

# Sensorless Sinusoidal Vector Control of BLDC Ceiling Fan on MC56F8006

by: Xuwei Zhou

## Contents

## 1 Introduction

The first ceiling fan appeared in the early 1860s and 1870s in the U.S., and it had some up and downs in the history. It is becoming more and more popular nowadays due to rapid development of material and control techniques. For the purpose of cost, performance and efficiency, BLDC motor of outer rotor type is widely used in the market. The blades are attached to the outer rotor shell and the stationary inner stator of the motor is fixed to the ceiling using a specific mechanism.

Ceiling fans are mainly used for ventilation. Usually, in summer, the direction of the fan rotation is set so that air is blown downward. The breeze created by a ceiling fan speeds the evaporation of perspiration on human skin, which makes the body's natural cooling mechanism much more efficient. In winter, the rotation of ceiling fan is set to turn the opposite direction and on a low speed, which evens out the temperature in the room, making it cooler near the ceiling and warmer near the floor.

Depending on the application of the ceiling fan, the distance between the fan and the ceiling, and the environment where fan is installed, the direction of fan must be set to blow upward or downward to realize the specific ventilation, but not sticking to the pattern mentioned above.

1	Introduction.....	1
2	Requirements of ceiling fan system.....	2
3	BLDC ceiling fan drive—sensorless sinusoidal vector control.....	2
4	Software introduction.....	9
5	MC56F800x family of DSCs.....	11
6	Experimental results.....	13
7	Conclusions.....	15
8	References.....	15

## requirements of ceiling fan system

MC56F8006 is a low-cost but high-performance digital signal controller (DSC) which is dedicated to motor control and power conversion. This application note deals with an implementation of BLDC ceiling fan system using MC56F8006 based on vector control.

## 2 Requirements of ceiling fan system

It is essential that ceiling fans rotate in both directions with adjustable speed of wide range. BLDC motor is applied since it has high power density, and vector control technique can further improve the efficiency and reduce the noise. The total cost of the system can be reduced and reliability can be improved using sensorless technology.

Here are some key requirements of a ceiling fan system:

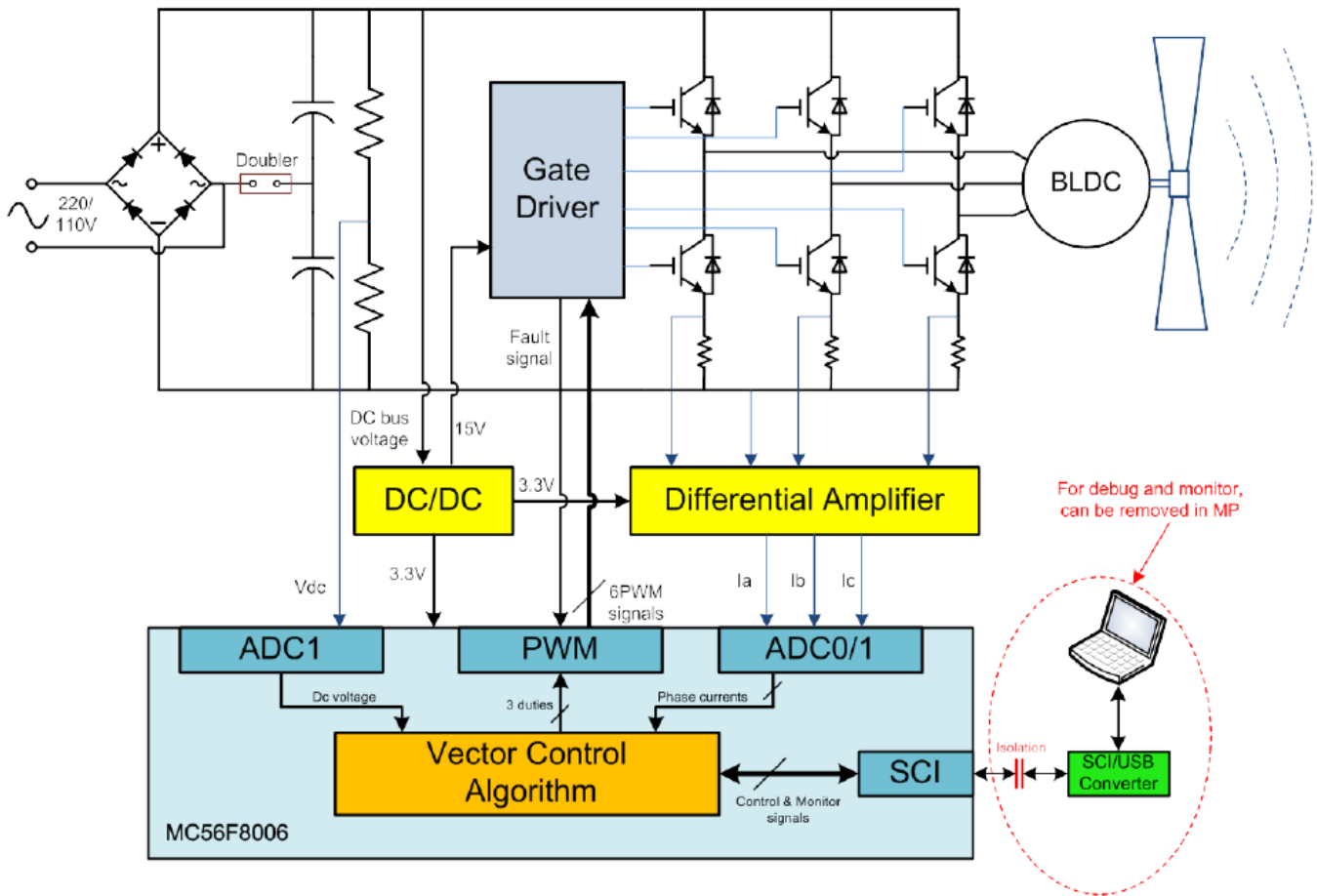
- The motor must be able to work at four quadrants with adjustable speed.
- Time of switching from counter clockwise (CCW) maximal speed to clockwise (CW) maximal speed and vice versa must be as short as possible.
- High efficiency and low noise are desired. Since fundamental part of BLDC's back electromotive force (BEMF) is much more dominating as compared to harmonics, "Id = 0" vector control strategy can be applied which leads to high efficiency, and sinusoidal phase currents contribute to smooth torque, and hence, low noise.
- Fan can be started even if the blades are still rotating freely due to inertia or breeze.
- Fan can't stop but must be able to work properly when AC input voltage is down for a couple of seconds.
- A ceiling fan system must have protection against overvoltage (OV), undervoltage (UV), and overcurrent (OC). The fan system must have the "lock of rotor detection" feature which means that the system has a mechanism coping with the situation where motor's rotor is locked due to any reason.

## 3 BLDC ceiling fan drive—sensorless sinusoidal vector control

The following section reveals the implementation of a BLDC ceiling fan system with sensorless vector control.

### 3.1 Hardware block

A three-phase inverter is used to drive the three-phase BLDC motor. The main power for the whole system comes from the outlet of 220/110 V 50/60 Hz, where voltage doubler may be necessary for 110 V input. This AC input voltage is rectified through a rectifier bridge, and DC bus voltage of the inverter comes from the output of this rectifier which is in the range of 280~320 V. A voltage of 15 V is derived from the DC bus through a DC/DC converter, which is used for inverter's drivers. And a voltage of 3.3 V is derived from this 15 V through a regulator, which is used for MC56F8006 and analog amplifier circuits. [Figure 1](#) shows the hardware block of the ceiling fan system.



**Figure 1. Hardware block of BLDC ceiling fan**

Three phase currents must be known to perform vector control. Shunt resistors on inverter’s lower legs and related amplifier circuits are used to get phase currents. Besides, DC bus voltage is also essential for motor control; it’s sampled using only divider resistors. The whole system can be controlled and monitored using FreeMASTER through SCI.

### 3.2 Motor control strategy

The whole control strategy is depicted in [Figure 2](#) and can be explained as follows.

- Three phase currents and DC bus voltage are sampled to realize vector control, or field-oriented control. Three phase currents are converted into direct and quadrature currents through Clarke and Park transformations.
- Two inner current loops calculate the direct and quadrature stator voltages required to create the desired flux and torque currents. Direct and quadrature voltages are transformed into voltages in Alpha-Beta stationary coordinate, where these voltages must be compensated per DC bus voltage.
- Three PWM duties are generated utilizing compensated Alpha-Beta voltages and SVPWM module.
- The required direct current is set to 0 since the permanent magnet of the rotor provides flux.
- The outer speed loop adjusts the reference quadrature current which is proportional to the torque. The required speed can be set through FreeMASTER interface.

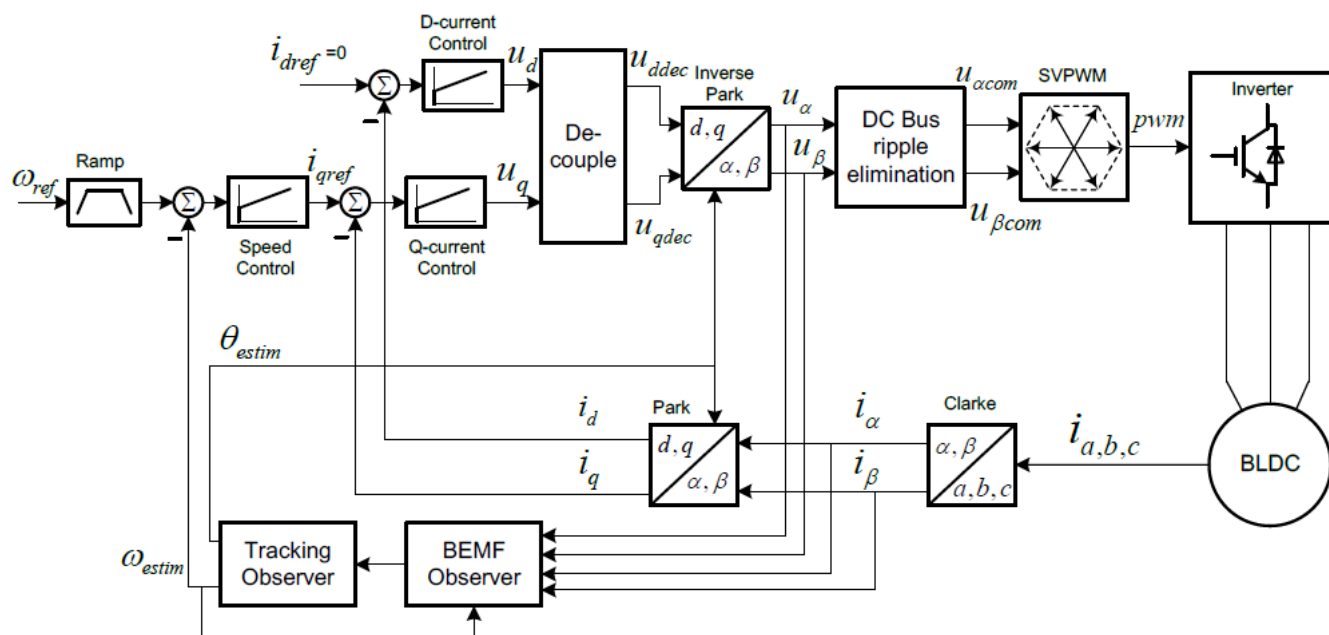


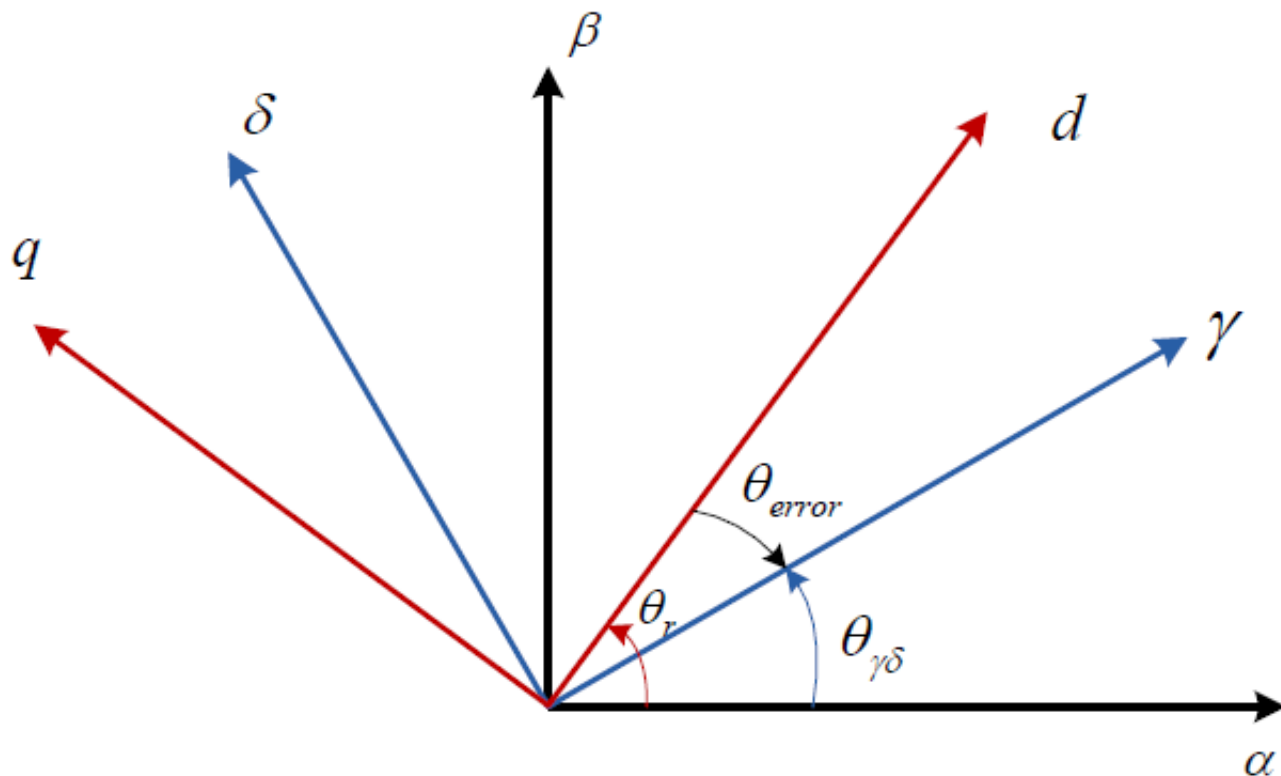
Figure 2. Vector control diagram

Almost all the blocks in Figure 2 can be found in Freescale Embedded Software Libraries (FSLESL) including all the transformations, PI controller, Observer, SVPWM, DC bus ripple elimination, etc.

### 3.3 Sensorless control

It is essential to know the angle between the  $d$ -axis of rotor and  $\alpha$ -axis of stator winding to realize the transformation between two-phase stationary coordinate and two-phase rotating coordinate in every current loop. And motor speed information is also needed to realize speed loop. Since there is no sensor on the motor due to cost problem, the position and speed of rotor are estimated through an observer.

The observer is based on the motor mathematical model, thus motor parameters must be available. It's a Luenberger type observer which estimates BEMF in a quasi synchronous rotating coordinate  $\gamma\delta$  using angle of  $\theta_{\gamma\delta}$  (angle between  $\gamma$ -axis and  $\alpha$ -axis) for Park transformation. The BEMF in coordinate  $\gamma\delta$  reflects the angle error ( $\theta_{error}$ ) between  $\gamma$ -axis and the  $d$ -axis of the rotor.



**Figure 3. Quasi synchronous rotating coordinate  $\gamma\delta$  and real synchronous rotating coordinate  $dq$**

Figure 3 shows the two coordinates  $\gamma\delta$  and  $dq$ . A Luenberger type observer is used to get BEMF information in coordinate  $\gamma\delta$  as shown in Figure 4. Then, a tracking observer is used to make  $\theta_{error}$  approach to 0, so that  $\theta_{\gamma\delta}$  will be the real rotor position in the end. Figure 5 shows the whole block of position and speed estimation.

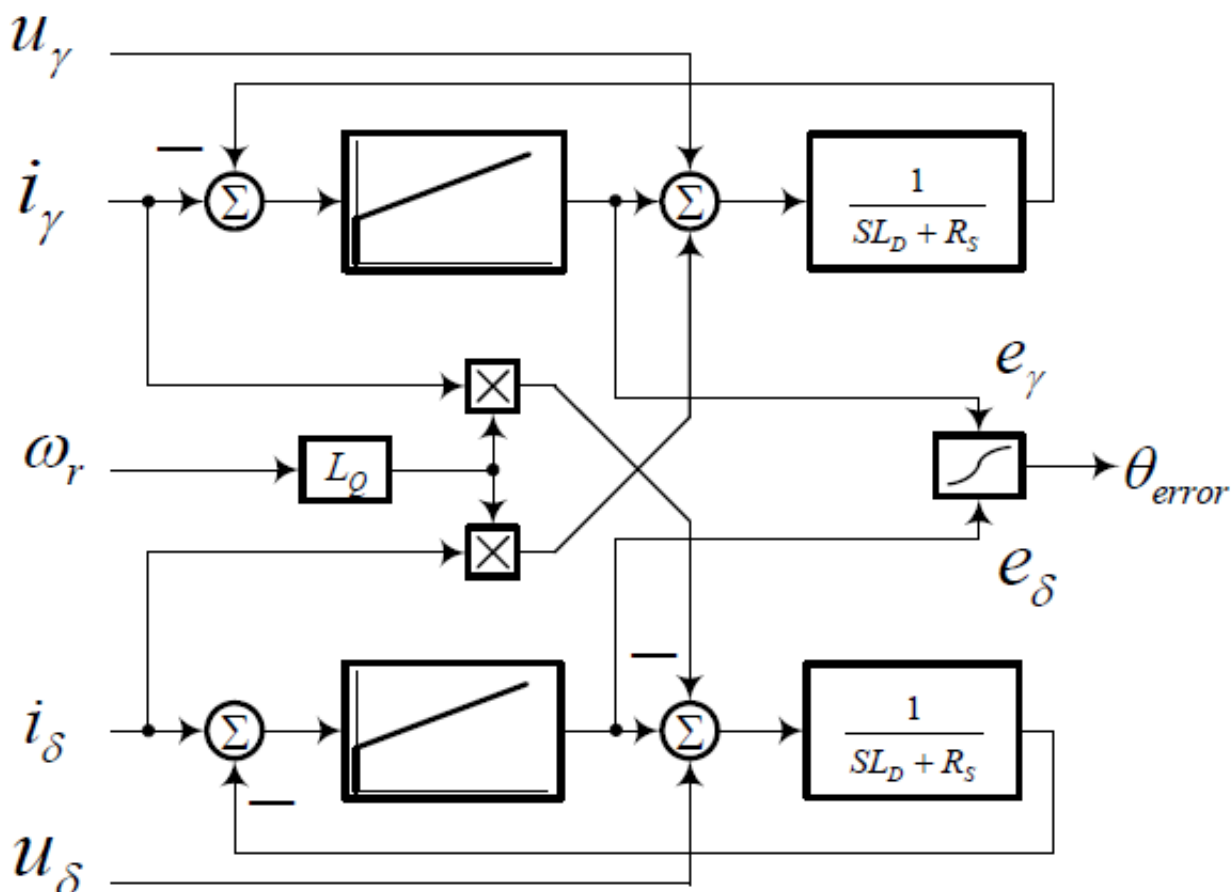


Figure 4. State observer for position error

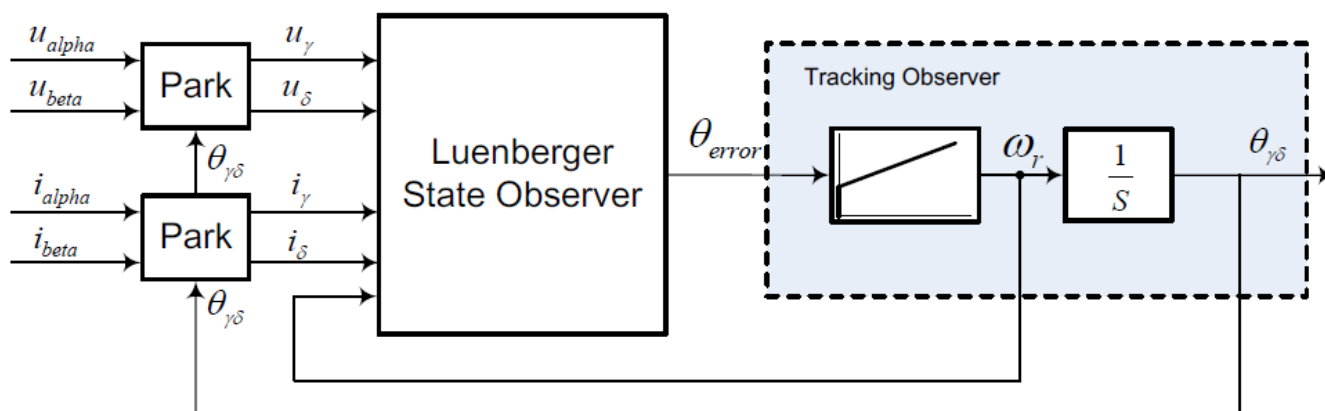


Figure 5. Speed and position estimation

### 3.4 Startup

Since the observer actually utilizes BEMF to get estimated rotor position and speed, there will be no reliable position or speed information when the motor is stopped or speed is too low because the BEMF is not large enough to be accurately observed. In this case, the motor is started by generating a slowly rotating stator current vector so that rotor is pulled to synchronize with this rotating stator current vector; this phase is called speed open loop phase. During open loop running, the observer works in parallel. When BEMF is large enough to be accurately observed, the estimated rotor position is used for

Park and Inverse park transformations and the estimated speed is used for speed loop control; this phase is called speed close loop phase. In both the phases, stator currents are controlled to be sinusoidal, so that smooth electromagnetic torque is generated, which minimizes acoustic noise and mechanical vibration.

### 3.5 Initial rotor position detection

The start torque could be very small or even not in the desired direction if the initial position of the rotor is not known. In this case, there might be little vibration during start up. If the initial position of the rotor is known, maximal start torque can be achieved, the time duration of speed open loop phase can be shortened and the motor can get into the close loop very soon.

A popular method is used to estimate the initial rotor position at standstill, utilizing the saturation effect of the stator iron core due to the permanent magnet. A stator inductance varies with the rotor position due to the saturation caused by the rotor magnetic field, as does the rate of change of the current in stator winding when a constant voltage is applied to the windings (See [References](#)). Six basic voltage vectors with the same length and lasting time which are used in the Space Vector PWM (SVPWM) module are applied to the windings one by one, so that corresponding six current pulses are generated and rotor position of 30 electrical degree resolution can be estimated according to the differences between the maximal values of these current pulses. An appropriate current vector can be generated according to this estimated initial rotor position to achieve the maximal startup torque. In this application, the time duration of open loop lasts about 5 electrical rotating periods and reaches 30 rpm (4 pole-pairs) before entering the speed close loop control.

### 3.6 Strategy of startup when fan rotates freely

The fan may rotate freely when it is to be started, under the following circumstances:

- The ceiling fan is installed in an open environment, and it is rotating due to the breeze;
- Couple of fans are installed in the same hall, and some fans are started ahead of the others, the fans started later may rotate due to the airflow generated by the first started ones;
- The fan is rotating and then turned off manually. It will continue to rotate due to inertia.

Each time when a fan is started, its rotating status must be checked to know whether it is rotating freely or not. Initial rotor position detection and start up will fail if it is rotating. A simple way to cope with it is like this: turn on the three lower switches of the inverter (turn off the upper switches) and sample the phase currents before starting the fan. Clarke transformation is applied to get the Alpha-Beta currents and then the length of the current vector can be calculated. The current vector length can be used to tell whether fan is standstill or not; fan is rotating if the current length is larger than a certain value and vice versa. Keep turning on the lower three switches of the inverter if fan is freely rotating, so that the motor works in generator mode and the mechanical energy will turn into heat consumed by stator winding resistance. The generated current vector length will decrease gradually until it gets smaller than a certain value, and the fan is assumed to be stopped at this point. Outer force is assumed to be big if the current vector length can't decrease to a certain value in a certain period of time, like 20 seconds. The fan can't be started in this case, and an error flag will be set. [Figure 6](#) shows the flow of braking the fan before startup.

The following situations may happen when the fan is started:

- Fan is already standstill during start up: The start up sequence is 1 -> 2-> 3 in [Figure 6](#).
- Fan is rotating freely due to outer force or inertia, and can't be stopped in 20 seconds:

The startup sequence is 1 -> 2 -> 4 -> 5 ->7 in [Figure 6](#). An error flag will be set and PWM outputs will be disabled. The fan can't be started in this case.

- Fan is rotating freely due to outer force or inertia, and can be stopped in 20 seconds:  
The start up sequence is 1 -> 2 -> 4 -> 6 -> 8 -> 9 in [Figure 6](#).

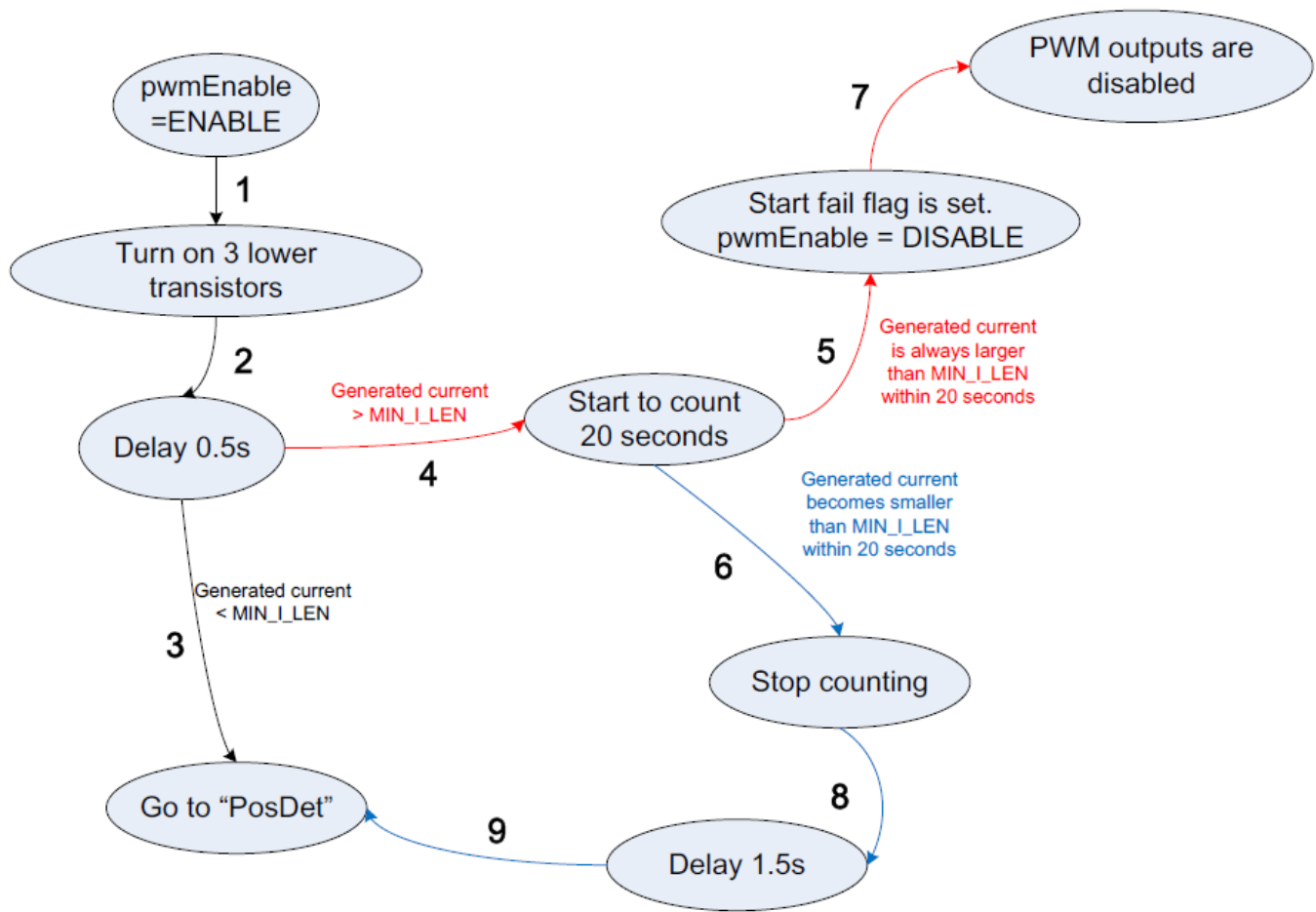


Figure 6. Brake the fan before startup

### 3.7 Strategy of coping with AC input power down for a couple of seconds

It is often required that the fan continues to run when AC input power is down for a very short period of time, (for example, for 2 seconds), and directly returns back to speed close loop when power is recovered. As seen in Figure 1, the DC bus voltage comes from the output of rectifier and is held by a capacitor. Once the AC input of the rectifier is down when the fan is running, the voltage of DC bus will decrease as there is no longer electric charging for the DC bus capacitor. The voltage of the DC bus must not be less than a certain value to keep the fan running at a speed above the minimal value where the observer can work properly.

An effective way to maintain DC bus voltage is to generate a braking torque so that fan works in Generator mode during power down. Speed is not controlled during power off, the quadrature current reference is set to the opposite sign value, and the direct current reference is still set to 0, so that Generator mode is achieved. It is essential that the observer works properly during this period. The fan will decelerate during this period of time because of the Generator mode. When AC input power is back and DC bus voltage is still above the minimal value that sustains the whole system, the speed loop can be enabled immediately and the fan will be forced to the desired speed under the control of speed controller, else an undervoltage error flag will be set.



## 4 Software introduction

Sensorless vector control algorithm is applied on the BLDC of the ceiling fan using MC56F8006. Conventional current PI controllers and speed PI controller are used to build vector control structure. The position and speed estimation is based on motor's mathematical model. A Luenberger type state observer and a tracking observer are used to get the position and speed. The frequency of PWM is 16 kHz, and current loop is executed every two PWM periods, that is 125  $\mu$ s. The speed loop is executed every 10 ms. PWM module triggers ADC to sample phase currents and DC bus voltage. Current loop and speed loop are realized in ADC interrupt service routine (ISR).

It is easy and efficient to build a vector control structure based on Quick-Start integrated in CodeWarrior. For more information, see AN4490: How to Build an FOC Code Structure Based on the 56F8006 Using a Quick-Start Tool, available on [freescale.com](http://freescale.com).

### 4.1 State machine

A state machine is realized in the ADC ISR to do the control, which makes the code easy to understand and modify. There are total 7 states in the whole flow as shown in Figure 7.

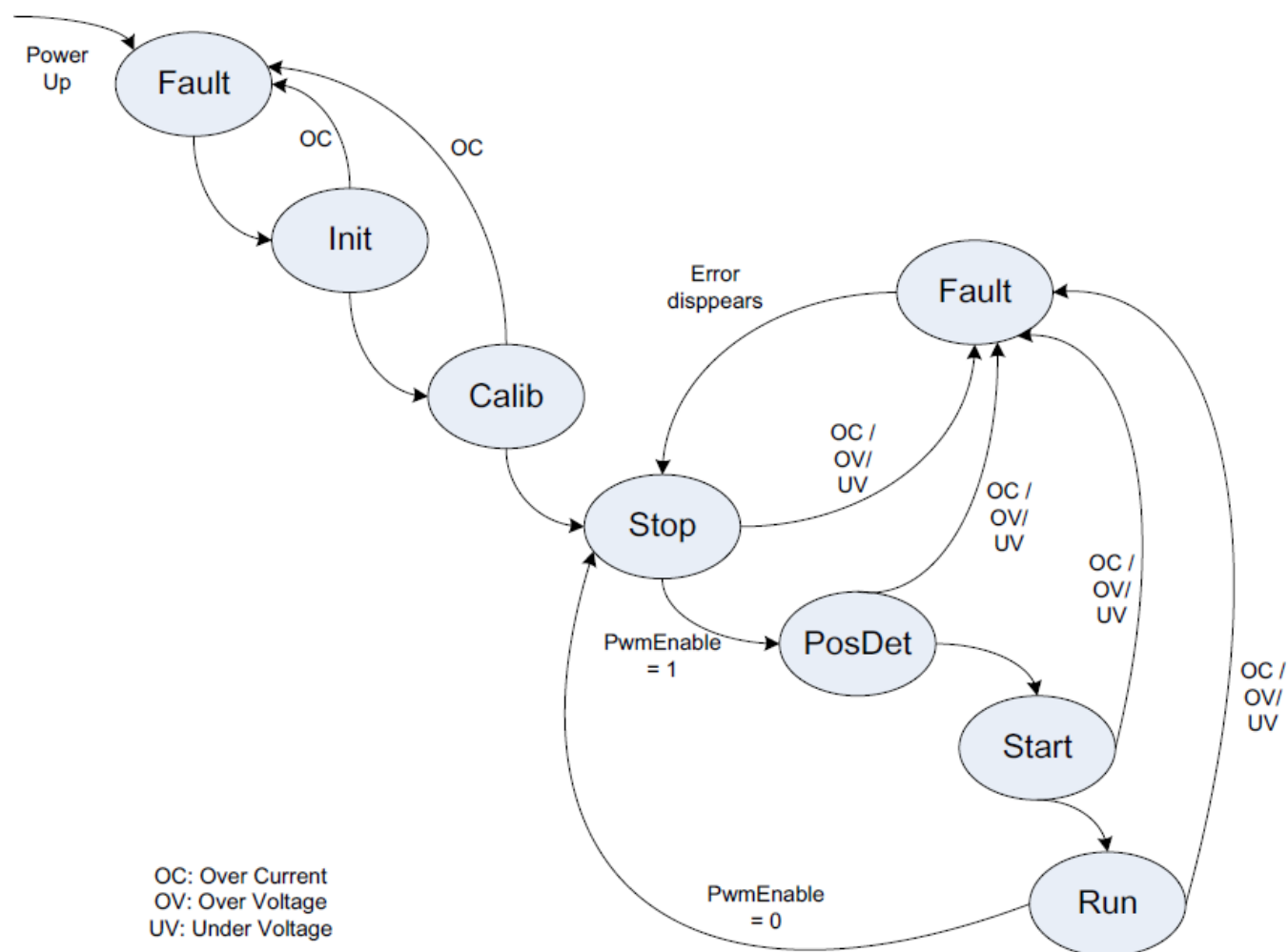


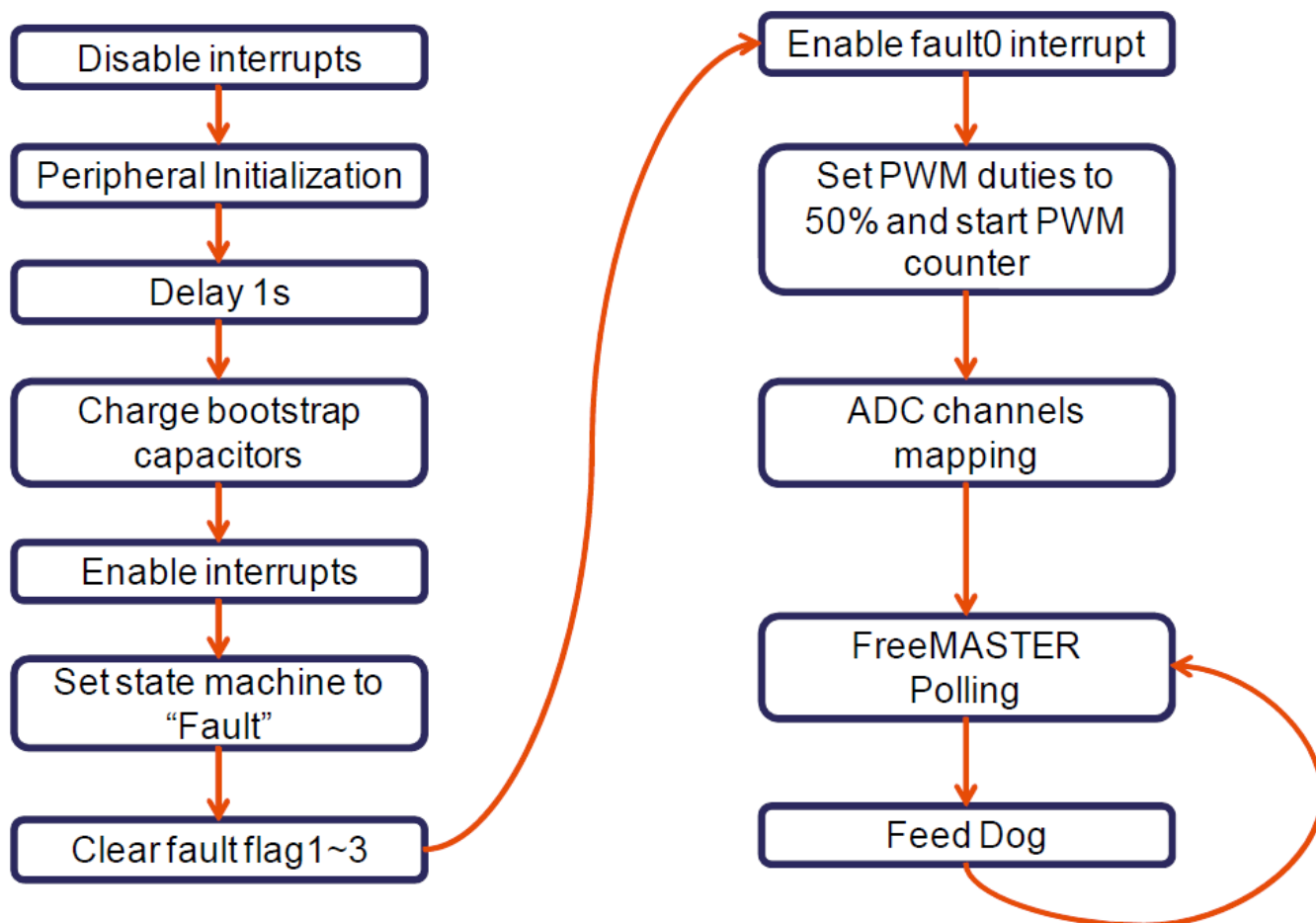
Figure 7. State machine

Following is a brief explanation of the seven states.

1. *Fault*: This is the first state to go in when the chip is powered up. If no overcurrent (OC) is found, it goes to the Init state. It also goes to this state when OC/UV/OV occurs in other states.
2. *Init*: All the algorithm related variables are initialized. It goes to the Calib state when it's done.
3. *Calib*: Four phase current sensing channels are converted here to get the offset value, because all six PWMs are disabled and there are no currents flowing on the shunt resistors.
4. *Stop*: The system will remain in this state if the variable `pwmEnable = 0`. It waits for Start command in this state. When `pwmEnable = 1`, it goes to the PosDet state only if the currents flowing in the shunt resistors are small enough which indicates that the motor is stopped. The motor must be started when it is completely stopped. The phase currents must be below the current value defined by the macro `MIN_I_LEN`.
5. *PosDet*: The initial position of the rotor is detected in this state. Maximal torque can be achieved if the initial position of the rotor is known, else the motor must be started very slowly.
6. *Start*: This state merely adds a delay of 6.25 ms between the PosDet and Run states.
7. *Run*: Once it enters this state, the motor will start running.

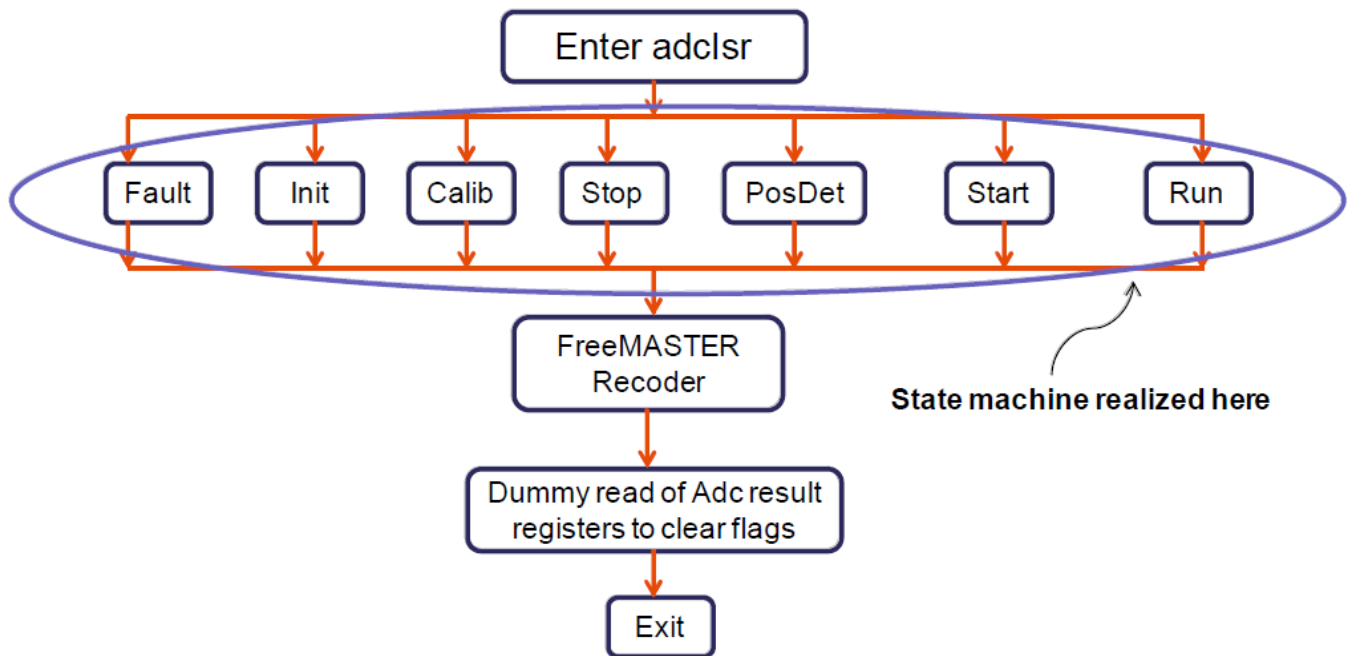
## 4.2 Software implementations

When the system is powered up, the initialization flow is shown in [Figure 8](#). Because the vector control algorithm is performed in the ADC ISR, only feeding dog and FreeMASTER polling are executed in the main loop.



**Figure 8. Initialization flow**

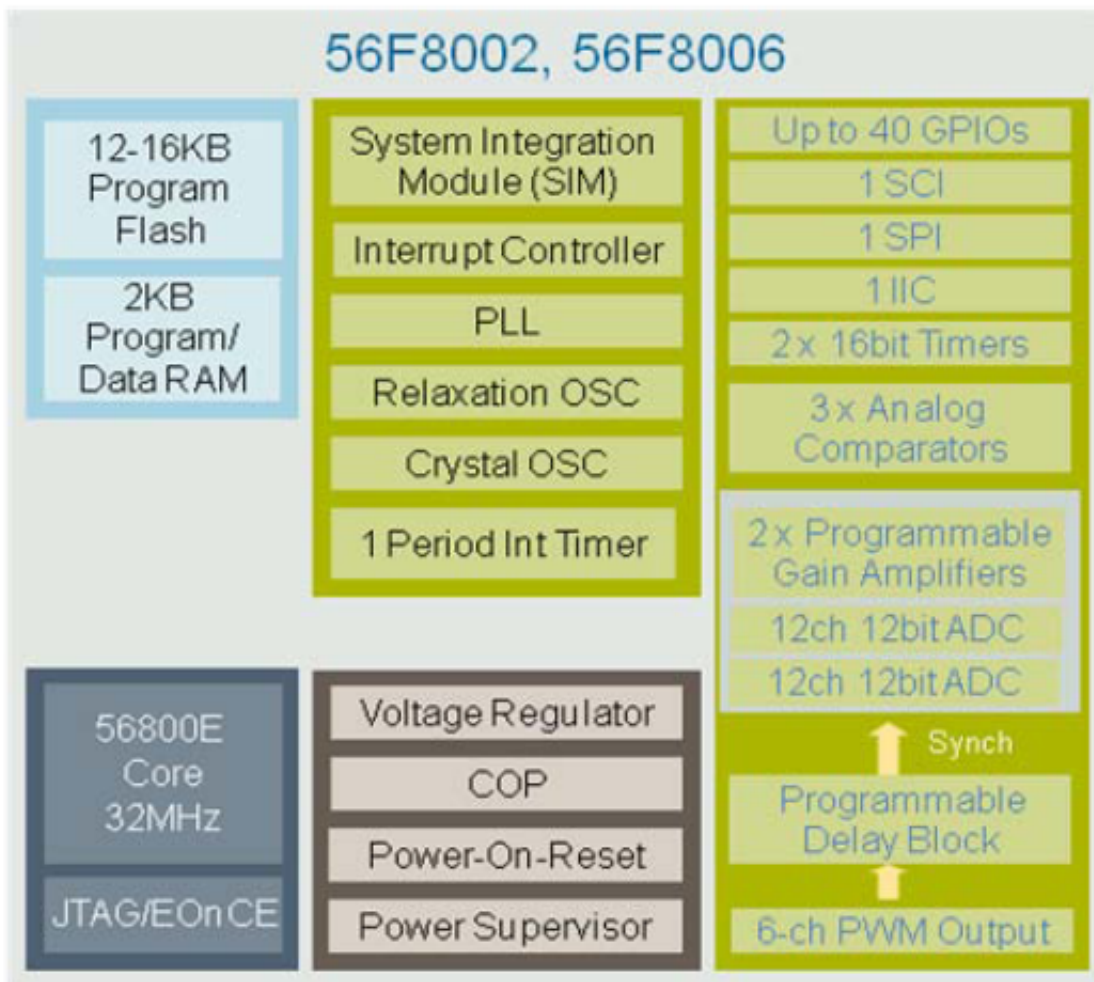
State machine is realized in the ADC ISR as shown in [Figure 9](#).



**Figure 9. ADC interrupt service routine**

## 5 MC56F800x family of DSCs

Freescle's 56800E core is an ideal solution for this particular application. It processes all motor control functions powerfully and efficiently. Digital control improves system reliability by reducing the number of discrete components found in early designs and facilitates advanced algorithms for optimal motor driving performance. All the functions mentioned above are implemented on the MC56F8006 DSC with all control routines using C-callable, optimal assembler language with fractional numerical representations, which are available in FSLESL. The block diagram of 56F8006 is shown in [Figure 10](#).



**Figure 10. Block diagram of 56F8006 with package of 28SOIC, 32LQFP and 48LQFP**

The MC56F800x family members provide these peripheral blocks:

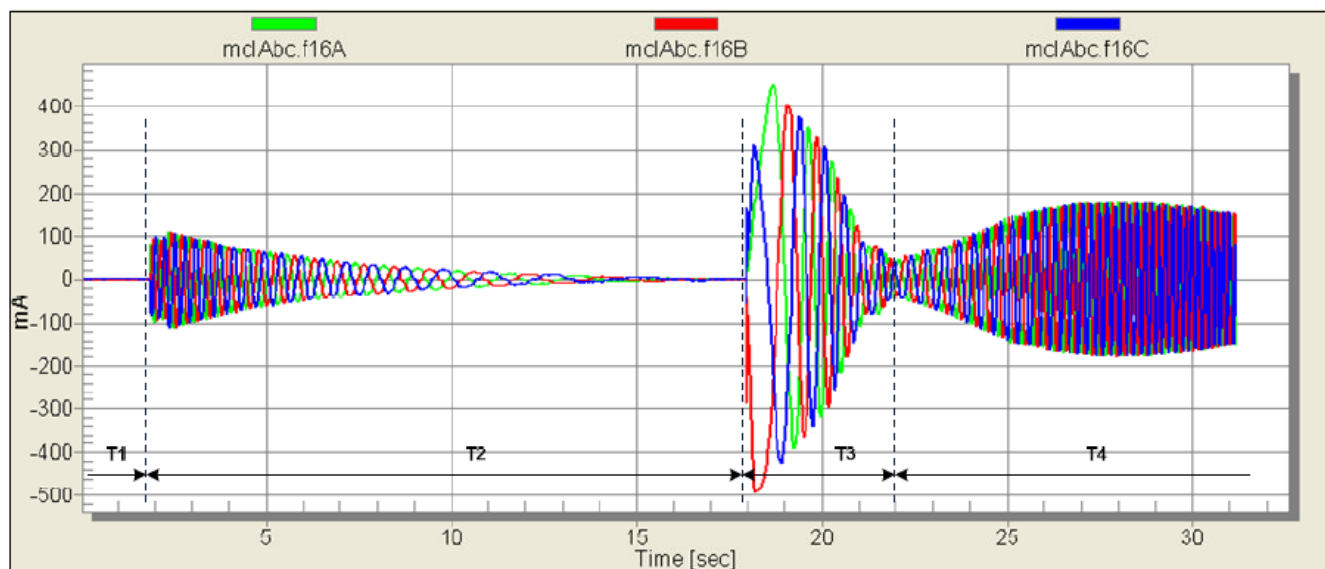
- One pulse width modulation (PWM) module with 6 PWM outputs, 4 fault inputs and hardware dead-time insertion function, supporting both center-aligned and edge-aligned modes
- Two 12-bit analog-to-digital converters (ADCs) with up to 24 inputs, supporting two simultaneous conversions. ADC and PWM modules can be synchronized through PDB module
- Two 16-bit multifunctional timers and one programmable interval timer (PIT)
- One real time counter (RTC)
- Two programmable gain amplifiers (PGA) with x2, x4, x8, x16 and x32 gains (clocked in order to cancel input offset)
- Programmable delay block (PDB) which provides precise control of ADC/PGA sample times relative to PWM reload cycles
- Three high-speed analog comparators
- One high-speed serial communication interface (SCI) with LIN slave functionality
- One serial peripheral interface (SPI)
- One SMBus compatible inter-integrated circuit (I2C) port
- Computer operating properly (COP)/watchdog
- Two on-chip relaxation oscillators with frequencies 1 kHz and 8 MHz (400 kHz in Standby mode)
- Integrated power-on reset (POR) and low-voltage interrupt (LVI) module
- JTAG/enhanced on-chip emulation (OnCETM) for non-intrusive real-time debugging
- 1.8~3 V operation range
- Up to 40 GPIO lines

In this application, the ADC modules work in ping-pong mode to convert analog feedback signals like DC bus voltage and three phase currents before being processed. The ADC is synchronized to the reload signal of PWM through the PDB module. The reload signal of PWM triggers the counter of PDB, and when the counter reaches a certain value, ADC is started. The PWM module works at a fixed frequency of 16 kHz, and it provides time base for current and speed loop, thus no other timer is needed for vector control.

The application allows communication with PC through FreeMASTER over an isolated serial link. All the variables can be monitored and modified in FreeMASTER's graphical interface on PC, so that code can be easily debugged and performance of the fan can be observed through current/speed waveforms.

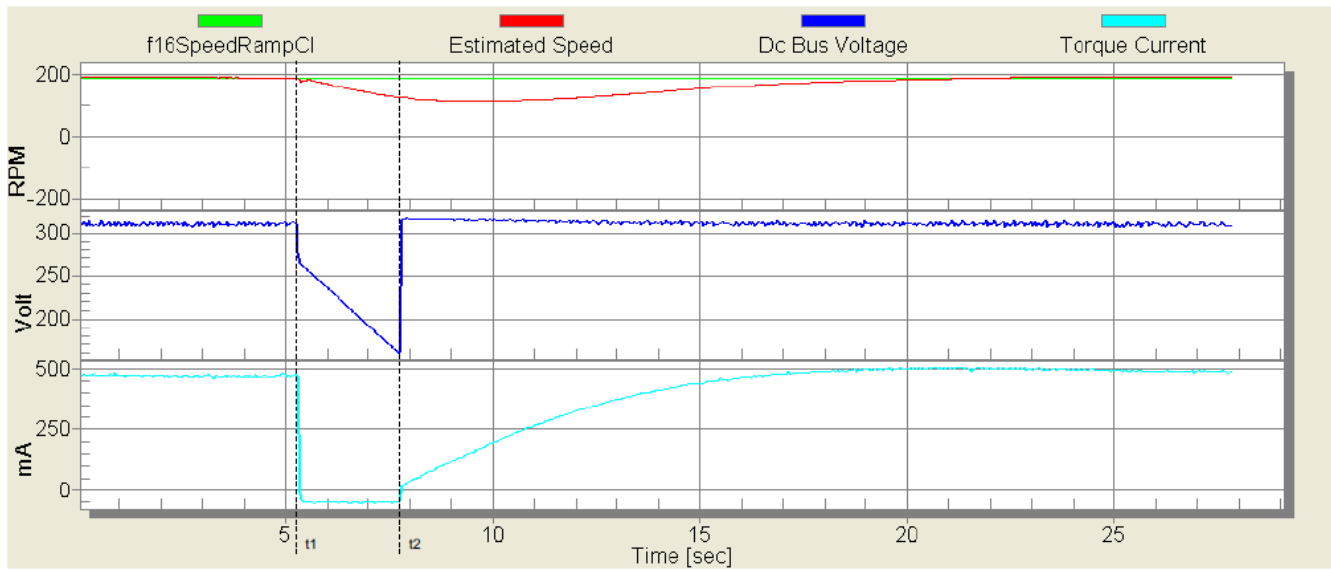
## 6 Experimental results

Figure 11 shows the start up three-phase current waveforms of the motor. During time interval T1, the fan is rotating freely due to inertia because it's just turned off. Fan is commanded to start at the beginning of timer interval T2, but it will not start until it is stopped through the Generator mode. During the period T2, mechanical energy of the fan is converted into heat consumed by winding resistance of the stator. The fan is assumed to be stopped at the end of T2 because the generated current is very small. The initial position of the rotor is detected at the end of T2. The motor runs at speed open loop phase in time interval T3. The position and speed of rotor can be reliably estimated at the end of T3 where motor runs at 30 rpm (4 pole-pairs); so it enters speed close loop using estimated position and speed in time interval T4.



**Figure 11. Startup current waveforms**

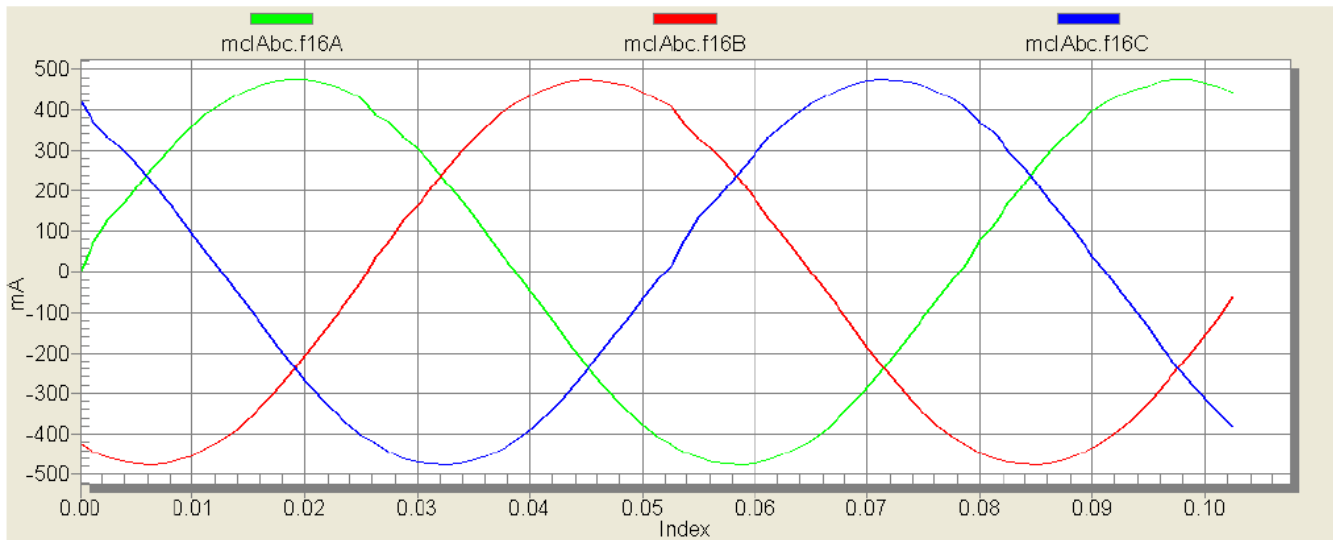
Figure 12 shows how the system works when AC input power is down for 2 seconds and the fan runs at 190 rpm.



**Figure 12. Input AC power is down for 2 seconds**

At the time point  $t_1$ , AC input voltage is off so that DC bus voltage immediately drops. As soon as DC bus drops to 270 V, speed loop is disconnected and the motor works in Generator mode by commanding a negative quadrature current reference. So, DC bus capacitor is charged in time interval  $t_1$ ~ $t_2$ , but the voltage still drops down because all the components on the board consume energy from the DC bus capacitor. At the time point  $t_2$ , DC bus voltage falls to near 150 V and speed of the fan falls to around 100 rpm. The whole system can still work properly at this time point. Then AC input recovers, the speed loop is enabled, and the quadrature current rises back to the appropriate value under the control of speed controller.

Figure 13 shows 3-phase current waveforms at 190 rpm (clockwise).



**Figure 13. Three-phase current waveforms at 190 rpm**

## 7 Conclusions

There is a trend that some old mundane household objects go high-tech and high-style, and ceiling fan is one of these objects. Vector control and sensorless technologies are used for this purpose since it not only eliminates sensors enabling cost-effective solution, but also leads to low noise, high efficiency, wide range of speed and flexible control ability.

A low-cost DSC MC56F8006 based on the Freescale 56800E core which combines both MCU and DSP capabilities is quite suitable for this ceiling fan control. Satisfactory performance has been achieved utilizing MC56F8006.

## 8 References

- A New Starting Method of BLDC Motors Without Position Sensor, by Wook-Jin Lee, Student Member, IEEE, and Seung-Ki Sul, Fellow, IEEE.
- AN4490: How to Build an FOC Code Structure Based on the 56F8006 Using a Quick-Start Tool, available on [freescale.com](http://freescale.com)

## **How to Reach Us:**

### **Home Page:**

[www.freescale.com](http://www.freescale.com)

### **Web Support:**

<http://www.freescale.com/support>

### **USA/Europe or Locations Not Listed:**

Freescale Semiconductor  
Technical Information Center, EL516  
2100 East Elliot Road  
Tempe, Arizona 85284  
+1-800-521-6274 or +1-480-768-2130  
[www.freescale.com/support](http://www.freescale.com/support)

### **Europe, Middle East, and Africa:**

Freescale Halbleiter Deutschland GmbH  
Technical Information Center  
Schatzbogen 7  
81829 Muenchen, Germany  
+44 1296 380 456 (English)  
+46 8 52200080 (English)  
+49 89 92103 559 (German)  
+33 1 69 35 48 48 (French)  
[www.freescale.com/support](http://www.freescale.com/support)

### **Japan:**

Freescale Semiconductor Japan Ltd.  
Headquarters  
ARCO Tower 15F  
1-8-1, Shimo-Meguro, Meguro-ku,  
Tokyo 153-0064  
Japan  
0120 191014 or +81 3 5437 9125  
[support.japan@freescale.com](mailto:support.japan@freescale.com)

### **Asia/Pacific:**

Freescale Semiconductor China Ltd.  
Exchange Building 23F  
No. 118 Jianguo Road  
Chaoyang District  
Beijing 100022  
China  
+86 10 5879 8000  
[support.asia@freescale.com](mailto:support.asia@freescale.com)

Information in this document is provided solely to enable system and software implementers to use Freescale Semiconductors products. There are no express or implied copyright licenses granted hereunder to design or fabricate any integrated circuits or integrated circuits based on the information in this document.

Freescale Semiconductor reserves the right to make changes without further notice to any products herein. Freescale Semiconductor makes no warranty, representation, or guarantee regarding the suitability of its products for any particular purpose, nor does Freescale Semiconductor assume any liability arising out of the application or use of any product or circuit, and specifically disclaims any liability, including without limitation consequential or incidental damages. "Typical" parameters that may be provided in Freescale Semiconductor data sheets and/or specifications can and do vary in different applications and actual performance may vary over time. All operating parameters, including "Typicals", must be validated for each customer application by customer's technical experts. Freescale Semiconductor does not convey any license under its patent rights nor the rights of others. Freescale Semiconductor products are not designed, intended, or authorized for use as components in systems intended for surgical implant into the body, or other applications intended to support or sustain life, or for any other application in which failure of the Freescale Semiconductor product could create a situation where personal injury or death may occur. Should Buyer purchase or use Freescale Semiconductor products for any such unintended or unauthorized application, Buyer shall indemnify Freescale Semiconductor and its officers, employees, subsidiaries, affiliates, and distributors harmless against all claims, costs, damages, and expenses, and reasonable attorney fees arising out of, directly or indirectly, any claim of personal injury or death associated with such unintended or unauthorized use, even if such claims alleges that Freescale Semiconductor was negligent regarding the design or manufacture of the part.

RoHS-compliant and/or Pb-free versions of Freescale products have the functionality and electrical characteristics as their non-RoHS-complaint and/or non-Pb-free counterparts. For further information, see <http://www.freescale.com> or contact your Freescale sales representative.

For information on Freescale's Environmental Products program, go to <http://www.freescale.com/epp>.

Freescale™ and the Freescale logo are trademarks of Freescale Semiconductor, Inc. All other product or service names are the property of their respective owners.

© 2012 Freescale Semiconductor, Inc.