead. Although this motor control is more complicated it has certain positive points which is the higher efficiency in comparison to the induction motor; more stable torque and lower noise in comparison to the BLDC motor.

3.6 Performance of Freescale Solution

The application uses two main loops – current and speed loops. The current loop is critical and is calculated on the PWM frequency of 10 kHz. The loop has several tasks:

- Reading of measured currents and voltage and reconstruction of the current from two values into three
- BEMF Observer + Angle Tracking Observer
- Clarke and Park Transformation
- D and Q current controllers and their limitation depending on the dc bus voltage
- DC bus ripple compensation
- Space Vector Modulation
- PWM Update
- ADC configuration for the next step

The duration of the current loop has been measured as 38 μ s. The speed loop runs at the period of 5ms and is not so critical. Its tasks are:

- Speed ramp calculation
- Speed PI controller calculation
- Field Weakening algorithm and controller

The speed loop duration has been measured as 5.5 μ s. The code occupies 3165 kwords of ROM and 279 words of RAM.

4 Definitions and Acronyms

ACIM	Alternating Current Induction Motor
ADC	Analog/Digital converter
AN	Application Note
API	Application Interface
BEMF	Back Electro Motive Force
BLDC	Brush-less DC Motor
DSC	Digital Signal Controller
FOC	Field Oriented Control
Motor control	In this article, means a process which controls an electrical motor such as BLDC, PMSM, AC-induction or other
PMSM	Permanent Magnet Synchronous Motor
PWM	Pulse-width modulation
SCI	Serial communication interface
FSLES�	Freescale Embedded Software Libraries, the software tool which can be downloaded on www.freescale.com .

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