Application Note

Switch reluctance motor control with µPD78K0/KX2

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Preface

This application note proposes how to implement a 4-Phase Switched Reluctance (SR) motor drive using the µPD78K0/KC2 along with an analogue Drive circuit.

Schematic, bill of material and board layout files are also provided.

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Chapter 1 Overview

1.1 Introduction

Switched reluctance motors are gaining wider popularity among variable speed drives. This is due to their simple low-cost construction characterized by an absence of magnets and rotor winding, high level of performance over a wide range of speeds, and fault-tolerant power stage design. For numerous applications, availability and the moderate cost of the necessary electronic components make SR drives a viable alternative to other commonly used motors.

Purpose of this application note is to show how a SR motor control is realised on the µPD78K0/KC2 along with a drive circuit. The software and hardware configurations published here are just examples and are not intend for mass production.

1.2 Overview of µPD78F0515D Series

Table 1-1 Functional Outline 1/2

Item			78K0/KB2							78K0/KC2				
			30/36 pins				44 pins			48 pins				
Flash memory (KB)			8	16	24	32	16	24	32	16	24	32	48	60
RAM (KB)			0.5	0.75	1	1	0.75	1	1	0.75	1	1	2	3
Bank (Flash memory)			-											
Power supply voltage			V_{DD} = 1.8 to 5.5 V											
Regulator			Provided											
Minimum instruction execution time			0.1 μs (20 MHz: V_{DD} = 4.0 to 5.5 V) / 0.2 μs (10 MHz: V_{DD} = 2.7 to 5.5 V) / 0.4 μs (5 MHz: V_{DD} = 1.8 to 5.5 V)											
Clock	Main	High-speed system	20 MHz: V_{DD} = 4.0 to 5.5 V / 10 MHz: V_{DD} = 2.7 to 5.5 V / 5 MHz: V_{DD} = 1.8 to 5.5 V											
		Int. high-speed osc.	8 MHz (TYP.): V_{DD} = 1.8 to 5.5 V											
	Subsystem		-				32.768 kHz (TYP.): V_{DD} = 1.8 to 5.5 V							
	Internal low-speed oscillation		240 kHz (TYP.): V_{DD} = 1.8 to 5.5 V											
Port	Total		23				37			41				
	N-ch O.D. (6 V tolerance)		2				4			4				
Timer	16 bits (TM0)		1-ch											
	8 bits (TM5)		2-ch											
	8 bits (TMH)		2-ch											
	Watch		-				1-ch			1-ch				
	WDT		1-ch											
Serial Interface	3-wire CSI						-							
	Automatic transmit/receive 3-wire CSI						-							
	UART/3-wire CSI[Note]		1-ch											
	UART supporting LIN bus		1-ch											
	I²C bus		1-ch											
10-bit A/D			4-ch				8-ch							

Item		Part number	78K0/KB2		78K0/KC2
			30/36 pins	**44 pins**	**48 pins**
Interrupt	External		6	7	8
	Internal		14	16	
Key interrupt			-	4-ch	
Reset	$\overline{\text{RESET}}$ pin		Provided		
	POC		1.59 V ± 0.15 V (rise time to 1.8 V: 3.6 ms (MIN.))		
	LVI		The detection level of the supply voltage is selectable in 16 steps.		
	WDT		Provided		
Clock output/buzzer output			-		Clock output only
Multiplier/divider			-		Provided
On-chip debug function			µPD78F0503D only	µPD78F0513D only	µPD78F0515D only
Operating ambient temperature			T_A = -40 to +85°C		

Note: Select either of the functions of these alternate-function pins.

Table 1-2 Functional Outline 2/2

Item			78K0/KD2 (52 pins)							78K0/KE2 (64 pins)							78K0/KF2 (80 pins)			
Part number			16	24	32	48	60	96	128	16	24	32	48	60	96	128	48	60	96	128
Flash memory (KB)			16	24	32	48	60	96	128	16	24	32	48	60	96	128	48	60	96	128
RAM (KB)			0.75	1	1	2	3	5	7	0.75	1	1	2	3	5	7	2	3	5	7
Bank (Flash memory)			-					4	6	-					4	6	-		4	6
Power supply voltage			V_{DD} = 1.8 to 5.5 V																	
Regulator			Provided																	
Minimum instruction execution time			0.1 µs (20 MHz: V_{DD} = 4.0 to 5.5 V) / 0.2 µs (10 MHz: V_{DD} = 2.7 to 5.5 V) / 0.4 µs (5 MHz: V_{DD} = 1.8 to 5.5 V)																	
Clock	Main	High-speed system	20 MHz: V_{DD} = 4.0 to 5.5 V / 10 MHz: V_{DD} = 2.7 to 5.5 V / 5 MHz: V_{DD} = 1.8 to 5.5 V																	
		Int. high-speed osc.	8 MHz (TYP.): V_{DD} = 1.8 to 5.5 V																	
	Subsystem		32.768 kHz (TYP.): V_{DD} = 1.8 to 5.5 V																	
	Internal low-speed oscillation		240 kHz (TYP.): V_{DD} = 1.8 to 5.5 V																	
Port	Total		45							55							71			
	N-ch O.D. (6 V tolerance)		4							4							4			
Timer	16 bits (TM0)		1-ch							2-ch							2-ch			
	8 bits (TM5)		2-ch							2-ch							2-ch			
	8 bits (TMH)		2-ch							2-ch							2-ch			
	Watch		1-ch							1-ch							1-ch			
	WDT		1-ch							1-ch							1-ch			
Serial Interface	3-wire CSI		-							1-ch							1-ch			
	Automatic transmit/receive 3-wire CSI		-							-							1-ch			
	UART/3-wire CSI[Note]		1-ch							1-ch							1-ch			
	UART supporting LIN bus		1-ch							1-ch							1-ch			
	I²C bus		1-ch							1-ch							1-ch			
10-bit A/D			8-ch							8-ch							8-ch			

Part number		78K0/KD2	78K0/KE2	78K0/KF2
Item		**52 pins**	**64 pins**	**80 pins**
Interrupt	External	8	9	
	Internal	16	19	20
Key interrupt		8-ch		
Reset	$\overline{\text{RESET}}$ pin	Provided		
	POC	1.59 V ± 0.15 V (rise time to 1.8 V: 3.6 ms (MIN.))		
	LVI	The detection level of the supply voltage is selectable in 16 steps.		
	WDT	Provided		
Clock output/buzzer output		Clock output only	Provided	
Multiplier/divider		-		Provided
On-chip debug function		µPD78F0527D only	µPD78F0537D only	µPD78F0547D only
Operating ambient temperature		T_A = -40 to +85°C		

Note: Select either of the functions of these alternate-function pins.

Chapter 2 Switched Reluctance Motor Basics

2.1 Switched Reluctance Motor Basics

A Switched Reluctance (SR) motor is an electromagnetic, rotary machine in which torque is produced by the tendency of its movable part to move to a position where the inductance of the excited winding is maximized. The SR motor has the simplest mechanical structure compared with other types of electrical machines. Both stator and rotor have salient poles, the stator winding is compromised of a set of coils, each wound on pole, the rotor is only made with steal lamination stacked onto the shaft. This is the main difference with conventional motors like DC or induction motors which have rotor windings or permanent magnets.

Various options of rotor and stator poles may be used. By increasing the number of phases the torque ripple can be reduced, but more electronic will be needed increasing the whole solution price. A compromise has to be chosen knowing that different number of rotor and stator poles and a minimum of two phases are necessary to start the motor, and three phases to choose the starting direction. This Application Note deals with a four phase regular 8/6 motor shown in *Figure 2-1* .This combination is far spread and provides lesser torque ripple.
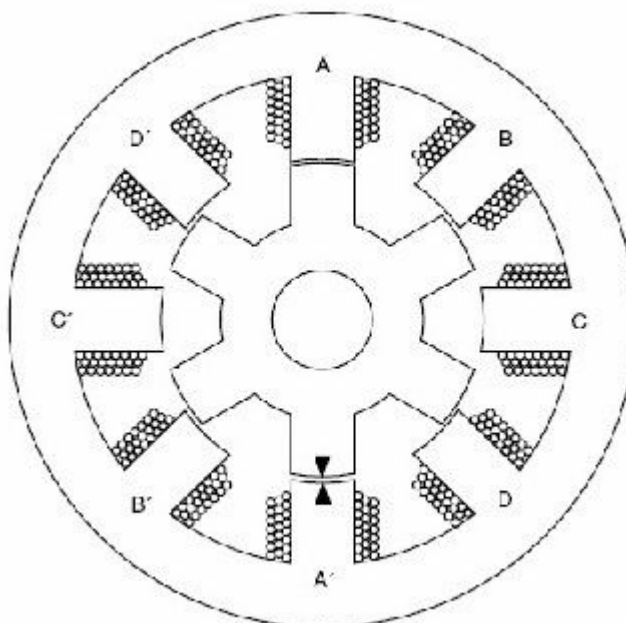

Figure 2-1   Four-phase 8/6 SR motor

The advantage of the easy build up rotor carries also some disadvantages. The reliance on a single excitation source, coupled with the effects of fringing fields and magnetic saturation, renders the switched reluctance motor nonlinear in its control characteristics.

As mentioned above the torque is produced by the rotors tendency to move to the position of least reluctance / highest inductance. The motor is excited by a sequence of current pulses applied at each phase. The individual phases are

consequently excited, forcing the motor to rotate. This way of driving is similar to the one used for stepper motors.

The basic movement of the motor can be best shown by reducing the defaults to the simplest arrangements. We look at the rotor as one pole-pair and the stator comes down to two magnetic poles with one phase.


a)   b)
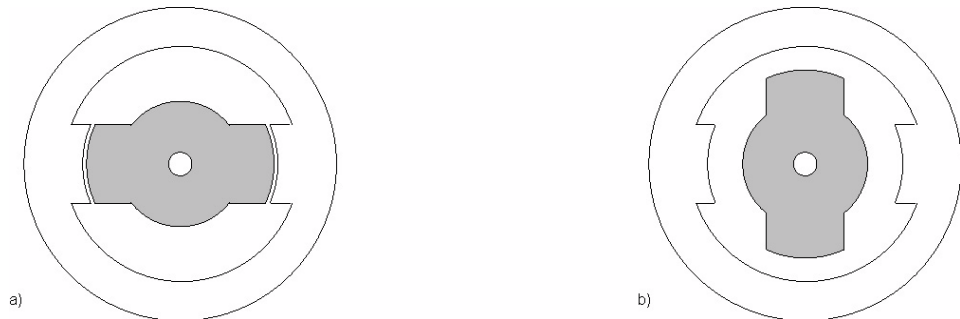
Figure 2-2   One-phase SR motor, aligned, unaligned position

In this simple machine the coil inductance L varies with the rotor position θ as shown in *Figure 2-3* . Assume that the coil carries a constant current. Positive motoring torque is only produced while the inductance is increasing as the rotor approaches the aligned position between positions J and A. At J, the leading edge of the rotor pole is aligned with the first edge of the stator pole; at A, the rotor and stator poles are fully aligned Figure 2-2 a). Thus J defines the start of overlap, A the maximum, and K the end of the overlap.

An important occurrence is that the torque changes direction at the aligned position. If the rotor continues past A, the attractive force between the poles produces a braking torque.

To eliminate these negative torque impulses, the constant current must be switched off during this pole separating time period.

The ideal current waveform is therefore a series of pulses synchronized with the rising inductance intervals. The cycle of torque production associated with one current pulse is called a stroke.
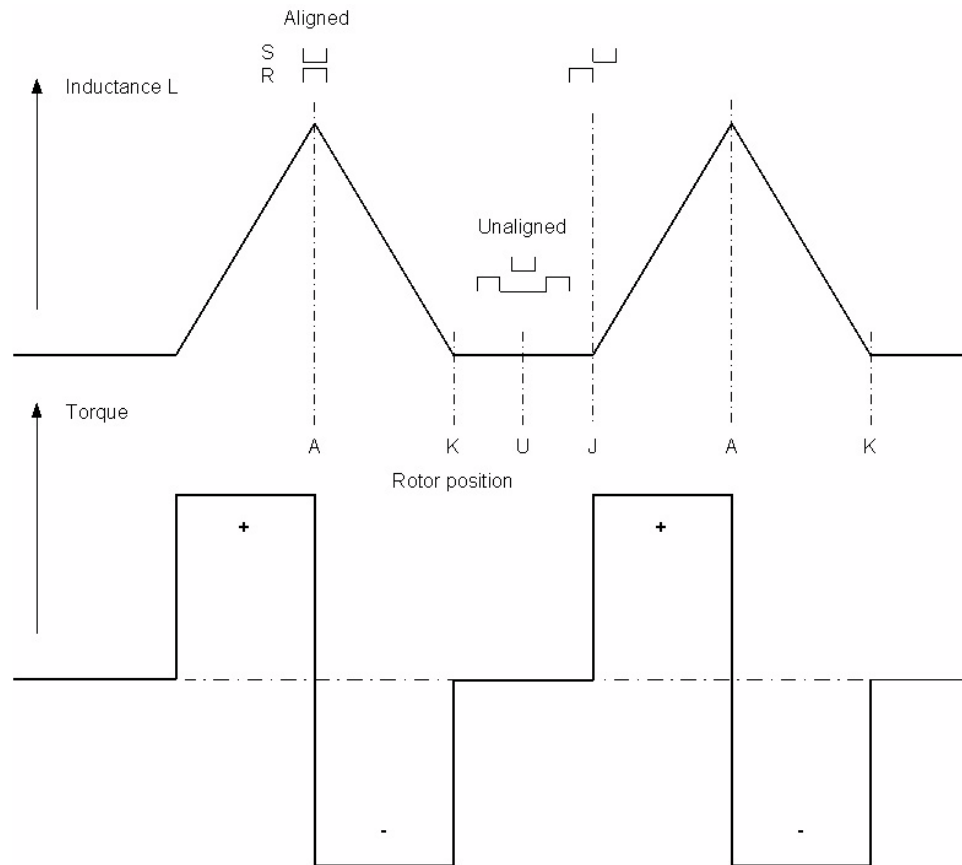
Figure 2-3   Variation of inductance and torque with rotor position

Although the torque maintains a nonzero average value during a rotation, it's discontinues and the rotation is only kept up due to the flywheel effect of the rotating inertia.

A big disadvantage is also that the motor can't self-start from every rotor position (e.g. the aligned position).

To compensate these disadvantages the motor is generally provided with additional phases which leads to more stator/rotor poles.

The number of strokes per revolution is related to the number of rotor poles N_R and the number of phases m

$$S = m * N_R \; (1)$$

The motor in *Figure 2-1* has m = 4 and N_R = 6, so S = 24. The so called stroke angle or dwell angle is now ε = 360 / 24 = 15°. The ideal current/torque pulses of the four phases are shown in *Figure 2-3* . The resultant torque is ideally constant and covers 360° of rotation.
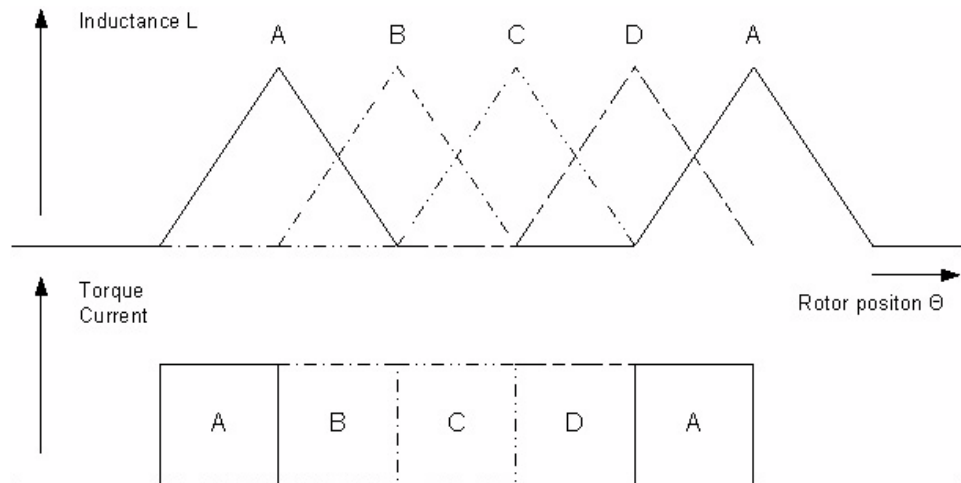
Figure 2-4 **Inductance profile 8/6 SR machine**

To get better understanding of motor control requirements a knowledge of the basic formulas for SR machines is required. For simplicity we ignore the effect of fringing flux around the pole corners, magnetic saturation and assume that all the flux crosses the air gap in the radial direction.

The voltage equation for one phase is

$$
\begin{aligned}
v &= R \cdot i + \frac{d\psi}{dt} = R \cdot i + \omega_m \frac{d\psi}{d\theta} \\
&= R \cdot i + \omega_m \frac{d(Li)}{d\theta} \qquad (2) \\
&= R \cdot i + L\frac{di}{dt} + \omega_m \cdot i\frac{dL}{d\theta}
\end{aligned}
$$

where v is the voltage across one phase, i the current, ψ the flux linkage, R the phase resistance, L inductance, θ is the rotor position, and ω_m is the angular velocity.

Due to the pole saliency, the magnetic path is different during the rotor motion since the reluctance is minimal when stator and rotor poles are aligned and maximum when poles are not aligned. Formally, the inductance can be written as follows:

$$
L(\theta) = \frac{N^2}{\Re(\theta)} \quad (3)
$$

with N number of coils and R phase reluctance. The equation above and the reluctance profile are responsible for inductive curves. Energy and inductance considerations lead to the following definition of the motor torque expression

$$T_e = \frac{1}{2} i^2 \cdot \frac{dL}{d\theta} \qquad (4)$$

The equitation above says that the torque does not depend on the direction of the current. In order to obtain positive torque the phase coil needs, as already mentioned, current only during the rising edge of the inductance profile.

The synchronization of the phase polarization with the rotor poles positions is the main task of the electronic driver.

2.2 Switched Reluctance Motor Control Requirements

In a switch reluctance motor drive the number of motor phases, the pole geometry, the possibility for more than one phase to ensure current flow, the whole commutation concept greatly affects the drive topology.

There is a wide variety of drive circuits in use and not one topology that fits all.

Voltage supply, number of external parts, current/voltage protection, and overall flexibility are just a few aspects to consider.

This Application Note deals with the drive topology shown in *Figure 2-5* , this "multiphase-switch" configuration is build up as an asymmetric bridge. The main advantages are the low power loss, few external parts and lesser complex drive algorithm. The circuit contains six power mosfets responsible for the current flow through the windings. Each coil can be energized in one direction by turning on the appropriate mosfets. Implicitly this configuration never energizes phases A, C or B and D at the same time.
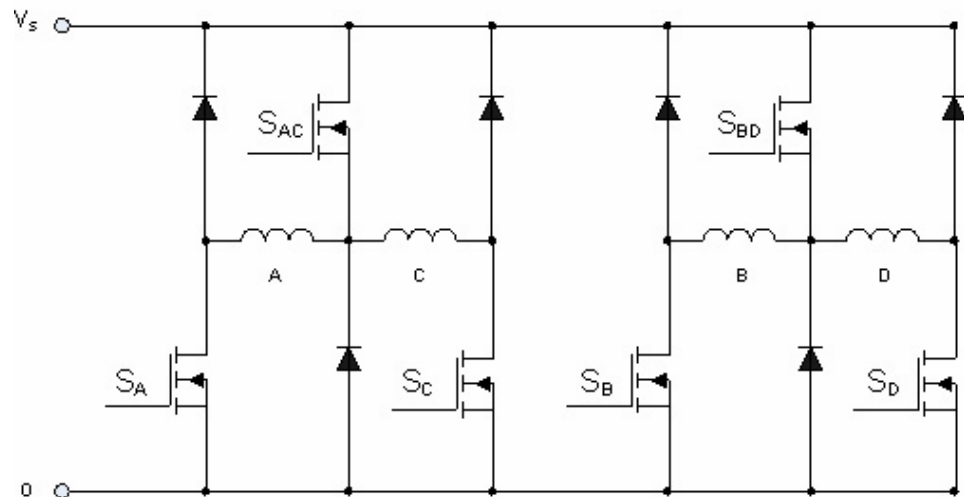

Figure 2-5   Multiphase-switch drive topology

In the following we want to look closer at this drive topology. Note that the ideal current and inductance waveforms imply a saw tooth waveform of flux-linkage $\psi = Li$. So the flux-linkage is build up from zero every stroke and diminishes to zero back again, to do so the voltage must be reversed at the end of each stroke. *Figure 2-6* shows the half-bridge phase leg circuit in detail. This circuit can supply current in one direction, but it can supply positive, negative, or zero voltage at the phase winding.
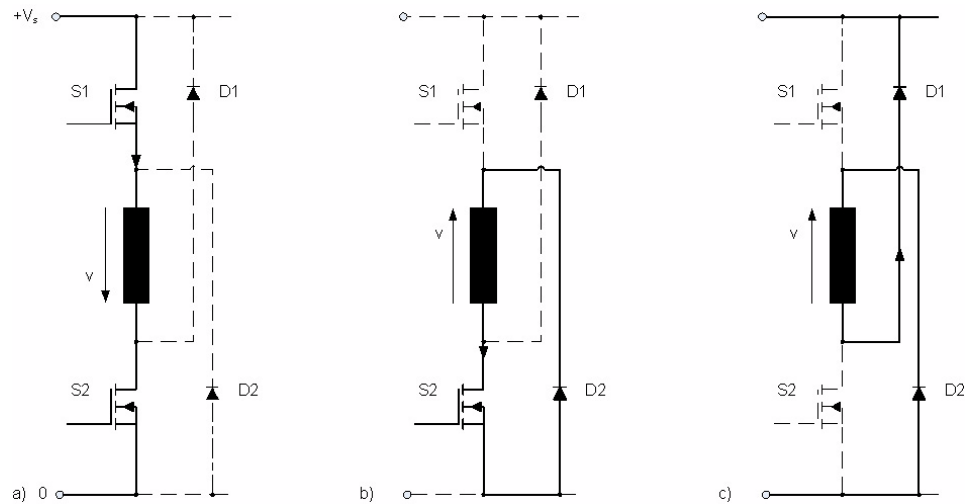
Figure 2-6   Single phase leg circuit

The whole working area of the motor can be divided in two parts, the Low-speed motoring and High-speed motoring phase. At low speed the motor EMF is low compared to the available supply voltage V_S, and the current can be regulated by chopping. At a certain "base speed" the back EMF rises to a level at which the transistors must be kept throughout the stroke to sustain the rated current. Any chopping would reduce the average applied voltage and therefore the current and torque. Here the torque can only be controlled by varying the firing angles, so called single pulse control. Both regulation forms are discussed in the following.

Low-speed motoring, the voltage applied to the phase winding is $+V_S$ if both mosfets are on, 0 if one is on and the other is off, and $-V_S$ if both power switches are off and the phase current is freewheeling through both diodes. These three conduction modes are shown in *Figure 2-6* .

The process of fluxing and de-fluxing is controlled by switching the supply voltage on at the turn-on angle θ_{On} and switching off at the commutation angle θ_C.

At low/medium motor speeds almost all supply voltage is available to force the increase in current, subsequently to the low back-EMF. Current control is necessary at low speed.

The method of current regulation is a question of timing and width of the voltage pulses. Broadly speaking there are two main methods: current hysteresis control and voltage-PWM.

In both cases, as mentioned above, there is a flux building interval from θ_{On} to θ_C, called dwell, and the interval where both mosfets are switched off and the flux decays to zero.

In Voltage PWM there is no closed loop control of the instantaneous current. The current waveform has its natural shape at all speeds, as though the supply voltage was chopped down. For safety issues a current limiting function must be included, but because no attempt is made to control the current instantaneous there is no need to sense the current in every motor phase. Voltage PWM tends to produce quieter operation than current hysteresis control therefore this regulation form was chosen in this Application Note.

Voltage PWM chopping can be realised in two ways with this drive topology, soft chopping and hard chopping. *Figure 2-7* shows the difference and the pertinent phase current, flux linkage, voltage and inductance profile. Soft chopping is when only the high side power switch is chopping; the other switch remains permanently on. Hard chopping is when both transistors are switched on/off

together. It generally produces more acoustic and electric noise, it also generates more current ripples, therefore soft chopping was realised in this application.
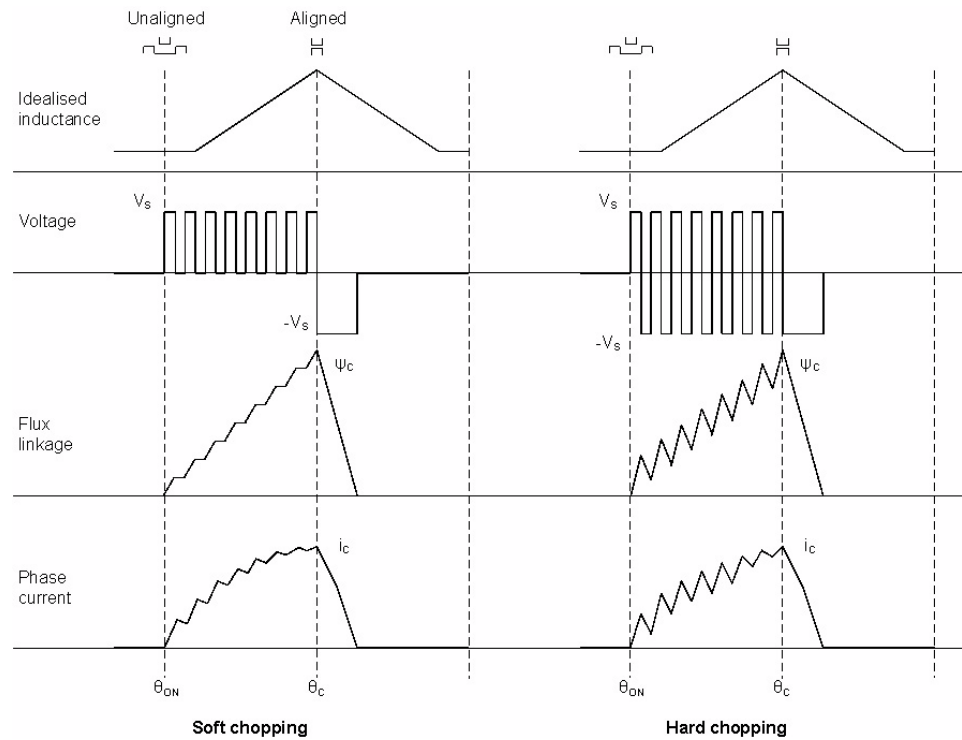
Figure 2-7   Voltage PWM – soft/hard chopping

This control principle can be applied until a certain speed limit is reached. Indeed as the speed increases, the current becomes harder to control because of the back EMF and because the PWM maximum duty cycle/ frequency is reached. For this final stage the speed could be increased by advancing the firing angles θ_{On} and θ_C, the torque being than maximum as soon as the inductance increases. This is even more convenient, as longer time will be available to decrease the current before the inductance starts decreasing.

As mentioned in this and the previous section, knowing the position of the rotor is a key issue to be able to control the current and then the torque. A good torque control will require knowing the inductance profile, the moment when it is at the maximum and minimum values.

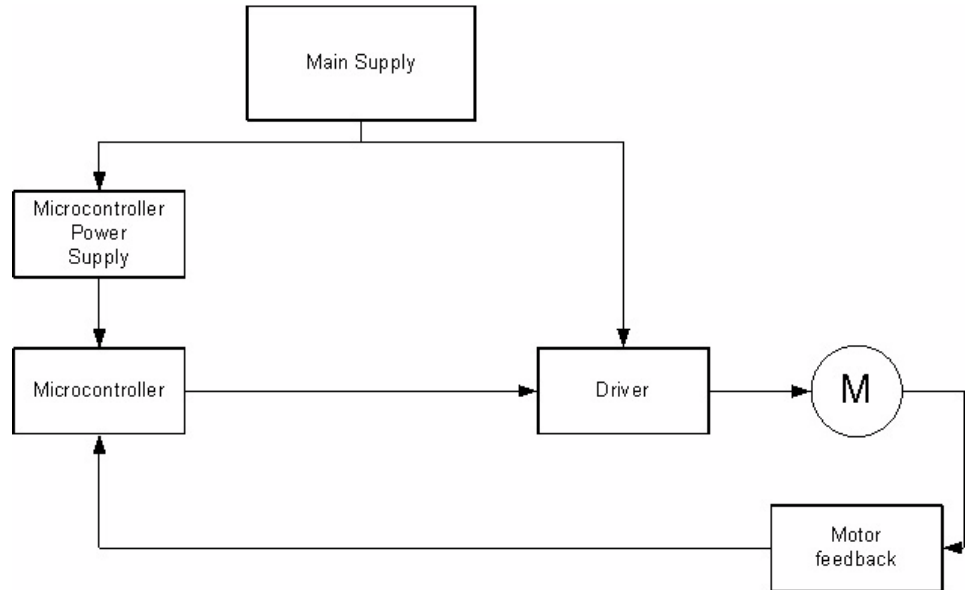The following figure shows a schematic for general motor control design with a microcontroller.

Figure 2-8   **General motor control design**

The functions of the components in detail:

Main supply	Provides circuit energy
MicrocontrollerPower Supply	Regulates voltage and current for the microcontroller
Microcontroller	Produces the accurate signals for switching the mosfets also contains protection circuit, which ensures that a certain current value is not exceeded. Microcontroller observes and regulates the motor velocity.
Driver	Switches the power necessary for the motor phases.
Motor feedback	Gives continuously information about the position of the rotor, speed and spinning direction.

Switched reluctance motor control requirements are summarized below:

• Driver circuit to provide necessary power for the SR machine

• Current limiting device (software based)

• Interrupted based microcontroller algorithm to produce exact output signals

For the velocity control of the motor

• Information about exact rotor position

• Measurement of the motor speed

• PWM Signal to control motor current and power

Chapter 3 System Design Concept

3.1 System Concept

Figure 3-9 shows the principal block diagram of the system concept for the switched reluctance motor.
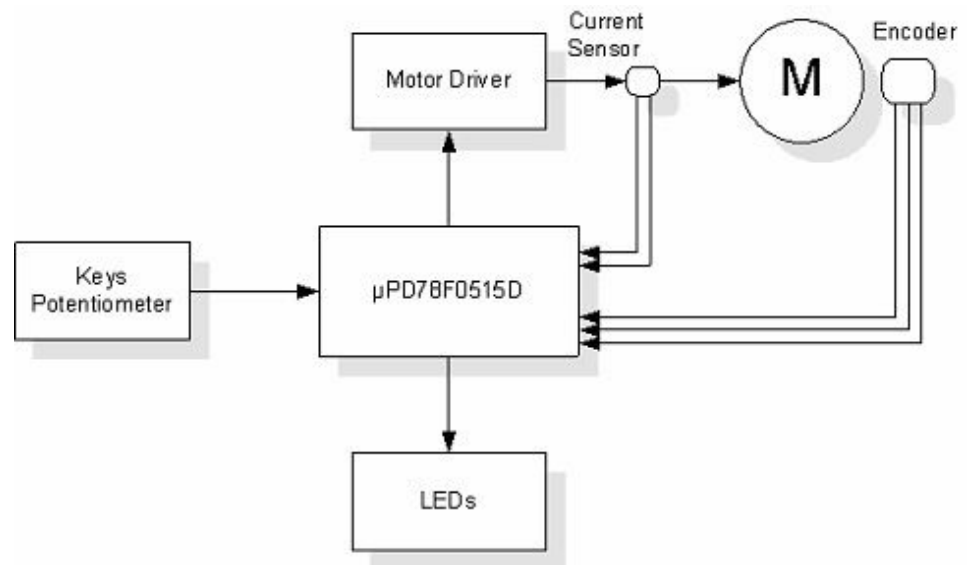

Figure 3-9   Principal block diagram of the system configuration

This system is designed to drive a 4-Phase SR motor. The application meets the following performance specifications:

• Speed control of SR motor with encoder position sensor

• Targeted for 78K0/Kx2 Series

• Variable line voltage up to rated 42V DC

• Control techniques incorporates

- voltage SRM control with speed closed loop
- motor starts from any position with rotor alignment
- two directions of rotation
- motoring mode
- minimal speed 600 rpm (can be set by user)
- maximal speed depended on line voltage 4320 rpm (can be set by user)
- • Encoder position reference for commutation
• User Interface (start/stop switch, right/left switch, potentiometer for speed adjustment, LED indicators)

• DC-Bus over current protection

3.2   System Configuration

Figure 3-10 shows the system configurations and the peripherals of the µPD78F0515D device used for the SR motor control.

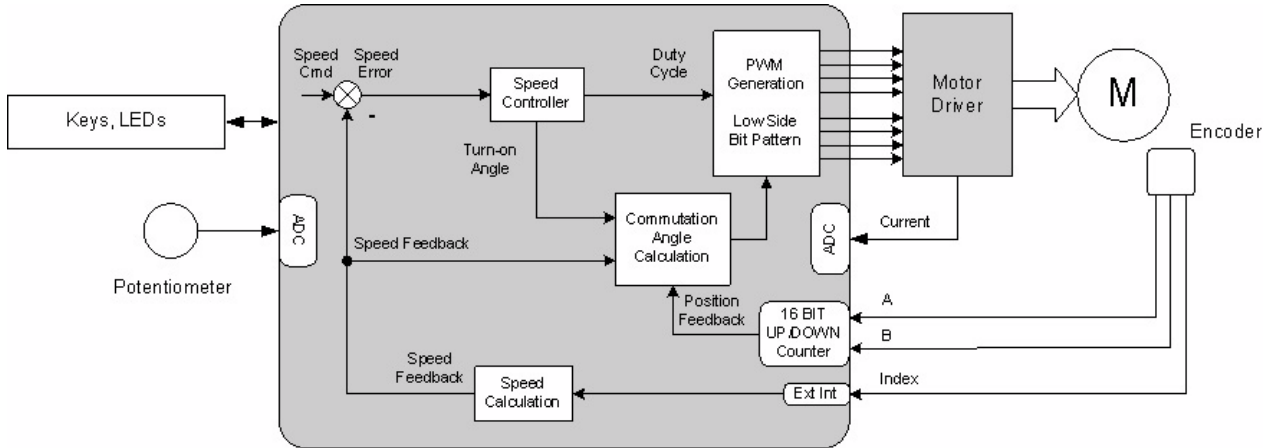**Figure 3-10   System Configuration with the peripherals of the µPD78F0515D**

The microcontroller runs the main control algorithm. It generates 4-Phase PWM output signals for the SR motor power stage according to the user interface input and feedback signals. The required speed is set by a potentiometer, furthermore a start/stop and right/left

switch is provided. When the start command is given the start-up sequence with the rotor alignment is performed and the motor is started in the desired direction.

The rotor position is evaluated using the external encoder and the commutation angle is calculated. When the actual position of the motor is equal to the reference position, the commutation of the phases in the desired direction of rotation is done; the actual phase is turned off and the following phase is turned on.

For the speed calculation no additional velocity sensor is needed, motor speed is derived from the position information.

The reference speed is calculated from user defined potentiometer value. The speed error between commanded speed and actual speed is used in the speed controller to manipulate the voltage applied to each phase winding and the firing angles. As mentioned earlier PWM Voltage regulation is used in low- and mid-speed regions, whereas advancing the turn-on angle in the single-pulse control comes active in the high speed area. The control algorithm is build up in such a matter, when the PWM regulation reaches its limits the single-pulse regulation takes over. Then during the PWM cycle, the actual phase current is compared with the absolute maximum value for the rated current. As soon as the actual current exceeds this value the PWM duty cycle is restricted.

The procedure is repeated for each commutation cycle of the motor.

3.2.1   Start-Up Sequence

As mentioned in the previous section one task of this application is to ensure rotor movement in both directions. Before the motor can be started in the desired rotation direction rotor alignment and initialization of the control algorithm must be performed since the absolute rotor position is not known. The start-up is

performed in several steps; the result is that the rotor is aligned to a known position. Therefore at first two phases are turned on simultaneously, after 50 msec one phase is turned off and the other stays powered. After an additional 550 msec, the rotor is stabilized enough in the aligned position in respect to the powered phase.

The whole stabilization takes about one second and after this period the motor is stable enough to reliably start the motor in any direction of rotation.

3.2.2 Position and Speed Sensing

The position information is a key factor to generate accurate switching for the power converters and is of most importance ensuring drive stability and fast dynamic control. Speed calculation can also be derived from the position information and there is no need for additional velocity sensors.

The presented application uses the on-chip 16-bit timer of the 78K0/KC2 as an Up/Down Counter. The timer counts the externally number of pulses provided by the encoder and the software determines the required values to load into the counter compare register in the correct sequence. In this application a 1000- line encoder is used so the 16- bit timer can produce defined interrupts with a resolution precision of 0.36°.

The speed can be computed by calculating the change in time of the index signal per resolution. An 8-bit interval timer is used to guarantee total independence of positioning sensing and speed sensing. It measures the time and provides the information in rpm to the system.

3.2.3 Commutation Algorithm

The SR motor commutation strategy uses rotor position feedback to drive the signals for the inverter switches. The core of the control algorithm includes the calculation of the commutation angles, and phases commutation.

Due to the 8/6 SR motor topology a fixed dwell angle of 15° is chosen to assure in cooperation with the turn-on angle that the flux should be zero throughout the period of falling inductance. Assuming the software routine outputs the commutations angles in terms of encoder counts then the next requirement is for the software to determine the required values to load into the counter in the correct sequence. The current flow through the stator windings is restricted to 15 mechanic degrees. A closer view at the Index signal of the encoder is also necessary to ensure right commutation values. To synchronize the software with the actual rotor movement, the compare value has to be manipulated every time the Index signal comes active.The values that are loaded into the timer are calculated as followed, T_{ON}, T_{OFF} are the appropriate turn-on turn-off angles:
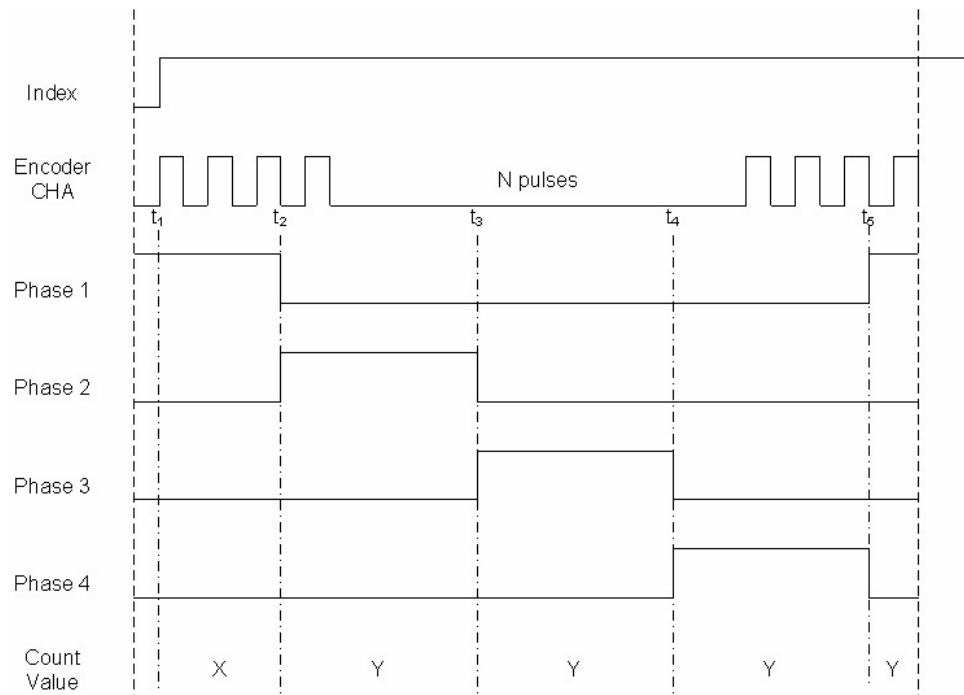
$$CountValueX = T_{ON} - (2 \cdot DwellAngle)$$
$$CountValueY = T_{OFF} - T_{ON}$$

The software determines the values at which the system has to react and change the commutation pattern.

Figure 3-11 shows commutation control with a high-resolution encoder and the distinct values x and y for the 16-bit timer capture compare register.

Figure 3-11   Commutation control with high-resolution encoder

The presented commutation algorithm does not allow parallel current conduction of two phases at the same time.

3.2.4   Current Limiter

The application deals with voltage PWM control, there is only need for a current security loop so rated current is not exceeded. As soon as this state is detected the PWM is manipulated to prevent further current rise.

3.2.5   Current Sensing

Current measurement needs to be investigated according to current sensors used and the influence of noise on the measurement

The quality of current measurement depends heavily on the type of current sensor used. In this application the voltage drop across a sense resistor is used to calculate the actual current. Shunt resistors in combination with RC Low-Passes are a cheap solution and the current only needs to be limited, therefore expensive Hall Effect sensors are not used.

The sensing needs to be synchronized with the actual PWM signal to ensure current flow and to reduce voltage ripples. *Figure 3-12* shows the actual phase current measured on the shunt resistor as described above.
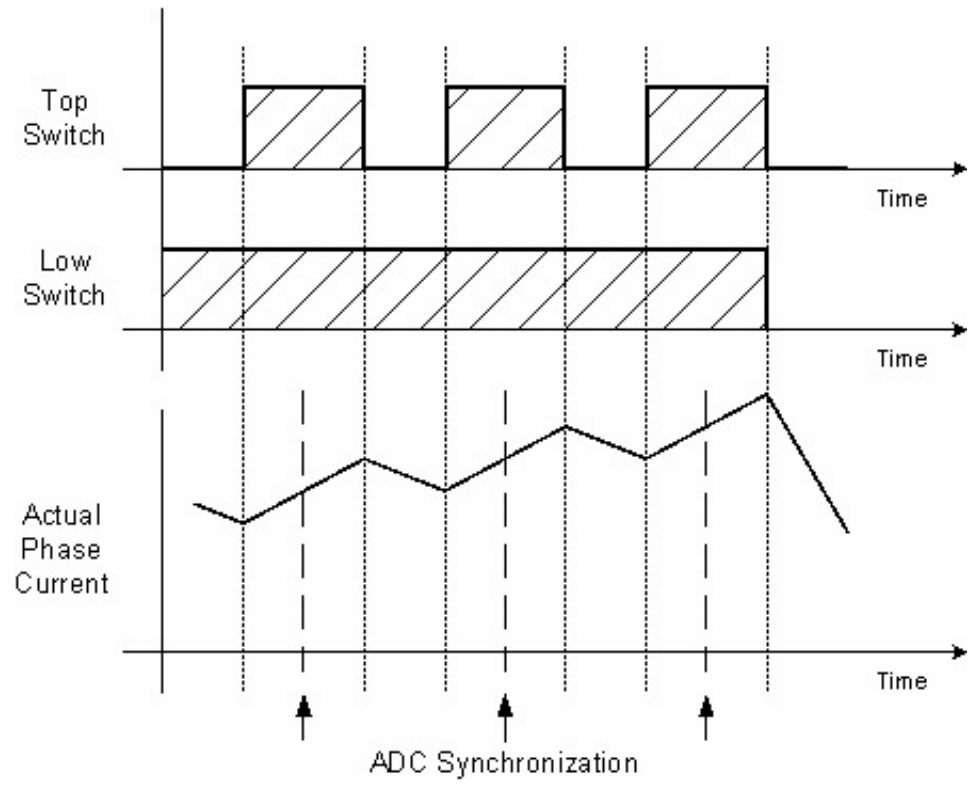
Figure 3-12   Soft switching current sensed on ADC

Chapter 4 Hardware Configuration

This section describes the hardware requirements for this application example.

4.1 µPD78K0/KC2 Configuration

The µPD78K0/KC2 device is a member of the high performance 78K0/Kx2 Family 8-bit microcontrollers. The configuration of the device and the operating environment used in this application is listed below:

- CPU: µPD78F0515D
- Operating clock: System clock 20 MHz
- Operating Voltage: 5 V
- Internal ROM: 60 Kbytes
- Internal RAM: 1024 bytes
- External expansion memory: not used

4.2 Peripherals I/O Assignments

Table 4-1 lists all pins of the µPD78K0/KC2 device and the ones that are used in this application are described with their associated function.

Table 4-1   **µPD78K0/KC2 Peripherals I/O Assignments**

Pin no.	Pin name	Mode setting	Function
1	P60/SCL0	Output	Not used
2	P61/SDA0	Output	Not used
3	P62	Output	Not used
4	P63	Output	Not used
5	P33/TO51	Output	Not used
6	P75	Output	Motor start/stop switch
7	P74	Output	Not used
8	P73/KR3	Output	Motor direction switch
9	P72/KR2	Output	LED green, regulator
10	P71/KR1	Output	LED yellow, rotation direction
11	P70/KR0	Output	LED red, motor running
12	P32/INTP3	Output	Not used
13	P31/INTP2	Output	Not used
14	P30/INTP1	Output	Not used
15	P17/TO50	Output	Not used
16	P16/TOH1	Output	Motor highside BD
17	P15/TOH0	Output	Motor highside AC
18	P14/RxD6	Output	Not used
19	P13/TxD6	Output	Motor lowside D
20	P12/SO10	Output	Motor lowside C
21	P11/SI10	Output	Motor lowside B
22	P10/TxD0	Output	Motor lowside A
23	AVREF		Connect to VDD
24	AVSS		Connect to ground
25	ANI7/P27	Input	Not used
26	ANI6/P26	Input	Not used
27	ANI5/P25	Input	Not used
28	ANI4/P24	Input	Not used
29	ANI3/P23	Input	Not used
30	ANI2/P22	Input	Current sensing BD+
31	ANI1/P21	Input	Current sensing AC+
32	P20/ANI0	Input	Potentiometer voltage
33	P130	Output	Potentiometer
34	P01/TI010	Input	Encoder channel B
35	P00/TI000	Input	Encoder channel A
36	P140/PCL	Output	Not used

Pin no.	Pin name	Mode setting	Function
37	P120/INTP0	Output	Not used
38	P41	Output	Not used
39	P40	Output	Not used
40	$\overline{\text{RESET}}$	Output	Reset input
41	P124/XT2	Output	Not used
42	P123/XT1	Output	Not used
43	FLMD0	Input	Not used
44	P122/X2	Output	System clock
45	P121/X1	Output	System clock
46	REGC	Output	Not used
47	VSS	Output	Ground
48	VDD	Output	Power supply

4.3 Motor Specification

The 4-Phase switched reluctance motor used in this application note has eight stator poles and six rotor poles. This combination yields 24 strokes per single revolution. The mechanical angle 60° corresponds to one electrical stroke.

Motor Type	4-Phase SR Motor
Stator/ Rotor Poles	8/6
Rated Volts	42VDC
Rated RPM	3500
Rated Power	200 W
Rated Current	10A / PH

4.4 Encoder Specification

The optional included encoder should generally have following specification and provide the signals shown in *Figure 4-13* .

Supplied Voltage	5V
Resolution per Step	1000 Counts
TTL Compatible	
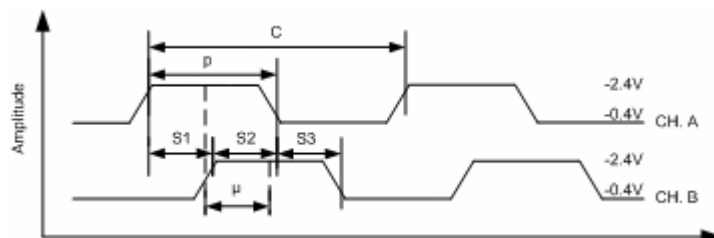
Figure 4-13   **General signal process of the encoder**

The encoder also provides an additional Index signal, which occurs once a revolution.

4.5 SR Motor Driving Circuit and User Interface Circuit

Figure 4-14 is a schematic of the driving circuit used in the development of this application note.

Complete part list for *Figure 4-14* :

Resistors	
R1, R2, R5, R4, R8, R9, R11, R12	10 Ω
R3, R6, R7, R10, R13, R14	0.01 Ω
Capacitors	
C1, C3	560 pF
C2, C4	100 nF
Diodes	
D1, D4, D5, D6, D9, D10, D11, D12	1N4148
D2, D7	BYW81P
D3, D8	BYV72
MOSFET	
Q1, Q2, Q3, Q4, Q5, Q6	IRFP150

Figure 4-15 is a schematic of the User Interface and micro peripherals used in this application note.

Complete part list for *Figure 4-15* :

Resistors	
R1, R2, R3, R4	330 Ω
R5, R6	10 kΩ
R7	1 kΩ
R8	10 Ω
R9, R10, R11, R12, R13, R14	100 Ω
R15, R16	500 Ω
Capacitors	
C1	470 µF
C2	0.33 µF
C3	0.1 µF
C4	100 pF
C5	1 µF
C6, C7	100 nF

Figure 4-14   Motor Driver for SR Motor
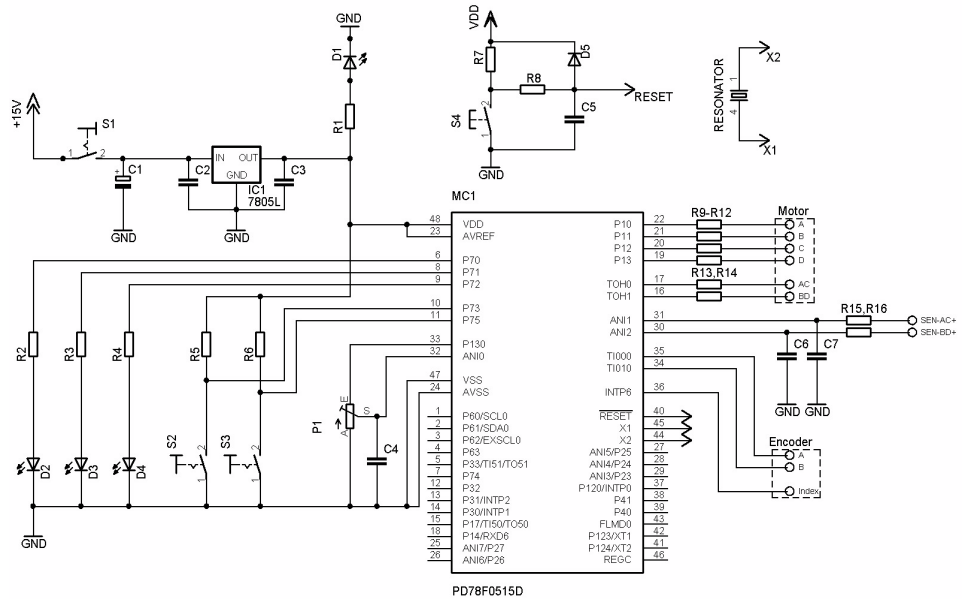
Figure 4-15   User Interface for SR Motor

Chapter 5 Software Process Description

This section describes the software implementation for this application example. *Figure 5-16* shows the principal data flow diagram and the relationship between the software modules and hardware peripherals that are involved in the control of the motor.
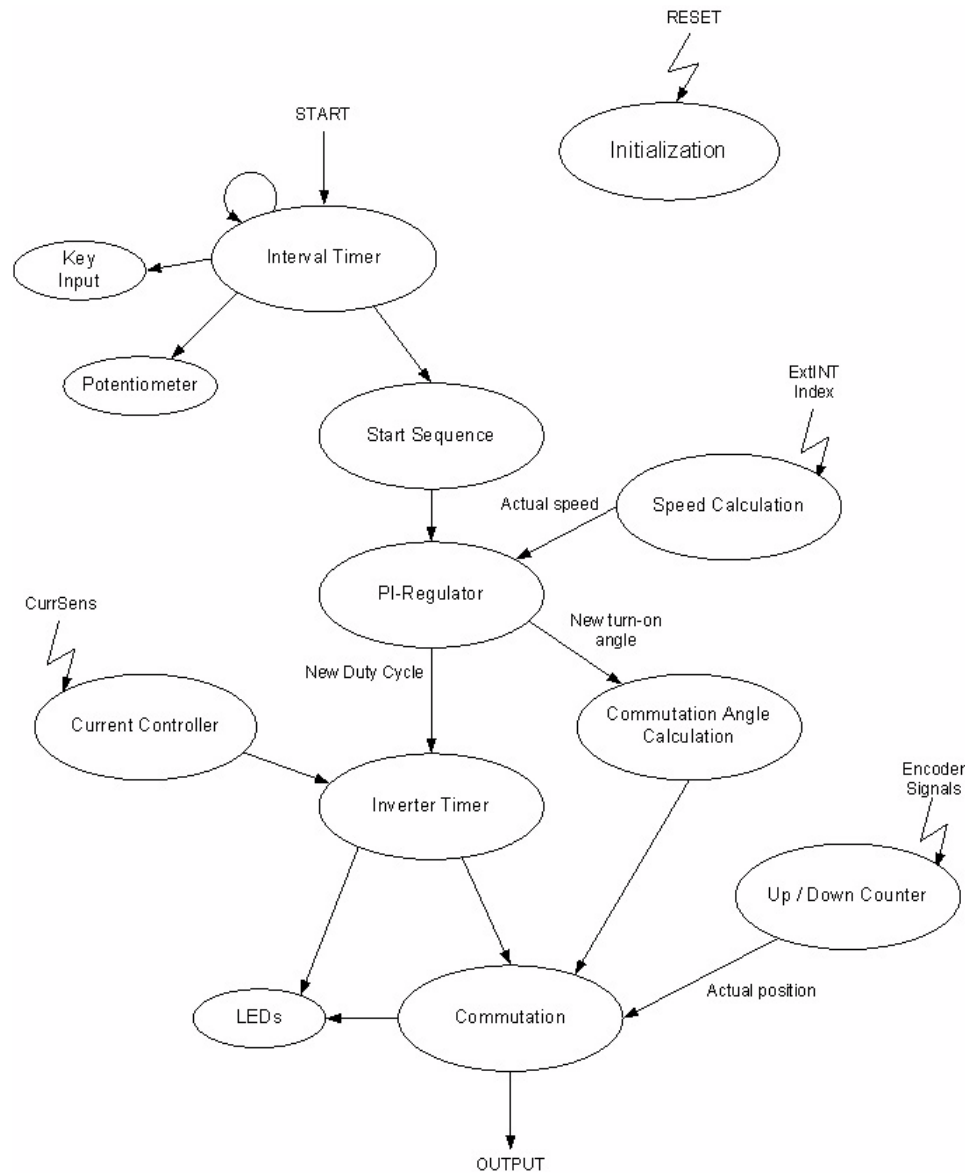
Figure 5-16   Principal data flow diagram

The functions of the system shown in *Figure 5-16* are sequential and implemented and executed in the main endless loop of the software. The individual processes are described in detail in the following sections.

5.1 Initialization

The initialization process is responsible for the initializing the µPD78K0/KC2 device after a system reset. It configures the basic clock settings of the device, initializes the peripherals that are used for the motor control application and disables/ enables interrupts. The initialization contains two parts as shown in *Figure 5-17* , the first part that initializes the configuration of the device and the second part initialize the peripherals with their operating mode.
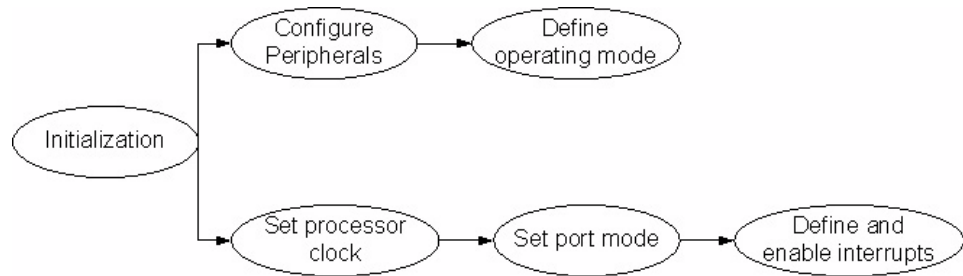
Figure 5-17   **Initialization process**

5.2 Interval Timer

An 8-bit timer is used to realize the interval timer function. It is used to generate an interrupt request at the preset time interval. The interval time length is set to the period of T = 998.3 µs. The function Interval Timer is used whenever specific time periods are needed. It controls the execution of the key input function and the potentiometer function. It's also responsible to start the SR motor with the start sequence of the system.

5.3 Key Input, Potentiometer function

These are the two functions that are responsible for getting the key inputs, to make the user able to make a choice between start/ stop and the spinning direction of the motor, and the actual potentiometer position, where the rpm of the motor can be manipulated. The Key Input function is event controlled and it is executed only when a key entry is recognized. The sample time of the key entry is defined with the elapse time of the Interval Timer function.

The Potentiometer function uses the same sample time and is also event controlled.

A software algorithm divides the potentiometer interval into user defined values, here in this application note 600 rpm for minimum and 4320 rpm for the maximum value was chosen.

A software filter is applied to the potentiometer routine for greater noise immunity. The system can immediately work with the newly adjusted speed.

5.4 Start Sequence

The start sequence of the system is the function that allows a non-reflecting start of the motor. As already described the motor needs to be aligned to a known position to be able to start in the desired direction of rotation. The fixed bit pattern for phases C and D is provided for the low-side driver, high-side driver PWM is set to 25% duty cycle. The sample time of the CD energizing is defined with the elapse time of the Interval Timer function. After the request flag is cleared phase C is turned off and after a short sample period the system is stable and can operate in its normal manner.

5.5 Speed Calculation

The process calculates the actual speed of the motor. The calculation is based on the evaluation of the index information. An extra 8-bit timer is used for speed calculation to ensure independent working. When the index signal occurs the timer starts to count up, as soon as the next Index signal follows the timer is read out and cleared to zero. Timer frequency is chosen to ensure all working areas of the motor, in this application 600 – 4320 rpm, no interrupts are generated to minimize microcontroller load. If an overflow occurs an OV Flag is set and the software can react to it.

The speed is computed by reading the time difference per pre-defined time sample.

A software moving average filter applied to speed measurement is incorporated into the process for greater noise immunity. The actual motor speed is calculated as the average value of at least two measurements. All calculations in the application use the onboard multiplier/ divider to keep microcontroller loads low and to ensure fast calculation times.

5.6 PI-Regulator

The PI-Regulator used is the classical Proportional Integral (PI) control method in the voltage control and turn-on angle control of the switched reluctance motor.

The regulator is based on the recursive PI algorithm known also as the speed algorithm and takes the form of:

$$G(s) = K_p + K_i \cdot \frac{1}{S}$$

transformed into a discrete form:

$$K_p \cdot X_d + K_i \cdot \left(\sum X_d \right)$$
$$X_d = X(n) - X(n-1))$$

where:

Kp	presents the proportional gain
Ki	presents the integral gain
Xp	presents the voltage error
$\sum X_d$	presents the accumulated voltage error

The coefficients KP and KI were derived empirically and optimized based on system behaviour produced by disturbances during the system testing.

The sample time of the regulator is set to distinct time period two times faster than the maximum velocity of the motor. The function also normalise the value and transforms the calculated regulated quantity into the duty cycle of the PWM signal or the appropriate turn-on angle. As mentioned before two control methods are necessary to guarantee best control over all speed periods, voltage PWM in low-, mid-speed regions and turn-on angle shifting in the high speed region. Both methods use the same basic PI structure, but differ in their Kp and Ki values. Every time the function is active both values are calculated, but only the one is used that is appropriate for the current situation. If voltage PWM reaches its critical settings the actual speed is stored and turn-on angle control takes over, if the ordered speed falls below the stored value voltage PWM takes back over. A control flag is set if both mechanisms reach their limit. Two 8 bit timers are used for the 20 kHz PWM output to ensure independently switching and low audio noise.

5.7 Commutation Angle Calculation

This process calls the commutation angle calculation routine which calculates the exact angles for phase firing. It also provides the accurate shifting of the turn-on angle and that the dwell angle is fixed to 15 degrees of mechanical rotation. All calculations in the application use the onboard multiplier/ divider to keep microcontroller loads low and to ensure fast calculation times.

5.8 Current Limiter

The main task of this routine is to assure that a certain user defined current value is not exceeded. The sampling of the ADC that is used to gather the voltage over the shunt resistors is synchronized to the PWM pulses. The process selects the proper ADC channels to be converted and reads and processes the results of the ADC conversion. The shunt voltage is filtered using a moving average filter. If the critical settings are reached the routine manipulates the PWM duty cycle and ensures lowering the actual current per phase.

A control flag is set as soon as the current controller has to react.

5.9 Commutation

This process provides the commutation of the motor phases. Here all information come together and control the motor. Depending on the actual position of the rotor the routine sets the output, the right bit patterns for the desired direction of rotation. The whole routine is based on interrupting the system as soon as the desired position for the next commutation is recognized. An ISR with high priority serves this duty. It is also possible to manipulate the bit patterns with an extern function. The System must be able to react at any given time to the position information.

5.10 LEDs

Three LEDs are used to show the different working conditions of the system. The red LED signals that the motor is running, yellow indicates the spinning direction and green shows when the regulation algorithm has reached its maximum.

Chapter 6 Software Flow Charts

This chapter describes the important functions used in the system of the switched reluctance motor control application. Please refer in the software source codes if more information about these functions is needed.

6.1 Concept and Main Flow Diagram

Figure 6-18 shows the main program flow chart.
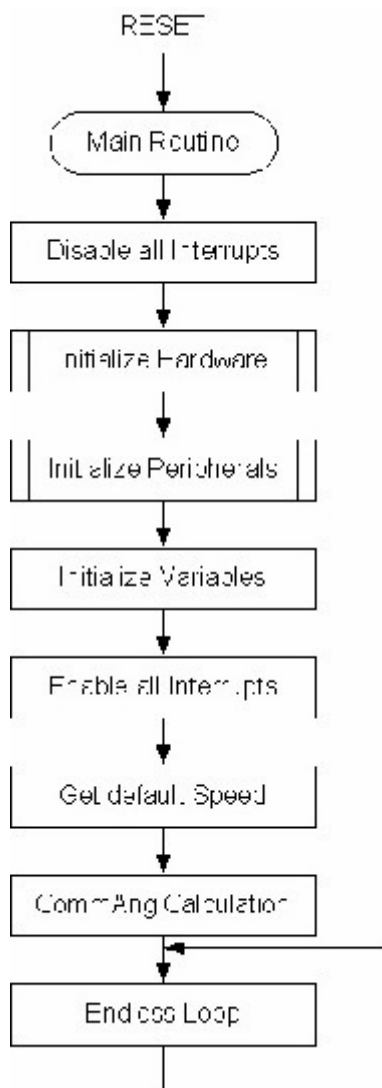
Figure 6-18   Main Program

6.2 Peripherals Initialization

Figure 6-19 shows the initialization of the used hardware peripherals of the µPD78F0515D device with their operation mode in this application.
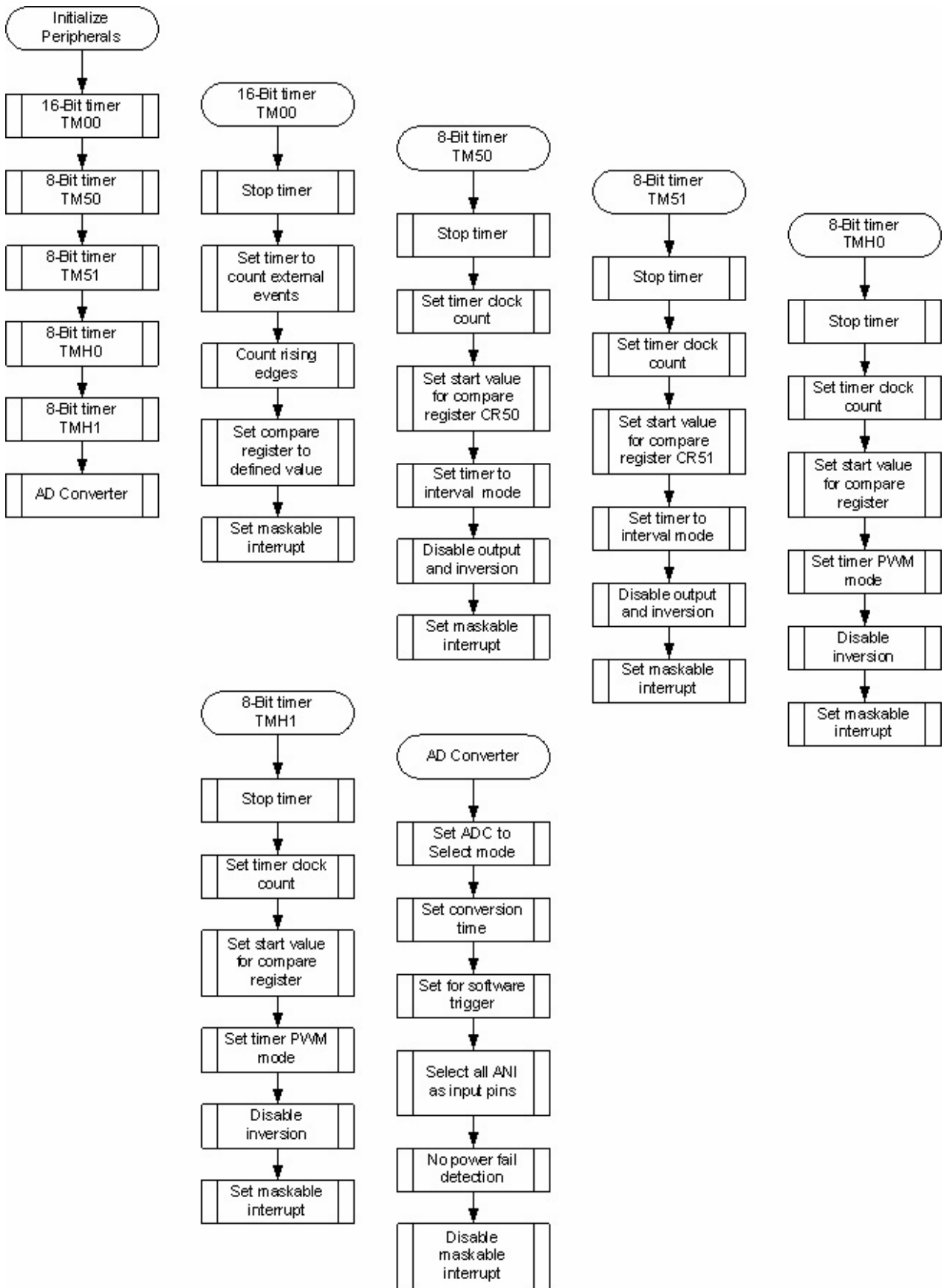
Figure 6-19   Peripherals Initialization

6.3 Main Loop

Figure 6-20 shows the endless loop of the main program used in this application.
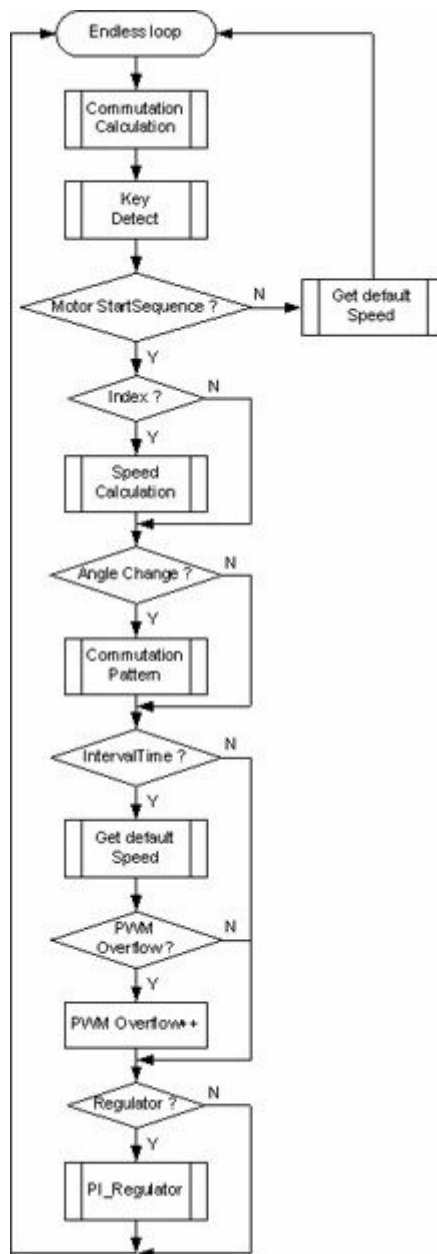
Figure 6-20   Endless Loop

6.4 Commutation Calculation

In *Figure 6-21* the flow chart of the commutation angle calculation is shown. The routine is calculates the appropriate turn-off angles and the required values Count Value X, Count Value Y for the 16-bit up/ down counter.
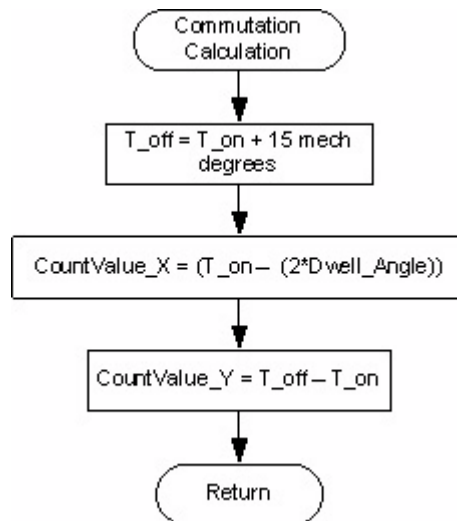
Figure 6-21   Commutation Calculation

6.5 Key Detect

Figure 6-22 shows the Key Detect flow chart.
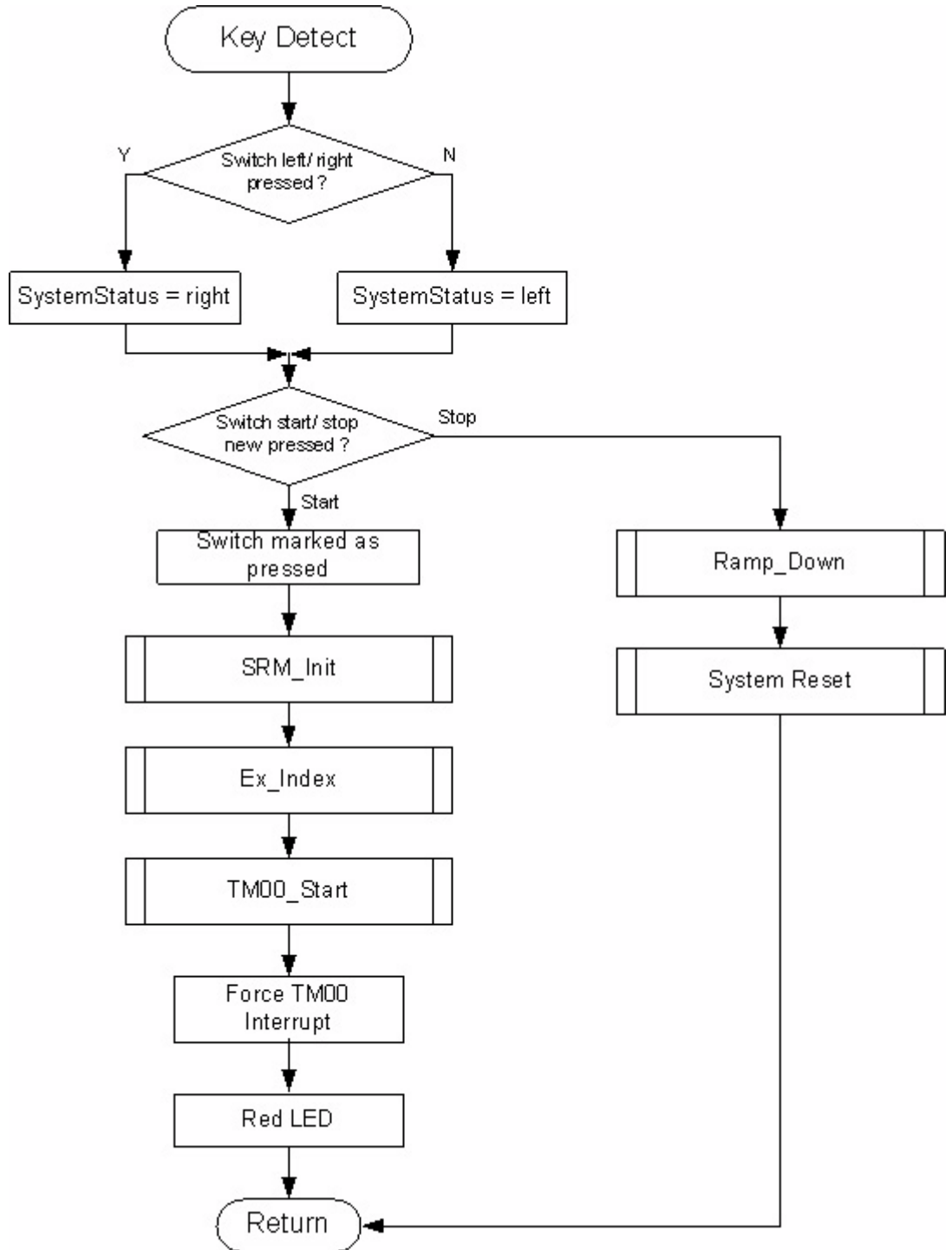
Figure 6-22   Key Detect

6.6 SRM Init

SRM Init provides the defined start position of the motor. *Figure 6-23* shows the associated flow chart.
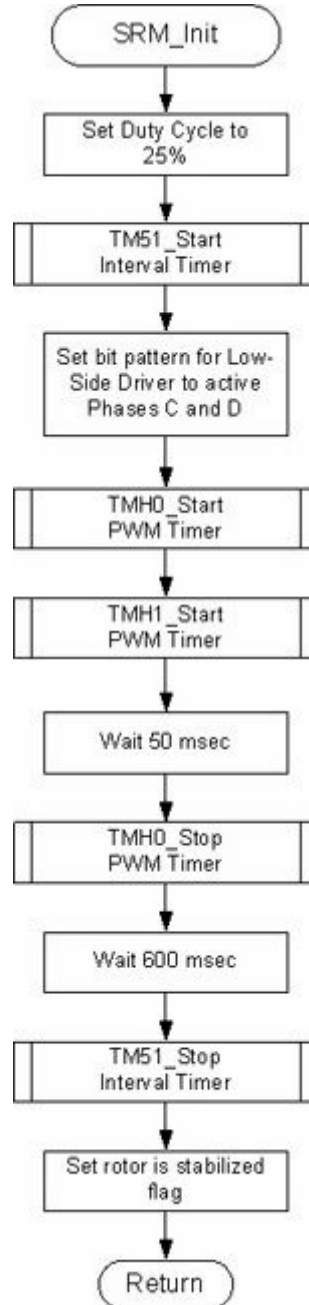
Figure 6-23   SRM Init

6.7 External Index

This function activates the external interrupt for the encoder Index signal and provides the action that has to be taken at this point.
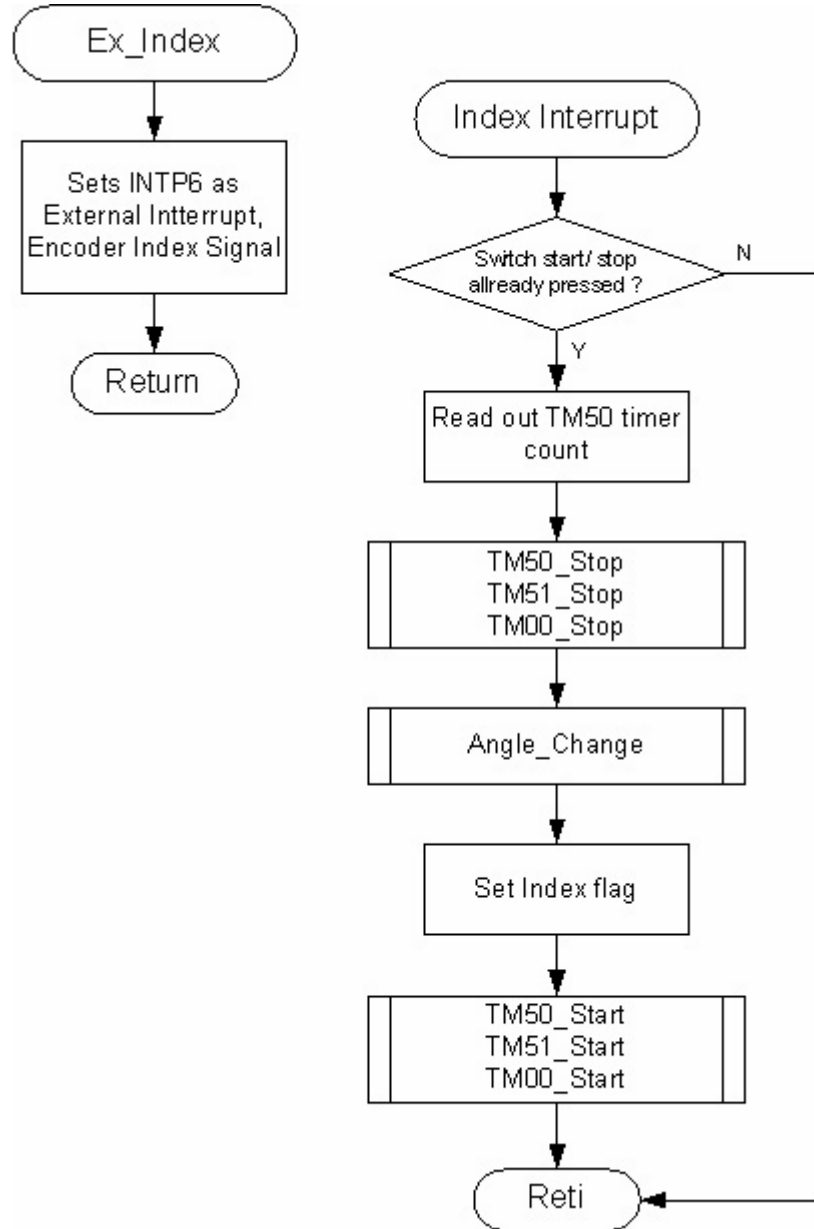
Figure 6-24   External Index

6.8 TM00 interrupt

16 bit up/ down counter TM00 interrupt based commutation control.
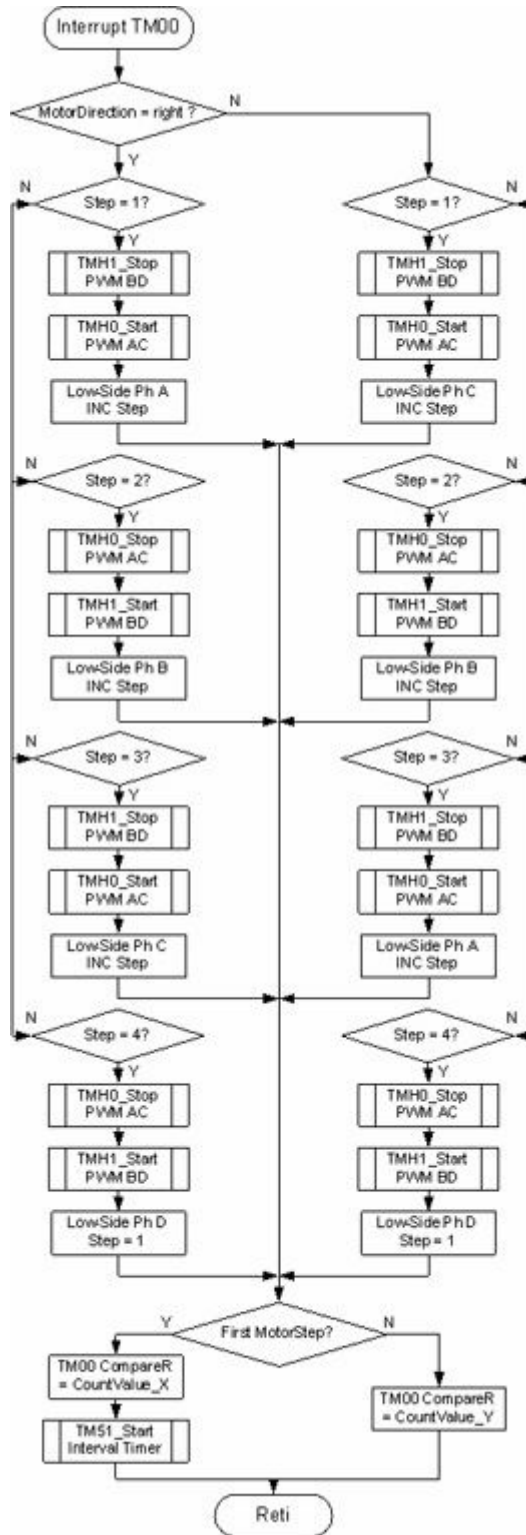
Figure 6-25   TM00 interrupt

6.9 Angle Change

This function is responsible to assure that if the firing angles are being shifted the right steps are maintained and a flag is set to immediately react to this new condition. *Figure 6-26* shows the flow chart.
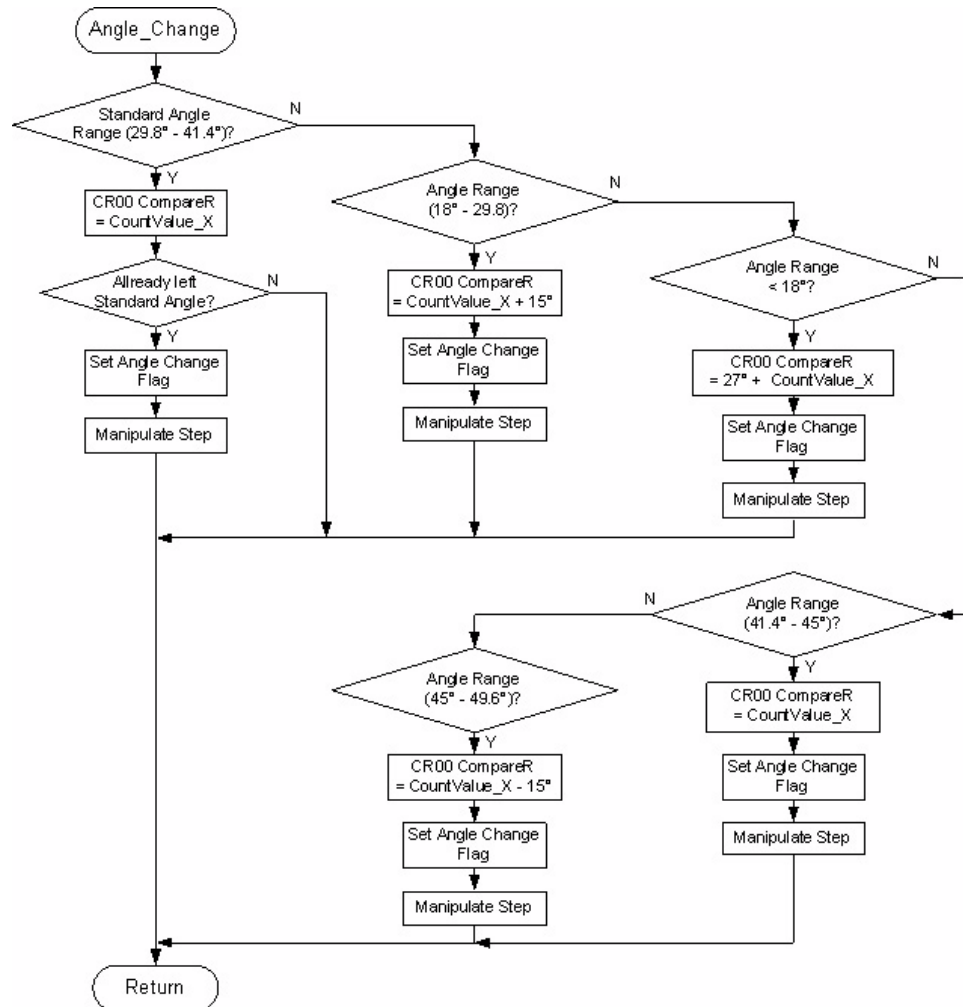
Figure 6-26   Angle Change

6.10 Commutation Pattern

Commutation Pattern reacts as soon as Angle Change Flag is set and works with the manipulated Step variable.
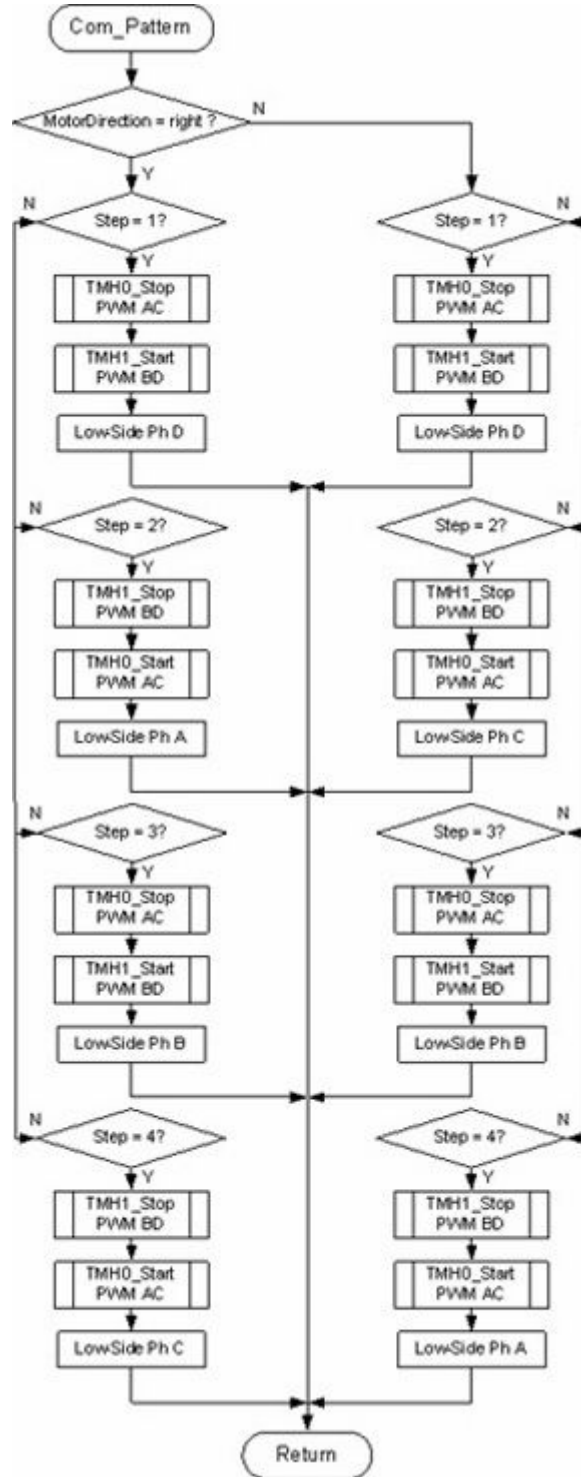
Figure 6-27   Commutation Pattern

6.11   Speed Calculation

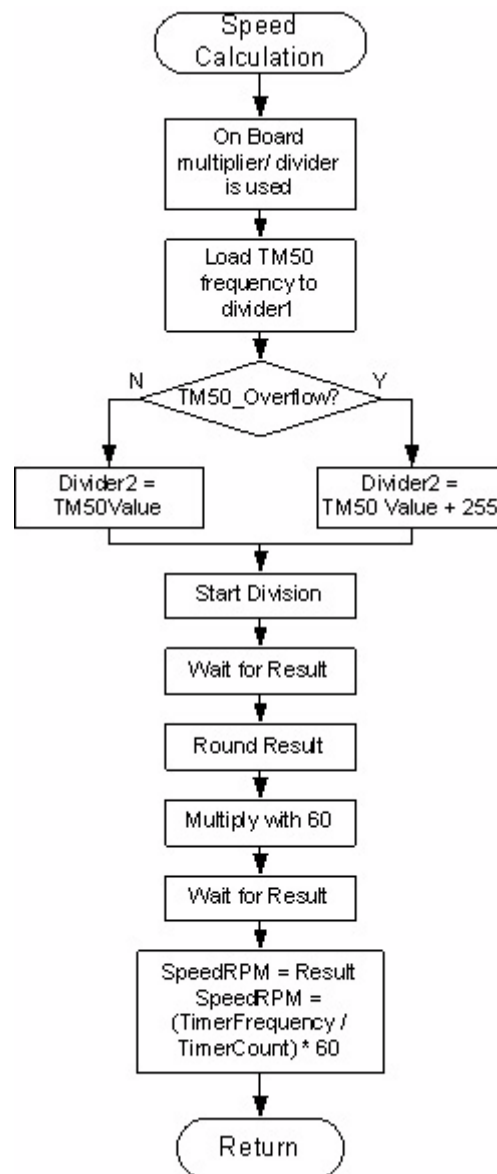*Figure 6-28* shows the Speed Calculation flow chart.

Figure 6-28   Speed Calculation

6.12 Get ordered Speed

A Potentiometer is used to get the ordered speed. *Figure 6-29* shows the flow chart.
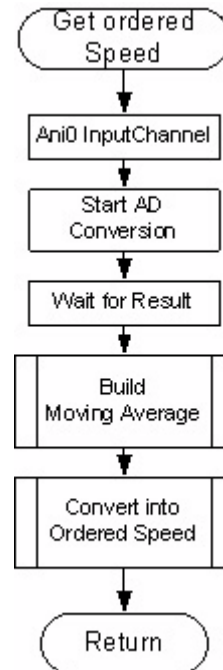

Figure 6-29   Get ordered Speed

6.13 PI-Regulator

Figure 6-30 shows the function flow of the implemented PI-Regulator in the system.

Figure 6-30   PI-Regulator

6.14 Ramp Down

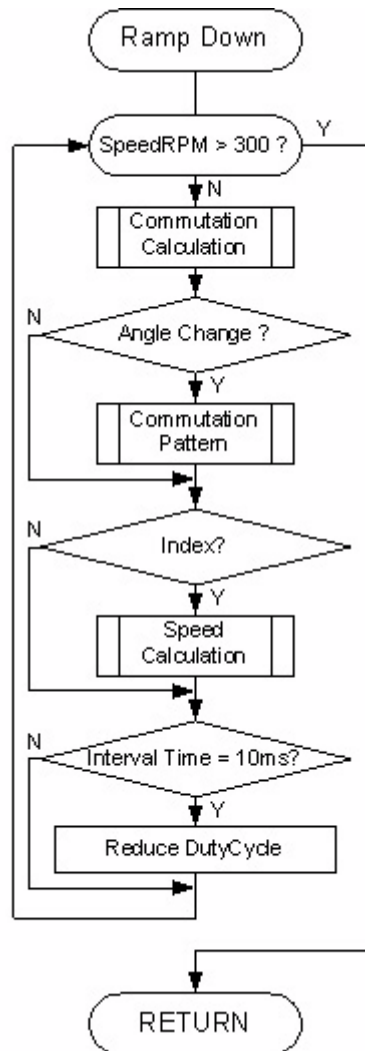*Figure 6-31* shows the Ramp Down flow chart.

Figure 6-31   Ramp Down