University of Belgrade
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Sensorless control of brushless DC electromotor

Diploma thesis

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Abstract

In this paper one brushless DC electromotor control method without position sensors on motor is considered. In first chapter we will be introduced to widely spread brushless DC motors. We will take brief pros and cons analysis of brushless DC drive. Later we will be introduced to the types of position sensing in one brushless DC drive – explicit and implicit. Than we will do thorough analysis of our method. Calculation of components and practical realization of position sensing circuit will be given. For a practical realization of entire system IRDAK 10 motor drive (International rectifier) will be used. It will be analyzed as well as microcontroller PIC16F873 (Microchip) which is the brain of our system. Afterwards, we will take a look at the changes that have to be done on IRDAK in order to connect our position detecting circuit on it. Software resources will be described. Performance analysis will be done. Possible applications and upgrades will be proposed.

1. Introduction

Brushless DC electromotor

Brushless DC (BLDC) electromotor is a name referred not only to a type of a motor but to a type of control also. BLDC can be any electromotor with permanent magnets on a rotor. Stator windings can be sinusoidaly distributed but it is not necessary, a simple linear distribution which produces a trapezoidal back electromagnetic forces (BEMF) will do the job. That is an advantage because motors with sinusoidaly distributed stator windings make motor more expensive.

The idea of BLDC motors is to have one phase disconnected, while the current which runs through the other two phases is controlled. This current causes torque which pulls rotor. When rotor gets into the right position we should do the switch, that is, we should disconnect one phase and turn on the one that was disconnected. The current will then decay through the diode. It resembles a step motor with six steps. If we have three phases, the steps are: A->B, A->C, B->C, B->A, C->A, C->B – meaning the current goes from phase A to phase B, from phase A to phase C, etc.(take a look at Fig. 1) The number of steps will be multiplied by a number of pairs of poles, but that will not have influence on a control of our motor, and will be neglected at this point, that is we will assume that motor has one pair of poles (2 poles)

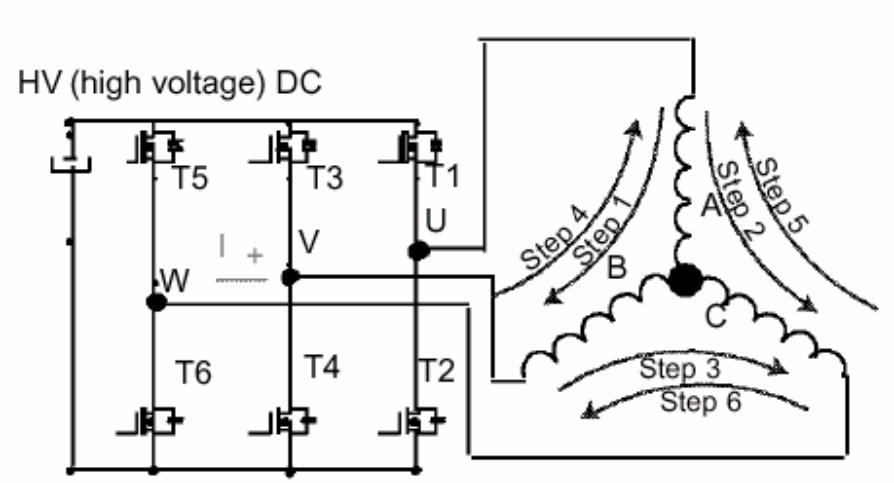


Figure 1-1: Brusshless DC motor functioning

The name BLDC electromotor comes from the similarity of a transfer function of this motor and a simple DC motor. If we connect our motor to a voltage it will react in the same manner as a DC motor with independent supplies of armature and stator. In that analogy permanent magnet plays the role of a stator in DC motor and stator plays a role of windings. Our digital hardware will do the job of the commutation, one advantage more we do not have brushes that would have to be changed occasionally.

Advantages and drawbacks of BLDC motor control

Hardware & software are more complex than in conventional DC motor control, but the motor itself is smaller, more efficient, cheaper, lighter, more rugged and reliable. On the other hand hardware and software are less complex than in regular synchronous control drives. The fact that we have to control only one current instead of three and still have, we can say vector control, makes BLDC a very desirable mode of control. We only need one PWM module – disadvantage is that the mentioned module has to have access to more pins, in our case six. Generally the processor which is used has less processing power than the ones used for a regular control of synchronous drives, but at this point we cannot do much generalization because required processor power depends on a peripheral hardware: current sensors, position detector etc.

Disadvantage of BLDC control are torque peaks which will occur due to commutations. These peaks are the consequence of a current decay and can not be eliminated. I have to say here that for a majority of applications these peaks are irrelevant. We cannot use brushless DC motor for a position control. In some cases we can, but it will be poor quality control, as we do not control position continually, our control is discrete.

At the end of this paragraph I would like to emphasize again, that in the BLDC control mode we do not have complicated space vector modulation nor multiple current sensing, that is, we only have to control one current with one PWM module. In spite of it is simplicity we still have vector control, that is, direct control of the torque.

2. Position sensing

Types of position sensing

In the machines with permanent magnets on rotor there are various types of determining rotors position. We can divide them in explicit and implicit. Explicit are the ones that are mounted on the rotor or inner side of the stator. They include: incremental indicators (encoders), resolvers and Hall sensors. Implicit sensors extract commutation information from phase voltages, and can be called sensorless. Probably the best ways of a position sensing are optical encoders and synchronous resolvers.. They can give us a very precise position of the rotor, and we can determine very precisely rotors speed by differentiating their position. These types of position detectors can give us position of rotor independently of a type of machine. Problems with these types of detectors are their price and the fact that they have to be mounted on the shaft which complicates the whole mechanism. In brushless DC motor there is no need for continuous position detection. We only need to detect position on every 60 degrees, in order to commutate properly. Low resolution sensors can be used; one optical sensor, for example. We must bear in mind that dust may cause these sensors not to function. So in BLDC drives, normally, if we want to control only speed, not position, optical encoders and synchronous resolvers are not used.

Most frequently used structure for position detection is the **set of three Hall sensors** on stator. Principle of their functioning is based on the Hall effect. Current which runs through the hall element in conjunction with magnetic field which we want to measure causes potential difference on Hall sensor (due to magnetic force **F**=q**v** x **B**). Sensors used in brushless DC motor are usually bipolar. On fig. 2-1 is one typical Hall sensor structure.

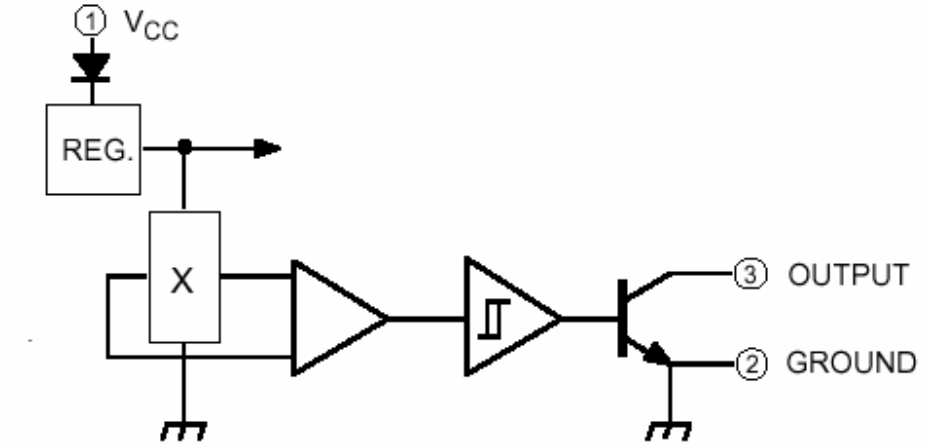


Figure 2-1 Position sensing via hall element

Hall element is marked with X – which means that magnetic field is getting into it from upper side of this paper. Block reg. provides constant current in Hall element. Potential difference on ends of sensor is fed to an amplifier and than on hysteretic comparator. When magnetic field is stronger than +threshold output is “1”, and when it is weaker than

–threshold output is “0”. State between thresholds is undefined. Output signals from three sensors are used as feedback in our control system. Disadvantage of this system is its sensitivity to PWM. Noise generated by PWM may cause this system to trigger incorrectly. The main problem here is high cost of Hall sensors and their mounting to the inner side of stator. That is why we will try to detect rotors position implicitly, without sensors.

Sensorless position detection

There are various types of position detection. All of them are based on extracting

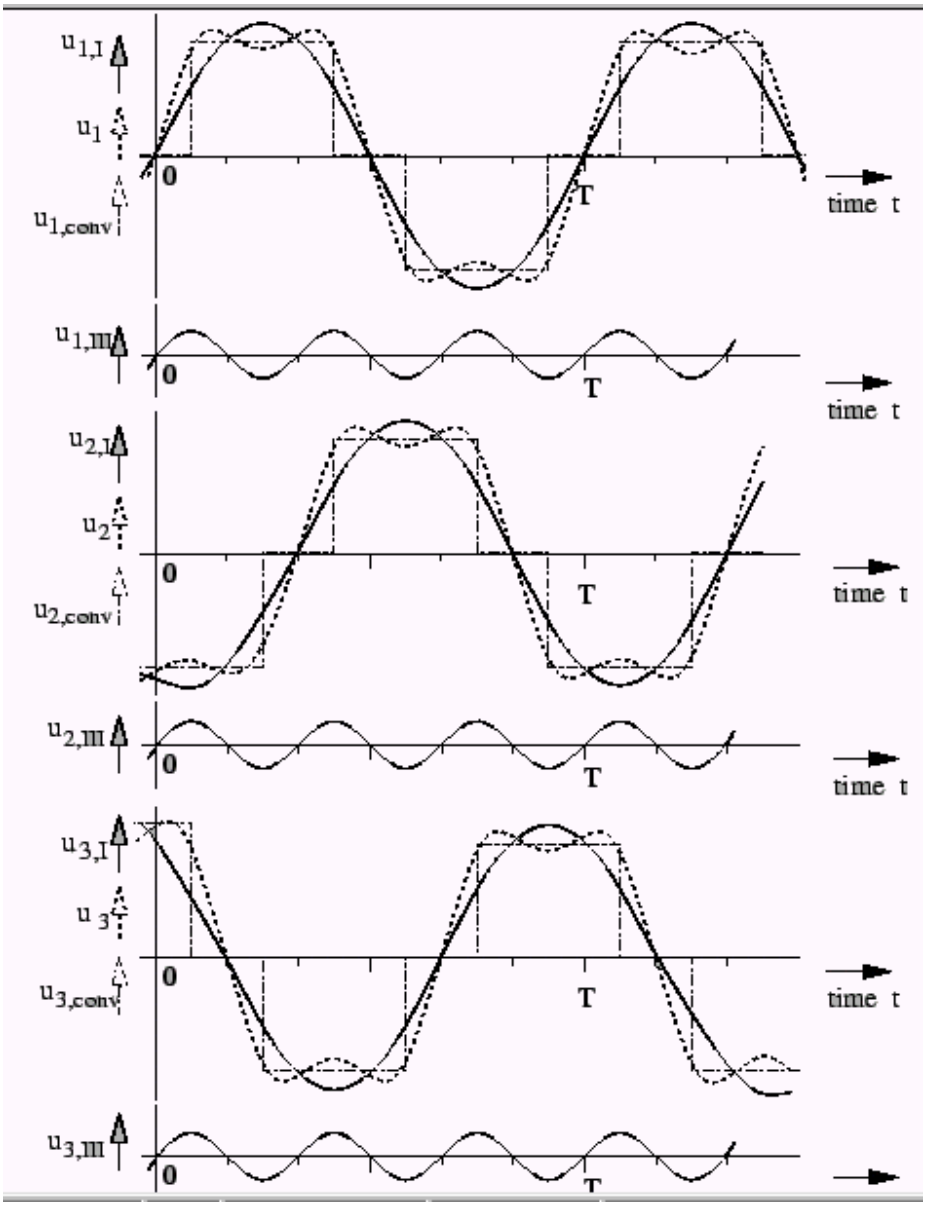


Figure 2-2 Diagrams of back electromotor forces

position information from terminal voltages and sometime currents. Position can be detected through **detection of saturation of phase inductance.** The stator is saturated by the magnetic field of the rotor in different axis, depending on the rotor position. The saturation results in a reduction of the motor winding inductance. The variation of the inductance can be detected with a high frequency voltage applied to the motor windings. The resulting high frequency currents are modulated by the varying winding inductance. If the machine is connected to a pulse width modulated frequency inverter the PWM frequency works as a carrier frequency for the rotor position detection. This sensorless method of detecting the rotor position works even in the standstill of the machine, which as we will see will not be the case of other sensorless methods. Unfortunately this circuit is quite complex and therefore expensive - in at least two of the three motor phases the current has to be detected. Using this sensorless detecting on a motor with high power efficiency will not work correctly, because there is very low saturation in the iron.

We can detect position of rotor by **detecting harmonics of induced motor voltages.** The induced motor voltages show harmonics of odd ordinal number (i=3, 5, 7…), because the flux in the air gap has a rectangular distribution. Figure 2-2 shows BEM forces broken down to harmonics. As we can see harmonic voltages with ordinal numbers divisible by three (third harmonic on the picture) create zero phase-sequence systems, which are not accessible by the connections of three phase conductors. We can also see that commutation moments coincide with maximal amplitude of third harmonic. All third harmonics are in the correct phase – they cancel each other out between the three phase conductors and therefore cannot be detected from the three phases of the motor in wye connection.

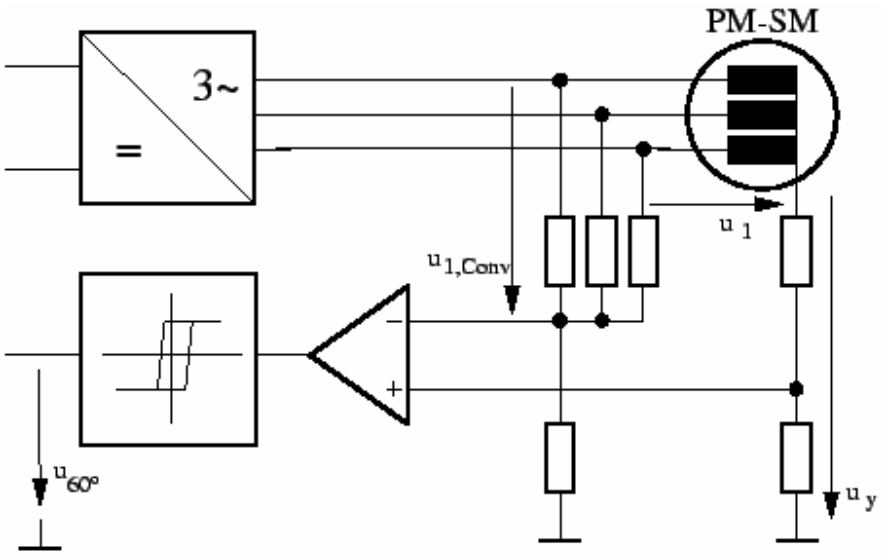


Figure 2-3 System for position derivation from third harmonic

If the wye connection of the motor is accessible, the zero phase-sequence systems can be detected between this and a virtual wye connection, realized with three resistors. Fig.2-3 shows the corresponding circuit. The voltages are tapped off by potential dividers. The reference potential of the sensing circuit may be anywhere between the positive or

negative potential of the DC link. Problem with this method is that it cannot operate at low speeds because BEM forces are weak- this will be problem with other sensorless methods too. The other problem is that it will not work with motors that have sinusoidaly distributed windings because there is no third harmonic in BEM forces.

There is a way of detecting commutation points by **detecting current slope variation.** When current runs from one phase to another we have:

$$V_l = 2RI + 2L\frac{dI}{dt} + (E_{ga} - E_{gb}) \tag{2.1}$$

, where Vl is a voltage between active phases, as it is shown on the following figure.

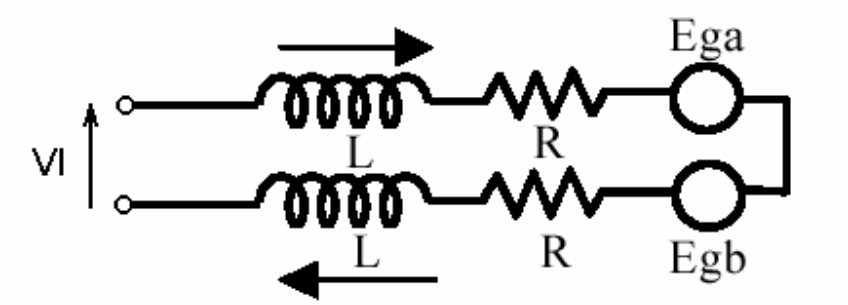


Figure 2-4 Two connected phase model

If we assume that terms RI and Vl are constant we can determine zero crossing of BEMF on a base of term 2L(dI/dt) which is proportional to slope variation. Although this type of position sensing can provide very precise position detection it requires at least two current sensors and a DSP with high processing power and fast A/D converters.

The method that will be presented in this paper will be the simplest of all methods. It is based on analog filtration of phase voltages and their comparison. It will work with both trapezoidal and sinusoidal BEMF, though this time better with sinusoidal. It will have some disadvantages also, as we will see in the following chapters.

3. Sensorless position detection – TVF method

Description

TVF stands for Terminal Voltage Filtration. We will use sensor here (do not let the name sensorless trick you), but it will be simple circuit attached to the phases of motor. It will have no mechanical parts, which would be attached to the body of motor, and that is why we can call it sensorless. This "sensor" can be permanently attached to the drive, so it can be considered as a part of the drive.

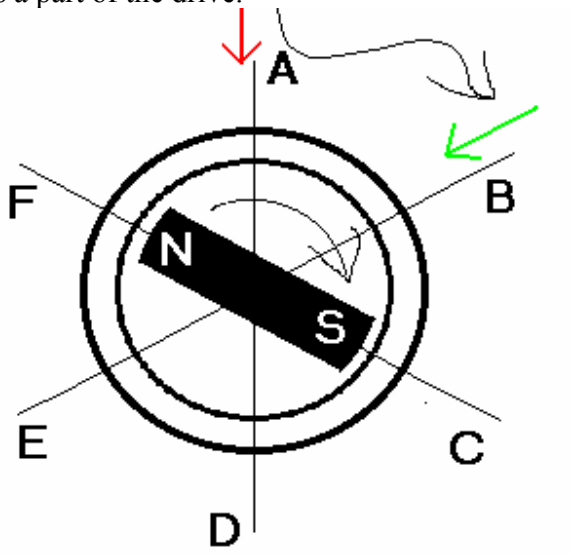


Figure 3-1 Brushless DC motor commutation positions

We want the angle between stator and rotor flux to be closest possible to 90 degrees – torque is proportional to sin(angle). That is the way to obtain maximum possible torque with constant current that is maximal electromechanical conversion – maximum efficiency. On figure 2 we can see motor with rotor in position for commutation. A – F are axis of possible stator flux. Angle between rotor flux and A axis (which is current position of rotor flux) is 60 degrees and it is decreasing, and the angle between B and rotor is 120 degrees, also decreasing getting nearer to ideal 90 degrees. It is obvious that we should shift stators flux from axis A to axis B in this position. Angle between rotor and stator flux will always be between 60 to 120 degrees, and that is the best we can gain with any brushless DC motor.

The other way to observe things is to take a look at the electrical model of our system (Figure 3-2). Current "I" goes from phase A to phase B; In phase C there is no current. BEM forces Ega, Egb, Egc are pulsating with frequency of rotors turning multiplied by a number of pair of poles. Gained power of electromechanical conversion is P=(Ega+Egb)*I. Lets suppose that the commutation that is to be done is from phase B to phase C. Egc will be increasing in the direction marked on the figure. In one moment it will become higher than Egb.

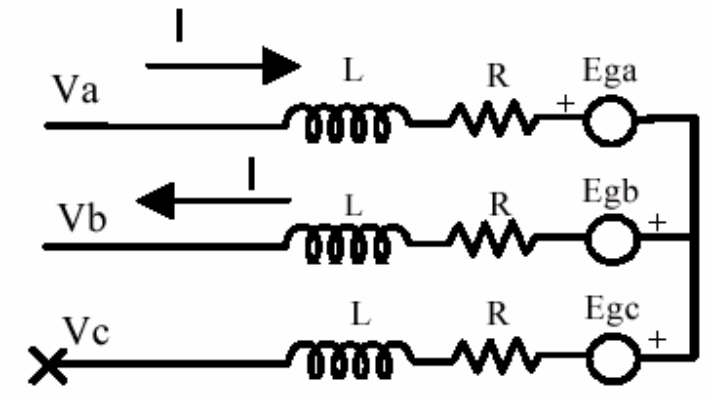


Figure 3-2 Electrical model of three phase brushless DC motor

That is the moment in which the commutation should be done in order to maintain the maximum torque. This type of examining is obviously equivalent to the first one (figure 2) as it will provide the same moments for a commutation.

There is no easy way to measure BEM forces because they are "buried" inside the motor, but there is a way to determine their values approximately as they are imaged in phase voltages. In our case from figure 3, shifting of current from phase B to phase C should occur when Egc becomes higher than Egb. Let us take a look at the phase voltages.

$$V_b = V_s - E_{gb} - L*\frac{dI}{dt} - R*I\ ,\ \ V_c = V_s - E_{gc} \tag{3.1}$$

Vs is wye voltage. We can suppose that motor speed is high enough to be Egxm>>R*I, so we can neglect voltage on the resistor. If we could eliminate voltage on the inductance we would have Vb'=Vs-Egb - > Vc-Vb=Egb-Egc. This means that one simple analog comparator could indicate which BEMF is higher.

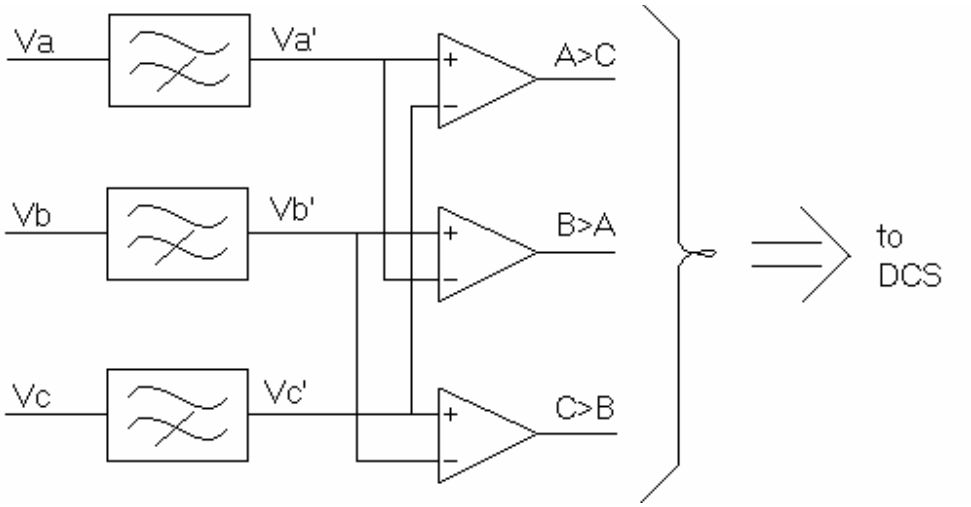


Figure 3-3 Position detector – first approximation

As we will see voltage on the inductance can be eliminated by filtering of terminal voltages. One low pass filter will provide us desired signals. Our system is shown on figure 3-3. DCS stands for Digital Control System.

Realization

In order to realize described system, we will have to do a brief time and spectral analysis of phase voltages. Phase that the current is coming from will be referred to as high side while the other end will be referred to as a low side. We will suppose that PWM is on the high side of the drive, similar result would be derived for low side. There are two cases. First one is when voltage that is to be compared with floating voltage (disconnected phase) is a high side PWM phase, and other when it is constant low side 0V. At this point we will suppose that BEM forces are trapezoidal. It will ease calculations but the results are similar for sinusoidal BEM forces. We will also suppose that current is constant, that is neglect current ripple, which is OK while our system is not in the process of commutation. BEM forces time diagrams are shown on the diagram (Figure 3-4)

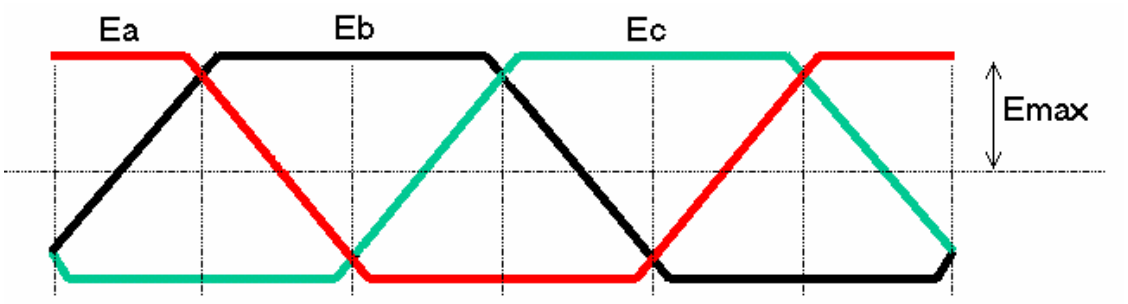


Figure 3-4 BEM forces diagrams

Commutation points will be on crossings of BEM forces as previously defined. In the time between two commutations, BEM forces are constant on connected phases. On figure 3-5 we can see diagram of high side voltage.

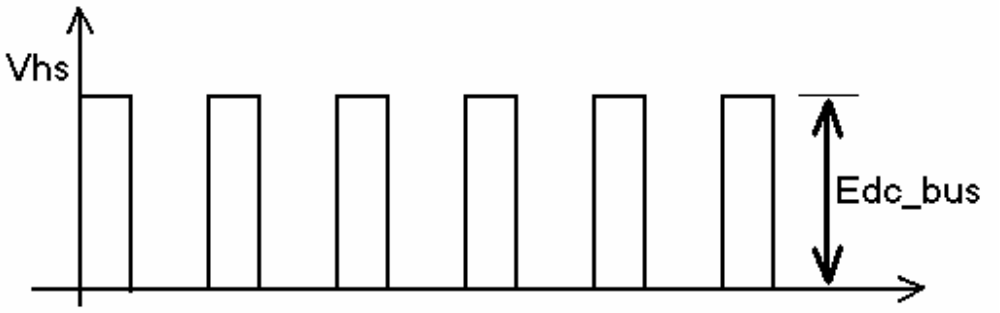


Figure 3-5: High side voltage diagrams

As PWM is applied voltage can be +Edc_bus or zero. Wye voltage Vs has the same as high side voltage, but half of its amplitude +Edc_bus/2. Voltage of disconnected phase is Vdp=Vs-Edp, where Edp is BEMF of disconnected phase. We will assume now that spectral diagram of high side voltage is like the one presented on the following diagram.

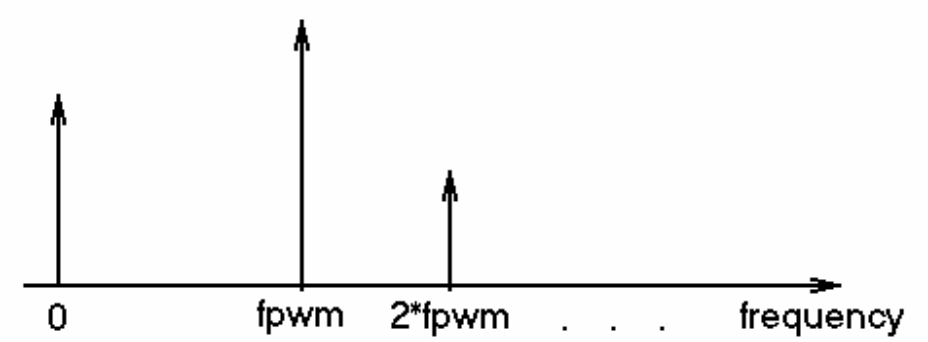


Figure 3-6 High side voltage spectral diagram

It has a DC component as we assume that this voltage is slowly changing term and a high frequency PWM terms. Spectral diagram of disconnected phase voltage will look like this:

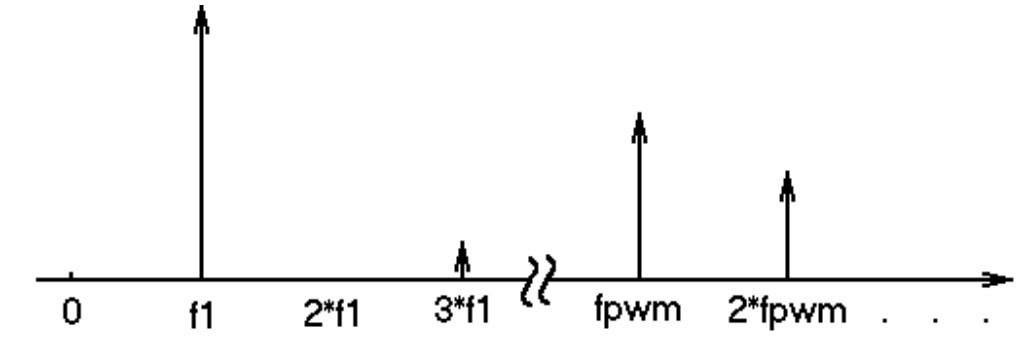


Figure 3-7 Disconnected phase voltage spectral diagram

Voltage on disconnected phase is Vdp=Vhs/2+Edf, so besides the PWM terms we have low frequency BEMF terms which we can call signal while we will be referring to the PWM terms as a noise. Term on frequency 3*f1 and higher terms, which are not on the figure because their value is insignificant, thus will not exist if our motor has sinusoidaly distributed windings. Now let us take a look at the voltage that we would like to compare to zero:

$$V_{\text{cmp}} = V_{\text{b}} - V_{\text{c}} = -RI - L\frac{dI}{dt} - E_{\text{gb}} + E_{\text{gc}} \qquad (3.2)$$

If we apply analog low pass filter that would cut PWM noise in Vb and Vc we will eliminate the voltage on inductivity also because it is a high frequency signal, that is, voltage on the inductivity is equal to zero due to volt second balance. We will neglect voltage on the resistor as it is very small in comparison to BEMF. Now we have:

$$V_{cmp} = V_b - V_c = -E_{gb} + E_{gc} \tag{3.3}$$

Now it is clear that zero crossing of this voltage is the right moment for a commutation.

In previous paragraph we assumed that filter will cut PWM noise and preserve BEMF signal so one could suppose that one analog first order filter with a pole placed on the frequency of highest possible BEMF frequency, let us call it Fh. In our system:

$$F_h = \frac{\omega_{nom}}{2 * \pi} * p \tag{3.4}$$

, where ω is nominal speed, p is number of pairs of poles (not to be mixed with filter poles). The problem that is neglected is the phase characteristic of our filter. If we place a pole on frequency Fh it will shift phase of our signal and provoke phase delay, which would result in delayed commutation that would degrade the performance of our system. It is well known that phase characteristic starts to bend one decade behind the pole, so placing a pole on frequency 10*Fh would be desirable. On the other hand, placing a pole on 10*Fh frequency will decrease rejection.

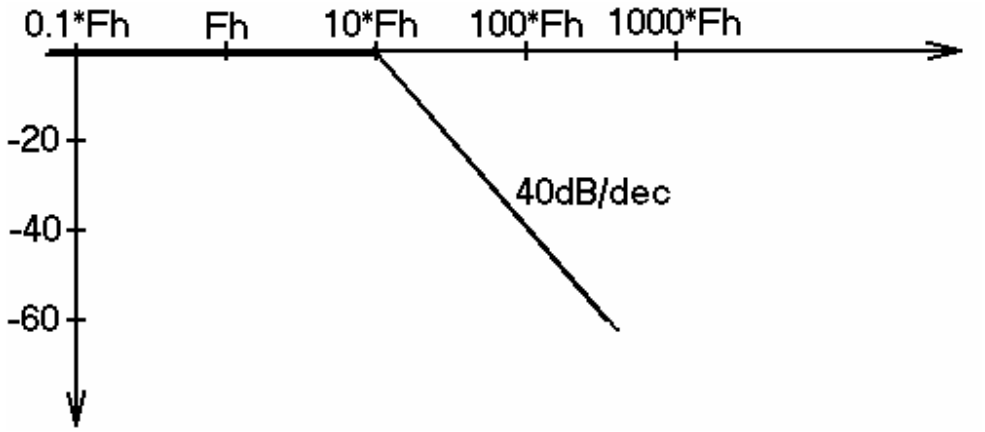


Figure 3-8 LP filter amplitude characteristic

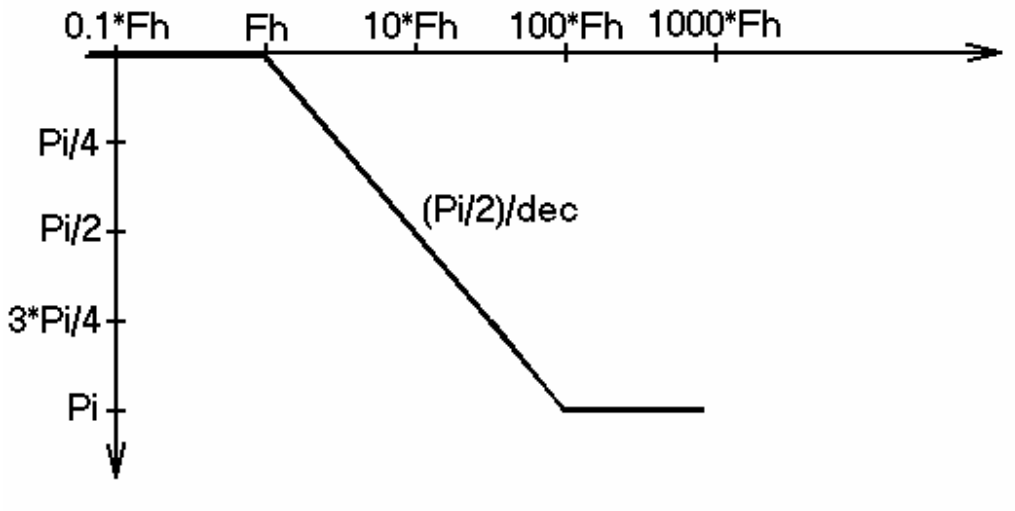


Figure 3-9 LP filter phase characteristic

My project decision is to place double pole on frequency 10*Fh. Amplitude and phase characteristics are shown on the previous figures (Bode approximation). As we can see from diagrams BEMF components will be completely preserved, and their phase will not be shifted. In order to analyze PWM noise rejection we will have to adopt PWM frequency and Fh – highest frequency in BEMF spectrum.

Practical realization

In order to understand the functioning of this system it is best for the reader to take a look at External signals control mode section at the end of this project (figures of six states and transition conditions)

In this thesis we will use motor FAST K1 of moog. It is nominal speed is 3000 rpm., it has four poles = two pairs which means that our frequency Fh is 100Hz. PWM frequency used in this work is 5000Hz. Rejection of PWM noise is:

$$A = -40 * \log\left(\frac{f_{PWM}}{10 * F_h}\right) = -27.96dB \qquad (3.5)$$

This is rejection of the first PWM harmonic, we will neglect existence of higher harmonics as their rejection is very high (>40dB). We can now calculate ripple of voltage on filter output. Ripple will be calculated for a duty ratio of 50% because that is the worst case. Amplitude of the first harmonic of PWM on filter input is:

$$U_{\text{PWMinput}} = U_{\text{DC\_bus}} * \frac{1}{\pi} * \int_0^{\pi} \cos(\theta) d\theta = \frac{2}{\pi} * U_{\text{DC\_bus}} \qquad (3.6)$$

Our rectifier is connected to a regular power grid, so we have:

$$U_{\text{DC\_bus}} = 220V / 240V * \sqrt{2} < 340V \tag{3.7}$$

always. Which means:

$$U_{\text{PWMinput}}^{\max} = \frac{2}{\pi} * 340V = 216V . \tag{3.8}$$

Voltage on filter output will be:

$$U_{\text{PWMoutput}}^{\max} = U_{\text{PWMinput}}^{\max} * 10^{-\frac{A}{20}} = 8.6V . \tag{3.9}$$

We have two cases of comparison. First is when a voltage from disconnected phase is compared to zero phase. Wye voltage is half of a high side so we will have:

$$U_{\text{PWM\_noise}} = 4.3V . \tag{3.10}$$

On the other hand, when voltage of a disconnected phase is compared to high side phase we have:

$$U_{\text{PWM\_noise}} = U_{\text{PWM\_noise\_highside}} - U_{\text{PWM\_noise\_disconnecte\_phase}} = 8.6V - 4.3V = 4.3V \tag{3.11}$$

This noise can cause commutation problems only at low speeds, because BEM forces are low, but at low speeds PWM duty ratio is significantly lower than 50%, so we can conclude that our filter will successfully eliminate undesired PWM noise.

It looks like the third harmonic of BEMF could cause errors in commutation, as our filter will shift it is phase, but if we take a look at chapter one – position sensing by detecting of harmonics of induced motor voltages, we will see that the third harmonics are equal in all three phases thus they will not affect the comparison.

In order to realize our system, a structure on a figure 3-10 will be used. Of course,

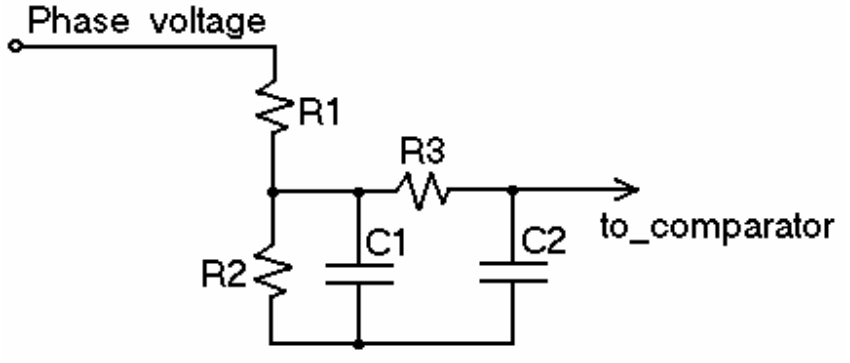


Figure 3-10 One phase LP filter model

we will have three circuits, because we have three phases. Let us calculate the values of resistors and capacitors. Our circuit will be connected to the phases of motor and will be

supplied from voltage sources of 5V and 15V, which we have on IRDAK. Ground of these voltages is common to ground of DC bus. Input voltage can be 380V, and voltage range on comparator will be 15V because we will be supplying it with 15V DC. That means:

$$\frac{R_1}{R_1 + R_2} \approx \frac{380}{15}. \tag{3.12}$$

We will adopt values R1=27K, R2=680K. These high resistances will provide low current sink. Voltage that capacitor "sees" is:

$$R_{C1sees} = R_1 \,||\, R_2 \,||\, R_3 \approx R_2 \,||\, R_3 \tag{3.13}$$

, as R1 has very high value, we can neglect it. If we choose R3 to much bigger than R2, we could neglect R3, and determine system poles separately due to a principle of poles separation. Lets say that $R_3 >> R_1$, we have $R_{C1sees} = R_2$. Now we can determine value of first capacitor, as we know that poles frequency should be 1000Hz (=10*Fh, Fh=100Hz).

$$\omega_p = 2 * \pi * 1000Hz = 6283.18rad/s\,,\ \omega_p = \frac{1}{R_{C1sees} * C_1} \tag{3.14}$$

$$\Rightarrow C_1 = \frac{1}{\omega_p * R_{C1sees}} = 5.9\text{nF}. \tag{3.15}$$

We will adopt value of 5.6nF, because that is a closest value commercially available, $C_1 = 5.6nF$ .We will adopt $R_3 = 270K$, ten times bigger than R_2. We choose $C_2 = 680\,pF$. More accurate value would be 560pF, but since we chose lower value for C_1, we are taking higher value of C_2, in order to balance our system. All of this will not affect significantly characteristic of our filter.

Since comparisons will be executed near ground voltage (half of them), we need to place one zener diode between ground of our filter and a system ground, to avoid errors during the comparison. One resistor is placed to provide diode polarization.

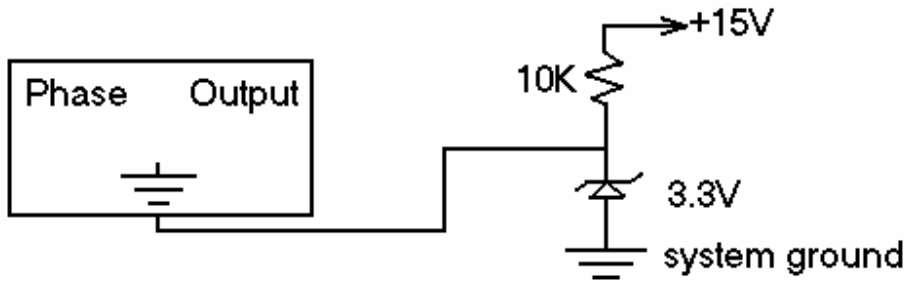
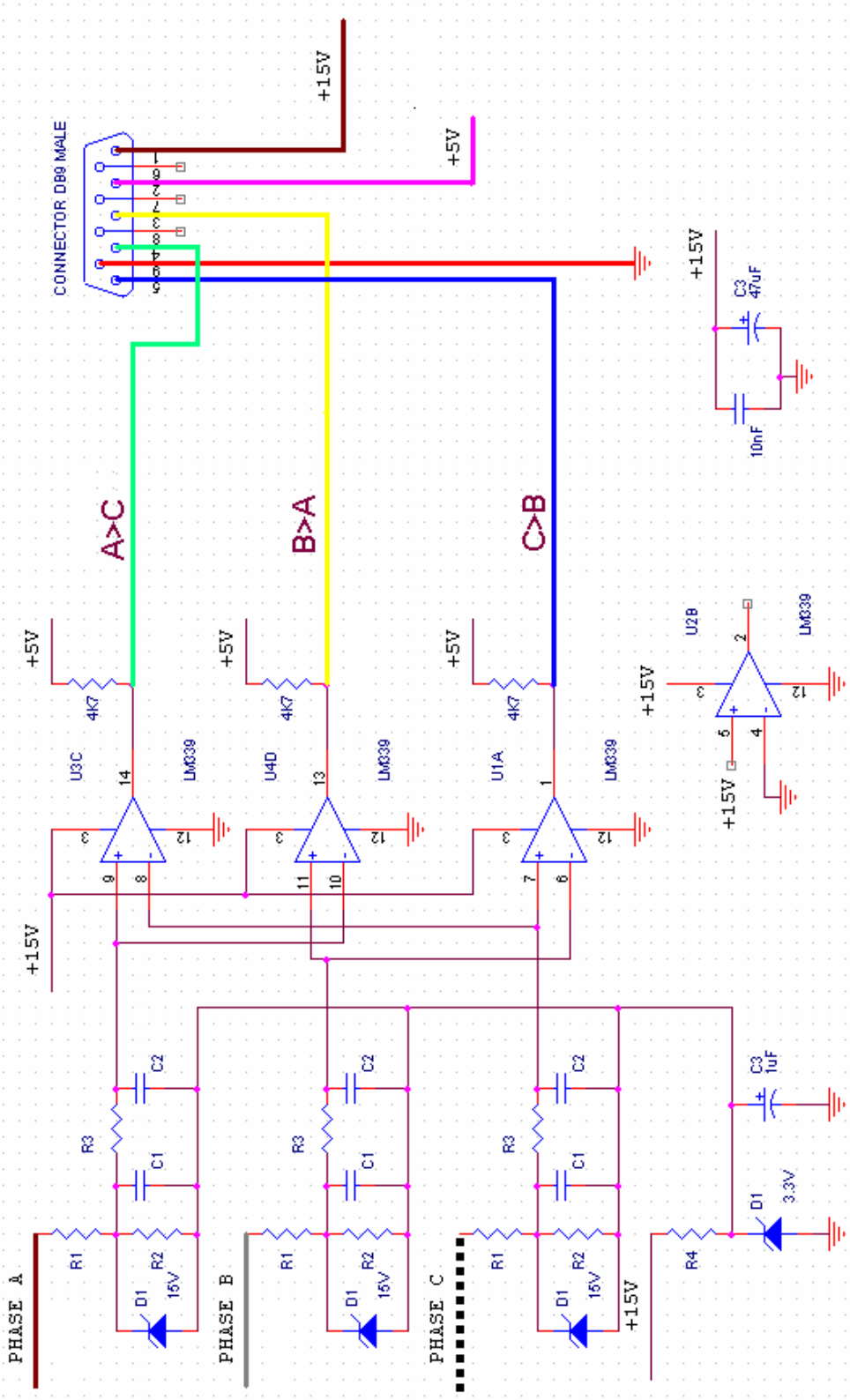


Figure 3-11 Zener diode circuit

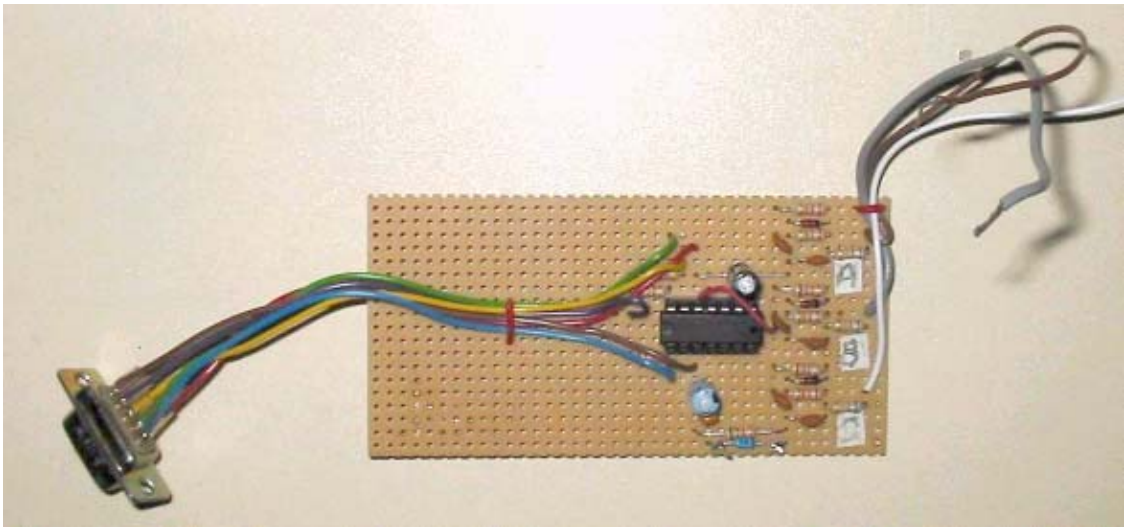
Rectangle block is a filter from previous figure. Entire circuit is shown on the next page.



Scheme 3-1 Position detecting circuit

Zener diodes with 15V breakthrough voltage are used for protection. Standard decoupling capacitor pair is placed between +15V and ground. A capacitor is placed in parallel with zener diode in order to prevent eventual voltage drops, due to current variations.

Standard LM339 chip with four comparator blocks is used for voltage comparison. Comparator outputs are "open collector transistors" which means that we need pull-up resistors. Pull-up resistors are connected to +5V, as IRDAK will require TTL compatible levels. We use only three comparators, output of fourth is always logical "1" state, that is, output transistor is turned off all the time. Besides lowering current sink, we are also preventing noise generation that could occur due to oscillating of comparators output. Standard DB9 connector will be used for a connecting of our circuit and IRDAK. On our circuit side is the male connector because it does not generate voltages, it is completely passive, it gets its voltages from IRDAK. I have to mention that voltages that come from IRDAK are not isolated, that is, their potential to earth can be very high, so when connected to IRDAK our circuit **should not be touched!.** Circuit inputs (phases) and outputs are marked with colors. The same are the colors of the wires that are used to make the circuit. The same are the colors of wires that are used on IRDAK female connector. All of this is done in order to ease the connection and avoid errors. Color of phase C input wire is white, I put a brown dash line so we can see it.



Picture 3-1 Position detecting circuit

Signals B>A, C>B, A>C are led to the pins of microcontroller 16F874, and can be read in any moment by our program. In the following chapters IRDAK drive and microcontroller will be described. Later we will get into the functioning of our circuit, software and the whole drive together.

Method TVF phase delay problems

In previous sections, while we were analyzing our circuits function, voltage on stator serial resistance was neglected, as our assumption was that it is very low, thus will

not affect the commutation. Here we will analyze the effect of stator resistance on commutation, we will see in some modes of brushless DC functioning it can cause significant commutation delay.

In order to do an analysis more complete than the previous ones, we will take another look at a following figure (there is the same figure in this section…)

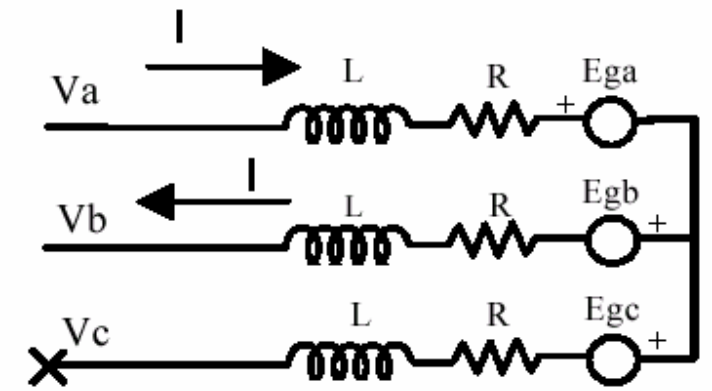


Figure 3-12 Electrical model of brushless DC motor

There are two cases, one for each direction of rotation:

1) $V_{CB} = V_C - V_B = L\frac{dI}{dt} + RI + E_{gb} - E_{gc}$, $V_B < V_C$, we are waiting until $V_B > V_C$, and than we commutate.

2) $V_{AC} = V_A - V_B = L\frac{dI}{dt} + RI + E_{ga} - E_{gc}$, $V_A > V_C$, we are waiting until $V_C > V_A$

In one case we are disconnecting high-side and in the other low side. We will analyze only the first case because its situation is very similar to the second. As the same filter is applied on both voltages that are about to be compared, we can apply low pass filter "on the equation" 1), we will have:

$$V_{\mathrm{CB}} = V_{\mathrm{C,low\_frequency\_signal}} + V_{\mathrm{C,high\_frequency\_PWM\_noise}} = V_{\mathrm{high\_frequency\_induction\_noise}} + RI + E_{\mathrm{gb}} - E_{\mathrm{gc}} \quad (3.16)$$

As analyzed in previous section, we can neglect high frequency PWM noise on phase voltages. Noise on inductivity will actually decrease total noise because its sign is opposite to a sign of phase noise, and its smaller in amplitude. That means that we can write:

$$V_{\mathrm{C,signal}} = RI + E_{\mathrm{gb}} - E_{\mathrm{gc}} \quad (3.17)$$

Term RI will cause commutation delay, as there is no way to eliminate it. We could add some elements in order to compensate for this voltage, but that would make our circuit

very complicated and expensive. On following figures we can see the effect of stator resistance on commutation, for sinusoidal and trapezoidal BEM forces.

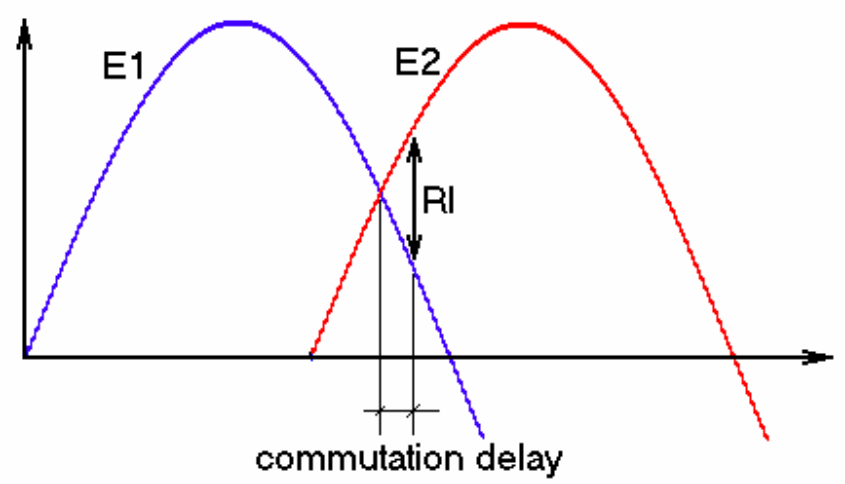


Figure 3-12 Phase delay in motor with sinusoidal BEM force

We can calculate delay angle approximately. If

$$E_1 = E\sin(\omega t),\ E_2 = E\sin\left(\omega t - \frac{2\pi}{3}\right) \tag{3.18}$$

, one commutation point should be at

$$\omega t = \frac{5\pi}{6} \tag{3.19}$$

, but term RI will delay the commutation for angle θ :

$$E*\left(\sin\left(\frac{\pi}{6}+\theta\right)-\sin\left(\frac{5\pi}{6}+\theta\right)\right) = RI \tag{3.20}$$

$$E\left(2*\sin\left(-\frac{2\pi}{3}\right)\cos\left(\frac{\pi}{2}+\theta\right)\right) \cong E*\sqrt{3}\sin\theta \cong \sqrt{3}*\theta*E = RI \tag{3.21}$$

$$\theta = \frac{RI}{\sqrt{3}*E} \tag{3.22}$$

approximations used here are $\sin(\theta)\cong\theta$, which is all right when θ is near zero. On the following figure we can see commutation delay effect at motor with trapezoidal BEMF.

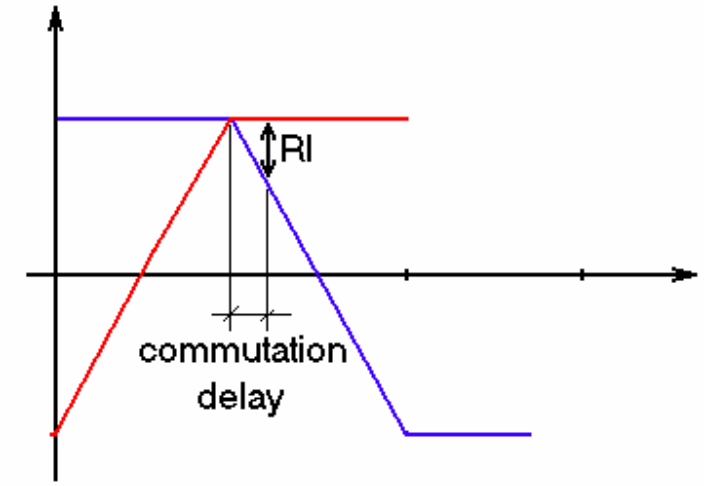


Figure 3-14 Phase delay in motor with trapezoidal BEM force

It is easy to calculate that

$$\theta = \frac{RI\pi}{6E} \tag{3.23}$$

which is very similar to the first result. That was expected, since higher harmonics will not affect significantly the comparison.

In both cases, commutation delay is proportional to a term:

$$\mu = \frac{RI}{E} \tag{3.24}$$

This term will be referred to as a phase distortion coefficient. It should be as lower as possible. That means that we should keep I low and E high. I is proportional to load torque, and E is proportional to speed. We conclude that undesired mode of function is at low speeds with high load torque – elevator applications.

4. IRADK motor drive

Introduction

IRADK is a three phase, variable speed motor drive for appliances and light industrial applications. It has 230V input in order to be supplied from standard European power grid. It has optically-isolated RS232 serial link interface to PC. Fault protection for over-current and over-temperature is provided also. There is a slot for standard 8-bit microcontroller. Using an adapter we can place a high processing power DSP. Auxiliary power supplies, 15V and 5V are integrated on IRADK. There is AC input EMI filter, which eliminates higher harmonics from the input current. On/off switch is placed on the phase of input voltage.

IRAMS 10UP60A plug and play power module is used as inverter. It is made in 600V NPT IGBT technology. It has current rating of 5A at temperature 100^{O}C. It has cross-conduction prevention logic. Reduced Emi is provided by optimized gate drive.

Drive circuit will be analyzed hare part by part. IRADK circuit contains the following sub circuits:

1. Power supply
2. IRAMS power module circuit
3. Phase current and DC bus voltage sensing circuits
4. Over current protection
5. Serial link galvanic isolation circuit
6. Additional features (LED, button, additional inputs – analog and digital)
7. 28 pin microcontroller slot
8. Connection strips

Power supply

High voltage rectifier circuit from IRADK is shown on the following figure.

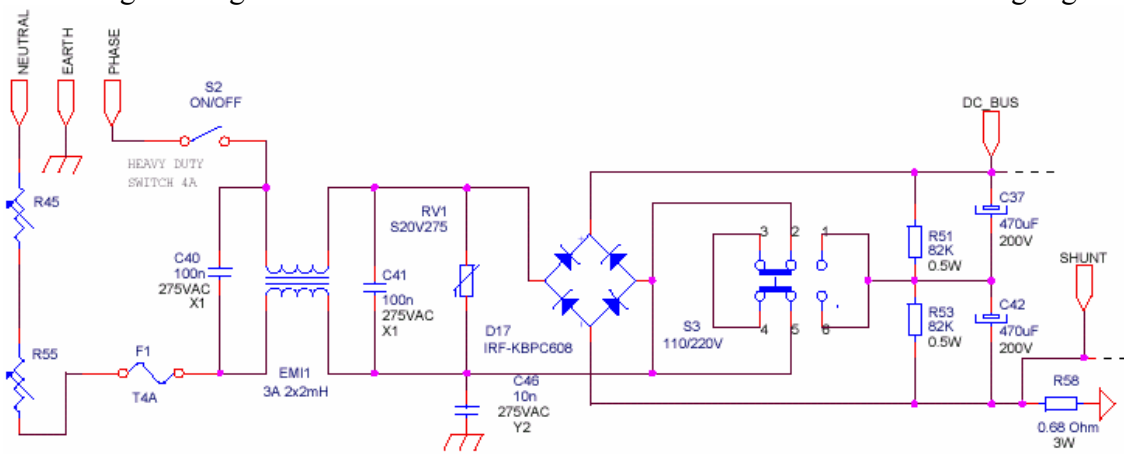


Figure 4-1 Rectifier circuit

Variable resistors R45 and R55 serve to limit input current during initialization. That is when we plug in our IRADK, it has a tendency to drain high current from power grid, as electrolytic capacitors C37, C42 are completely empty. Capacitors C40 and C41 in conjunction with EMI inductances block higher harmonics of input current (EMI filter). Element RV1 serves to limit voltage on its connections, as it will start to conduct thus will lower the voltage when it gets too high (275V). Capacitor C46 is placed between ground and zero connection, its purpose is to collect static electricity from our device case, when ground is accidentally disconnected. Selector S3 is not placed in its position, that is, it is always in the position on the picture, thus this IRADK can only be used in Europe. We could place S3 on the board, but as it is highly unlikely that we will use this circuit both in Europe and United States, and it is very possible that we will destroy IRADK by toggling the switch accidentally, for that reason we did not put it. Resistors R51 and R53 are used in order to balance the voltages on electrolytic capacitors, as tolerance in electrolytic capacitors values is very high ($\pm 20\%$ at 120Hz, 20^{O}C).

On following figures we can see switching power supply which provides us 15V source.

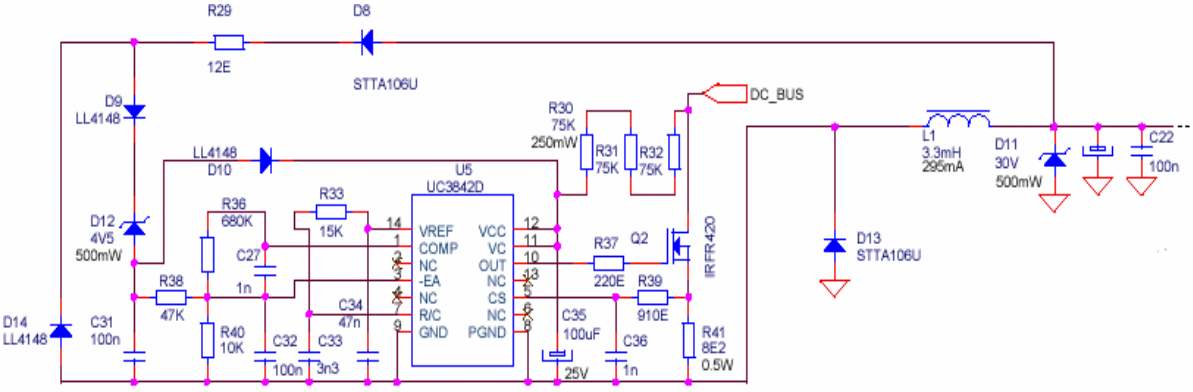


Figure 4-2 Switcher circuit

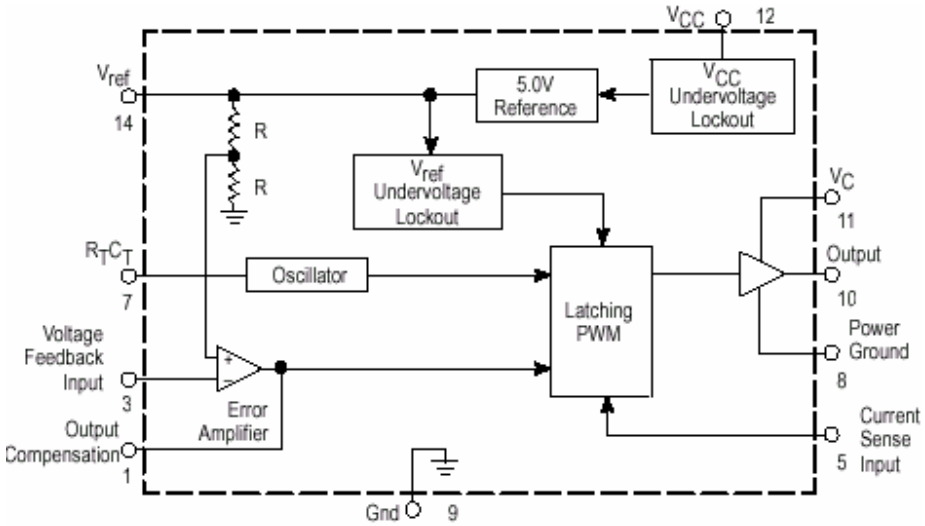


Figure 4-3 Internal structure of switching power supply control chip

MOSFET Q2, inductance L1 and diode D13 compose buck converter. It is a very frequently used structure for lowering the voltage. Purpose of UC3842D chip is to provide us control of output voltage, through "current mode" control. Internal structure of the chip is shown in the second figure. Values of capacitance C33 and resistance R33 will determine the frequency of internal oscillator that is PWM controller frequency. Current is measured on shunt resistor R41 and fed back to a controlling chip. Resistor-capacitor pair R39, C36 will filter the information from shunt resistor. Output signal will toggle on/off our transistor as it will pass to the output voltages on pins 11 and 8 respectively. We will not need high-side drivers to toggle transistor because entire circuit is "floating", that is entire circuit is on the high-side. Circuit power supply is provided through resistors R30-32. We may wish to supply entire IRADK with lower voltage in that case we will have to short-circuit one or two of these resistors in order to provide sufficient current. Circuit on the left side of the control chip serves to provide voltage sensing. When transistor is off, diodes D8, D9, D12 and D13 conduct the current proving us information about output voltage. The rest of this circuit filters this information. Compensation is done by a local feedback through compensation pin 1, it serves to provide stability of our control loop. D10 and D14 are protection diodes.

Output of our power supply is fed to a 15V linear regulator. Stabilized 15V source is used as a supply of certain blocks on IRADK as well as input of a 5V linear regulator – following figure.

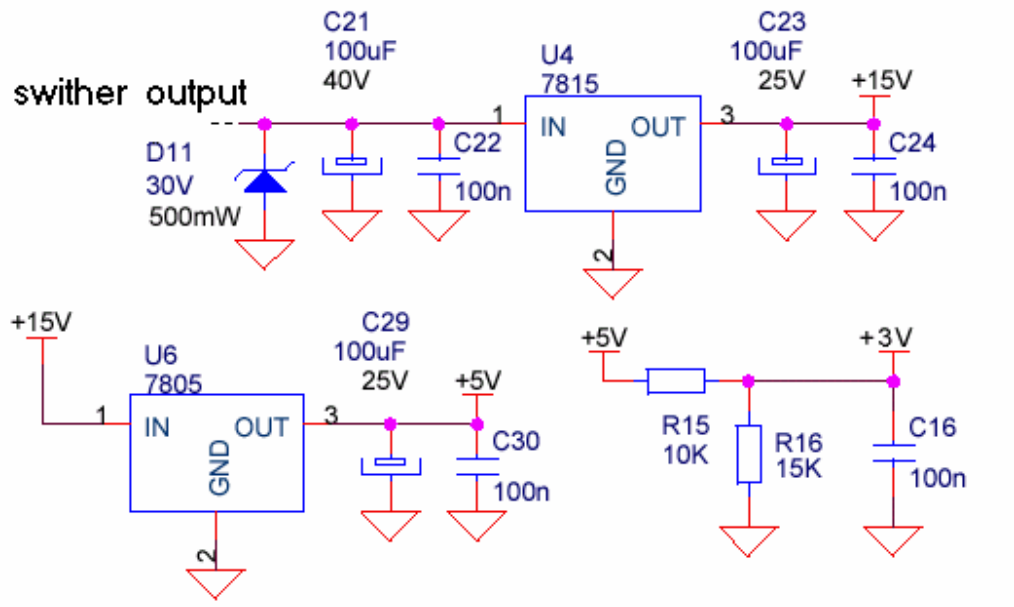


Figure 4-4 Stabilizing circuits on IRADK

5V source is used as a microcontroller supply, it also servers as a supply for some blocks. On the figure we can also see a 3V source. It is made using potential divider and capacitor, which is fine if we bear in mind low current capacity that will be required of this source. It will serve us as a reference source for microcontrollers A/D converters as well as a reference in protection circuit.

IRAMS10UP60A power module

Utilization of this chip will provide extremely simple and compact solution.

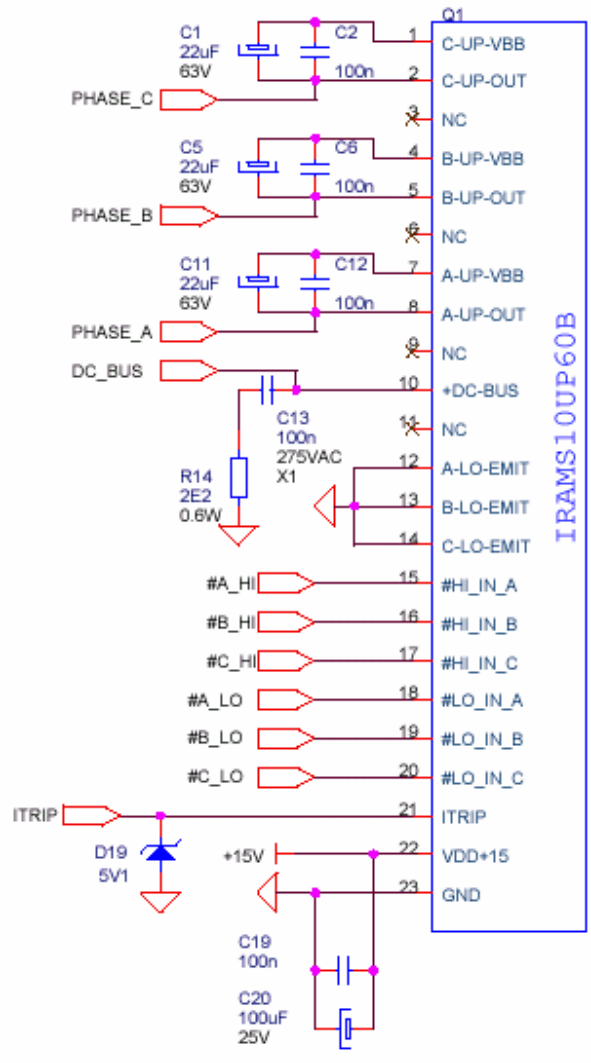


Figure 4-5 IRAMS inverter connection on IRADK

It is one modern inverter. It has integrated gate drivers and bootstrap diodes. It has temperature monitor as well as temperature and over current shutdown. Package is fully isolated. It has matched propagation delays for all channels, 5V input Schmitt trigger inputs, cross-conduction prevention logic, isolation up to 2500Vac/min. Inverter power rating is 0,4KW at input voltage 100-253V. More information can be found on internet (pdf files related to IRADK 10). On the figure we can see IRAMS connection to IRADK. Purpose of capacitor C13 and resistor R14 is to delay DC bus voltage appearance, as it needs to be delayed to the occurrence of 15V voltage, if we want our circuit to function correctly. Power supply for hi side drivers is ensured through electrolytic capacitors C1, C5, C11 and their bipolar capacitor pairs. For all phases of inverter, these capacitors are

filled when lower transistor is turned on, so they could supply power when high side transistor is on – figure (simplified scheme).

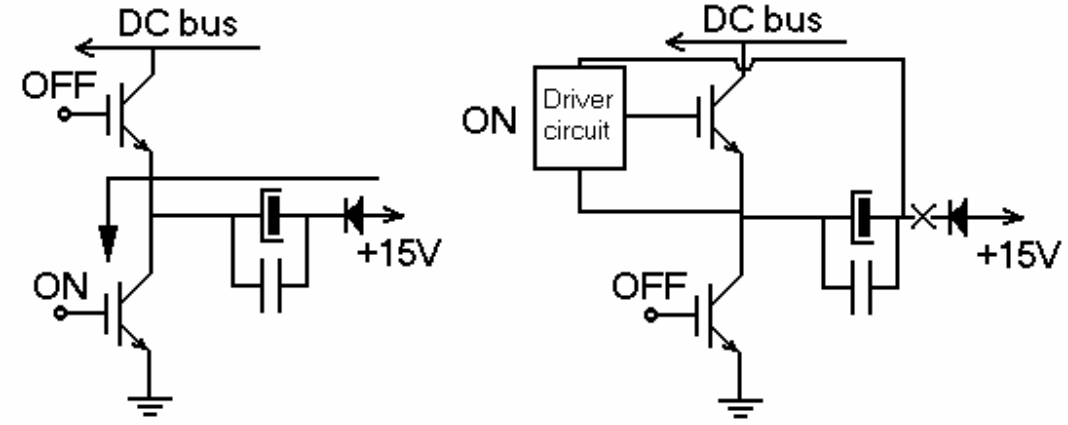


Figure 4-6 Simplified functioning of bootstrap diodes in IRAMS

When we turn off lower transistor, diode turns off also, leaving the capacitor with floating voltage, which can power up a driver circuit. This is the cheapest way to realize high side power supply. Other types of supply would include transformer for a galvanic separation, and that is expensive. Disadvantage is that we cannot hold upper transistor turned on all the time. We have to turn it off in order to refill capacitors. It is recommended that upper side transistors be off at least 10% of time. That is the reason why I chose PWM to be on upper transistors – high side. The PWM side transistors will conduct less time than the ones on the non-PWM side. One might think that this disadvantage may stop us from holding motors shaft fixed position as we need to have one upper side transistor turned on all the time, but it is possible. When capacitors gets empty transistor will turn off, but current from the motor inductance will turn on lowers IGBT diode, capacitor will refill, also from the inductance current, and upper transistor will start to conduct again. Of course it will not be conducting all the time.

Signals A_HI, B_HI, C_HI, A_LO, B_LO, C_LO are the ones that control states of transistors in IRAMS. They are TTL compatible, 0-5V, so they can be connected directly to the pins of microcontroller. They work in negative logic. When one of them is on low level (0V), target transistor will be turned on, and vice versa. We must take care not to turn on 2 transistors from the same phase at the same time. That can damage our inverter, although it has protections – integrated and in our case outside protection also (protection circuit). We have to take special care while writing software.

ITRIP is the signal from the protection circuit which will be discussed in one of the next sections. When it is “on” due to a high current, control signals will be ignored and all transistors will be turned off.

Phase current and DC voltage sensing circuits

In order to provide a high-quality torque and speed control we need to control current in motor. To control it, we need to measure it. Beside the information about the current we also need the information about the voltage on DC-link. On the following

scheme we can see the part of IRADK circuit which is in charge of voltage and current sensing.

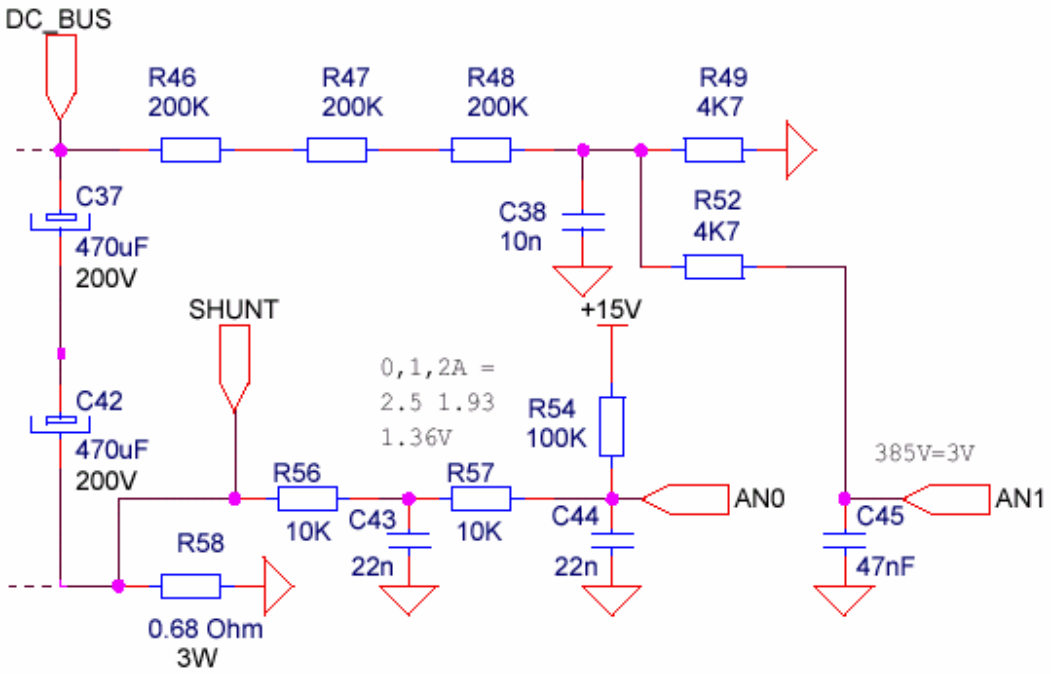


Figure 4-7 Phase current and DC bus voltage measuring circuits

As we can see it leans on the circuit of rectifier from the first section of this chapter. Voltage measurement is realized on upper part of the image. AN1 presents analog input of our microcontroller. Voltage on it will be proportional to the voltage of DC bus. For a DC bus voltage of 385V, voltage on AN1 will be 3V, which is maximum input to A/D converter as the A/D reference voltage is also 3V. This result is marked with gray color on the figure. It can be calculated easily as the resistors placed between DC bus, AN1 and ground are a simple voltage divider. Capacitors serve for noise rejection.

Current sensing problem is more complicated. Circuit dedicated to it is on the lower part of figure. We are measuring current in DC link Current from electrolytic capacitors supplies motor through inverter, as well as other parts of IRADK. Assumption is that all current taken from this source is negligible in comparison to the current that goes to motor. This is all right because the current that goes to IRADK is "seen" as current that goes out of DC link multiplied with factor f:

$$f = \frac{15V}{DC\_bus\_voltage} \tag{4.1}$$

due to switcher function. So we can say that the current which runs through the shunt resistor R58 is approximately equal to the phase current of the motor. Since we are working with brushless DC motor, one phase will always be disconnected, so voltage on shunt resistor will all the time be proportional to the only current that runs in our motor.

When working with other types of motors, currents have to be calculated from this piece of information only. That can be difficult and sometimes impossible.

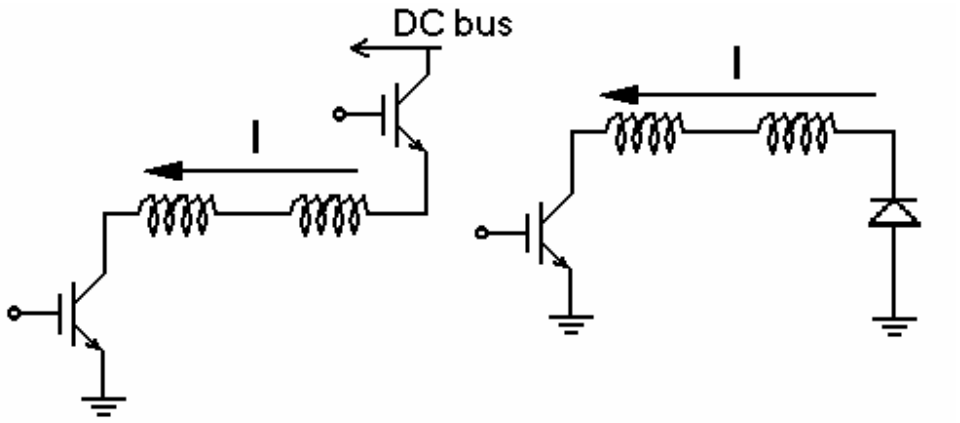


Figure 4-8 Switching process

The problem that we have here (which will be problem with other motor types also) is that we will have current information on shunt resistor only while current runs from one phase to another through upper transistor. In PWM interval in which upper transistor is off, current will run through the diode and will not close through shunt resistor (figure). Shunt signal is fed to a filter that will cut higher frequencies. Its poles are placed at about 1500Hz. That means that PWM component of our signal will be significantly rejected. In order to measure the current we will have to multiply a value that A/D converter gives us with PWM duty ratio factor in order to obtain the correct value. This multiplication has to be done in software and can be problematic. We could use a peak detector to hold the value that is measured during the first interval of PWM period (when high side transistor is on, current runs trough the shunt). It would consist of diode and capacitor, and perhaps operational amplifier. Analog voltage values on AN0 pin of microcontroller obtained by measuring the current are marked on figure with gray color. They are valid for the case of current that runs through the shunt resistance long enough that we can neglect the existence of capacitors on the scheme.

Protection circuit

This is a very important feature of IRADK. Its purpose is to block the inverter when phase current gets too high. Input in this circuit is voltage on shunt resistor that was discussed in previous section.

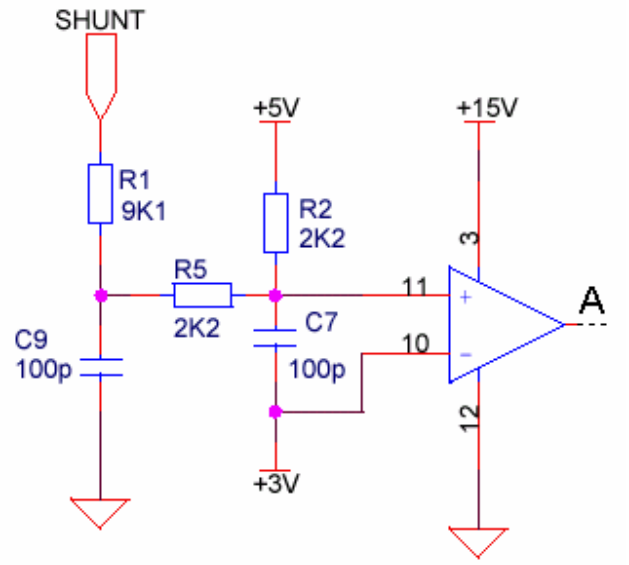


Figure 4-9 Protection circuit 1/3 (part 1 of 3)

The first part of the circuit is shown on the figure 4-9. In the whole circuit there are four comparators, chip LM339, the same that I use for a position detecting circuit, only this one is SMD. In normal functioning mode output of the first comparator will be logical "1". Output transistor of the open collector comparator will be turned off. Rising of current will be followed by falling of voltage on shunt connection (which is the same one from the previous section). At the current of 10.7A – temporary value, comparator will change its state. Output transistor turns on. Second comparator in the chain changes its state (figure below – second part of the circuit, point A is the one from the first part of the circuit).

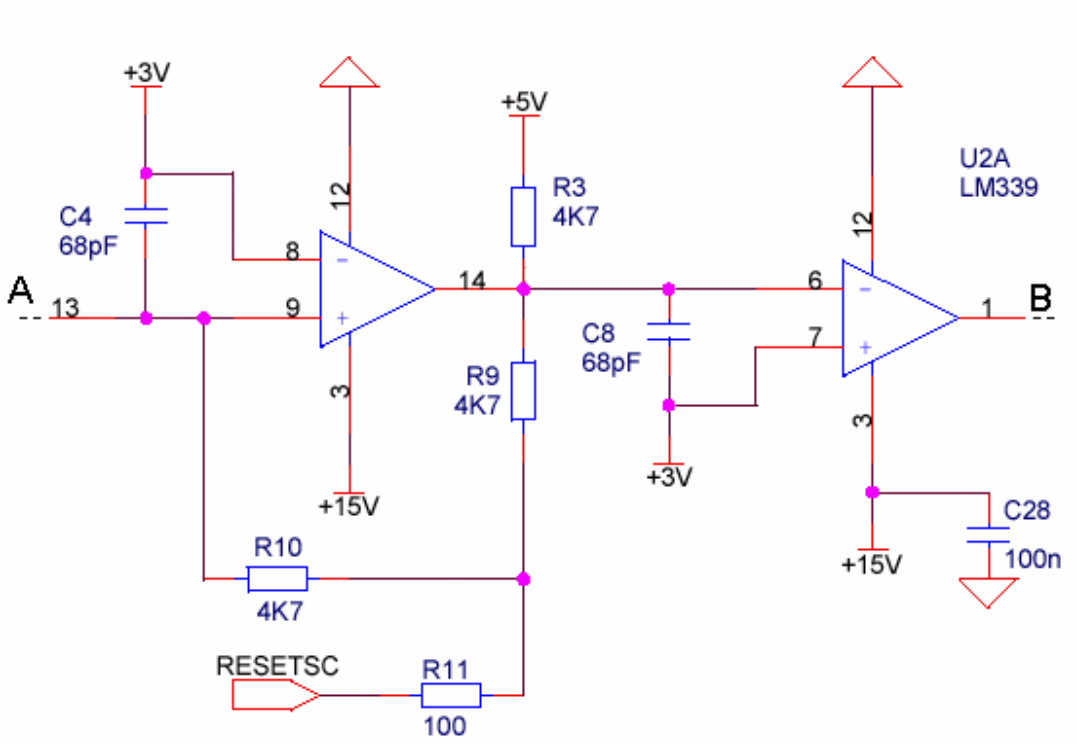


Figure 4-10 Protection circuit 2/3

After the first and second comparator, the third and fourth comparator will also change states (as we will see) and ITRIP signal will become high, IRAMS will shut down. If the current returns to normal IRAMS will stay shut down, because current overload is latched on second comparator. If we examine circuit from the last figure, we will see that it has two stable states due to positive feedback. 1) Output is low {voltage on + pin 5V, voltage on – pin 3V) 2) Output is high, output transistor is ON {V+=0V, V-=3V}. RESETSC signal is in high impedance state. When everything is fine, and our circuit is functioning normally, circuit is in state 1). Current overload will change circuit is state to 2). We can return our system to state 1) if apply low voltage at RESETSC pin. That is what we will do in software. When system gets to state 1) we have to return RESETSC pin to high impedance state, otherwise, **current overload protection will be disabled,** this must be avoided, as consequences can be fatal – transistors from active leg can be destroyed due to high dissipation.

Third comparator inverts the comparison value from second comparator. Fourth comparator is one form of logical or gate. Its output will set ITRIP signal if occurred current overload, or if ENABLE signal is zero. ENABLE signal is connected to the pin of microcontroller, thus can be modified in software.

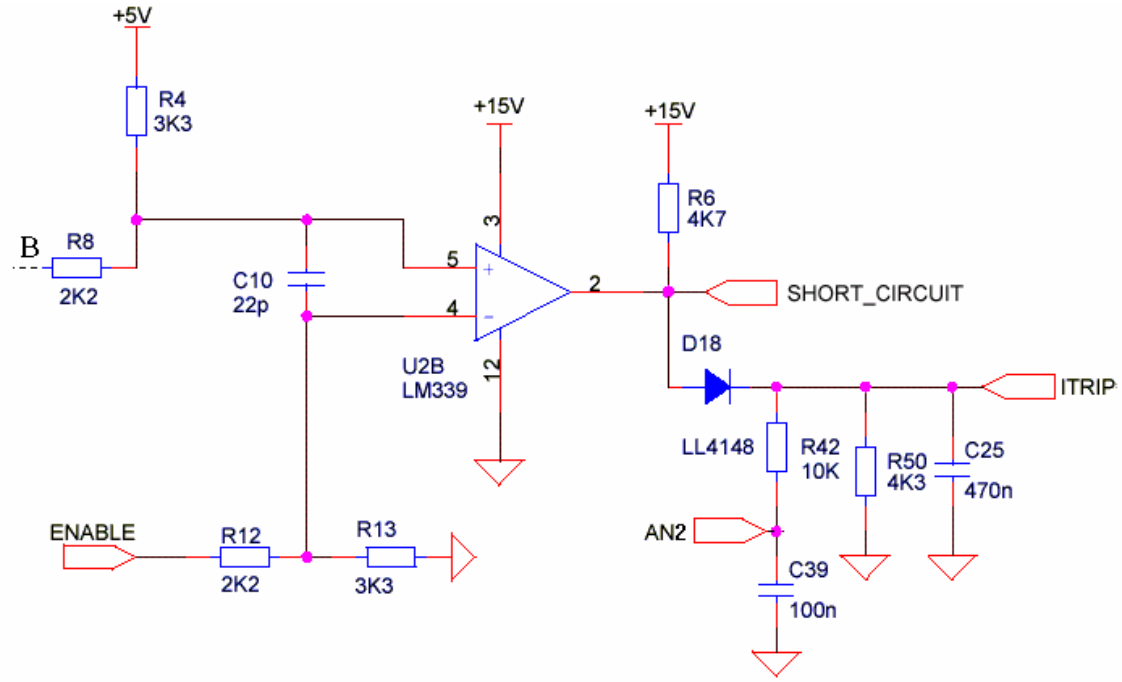


Figure 4-11 Protection circuit 3/3

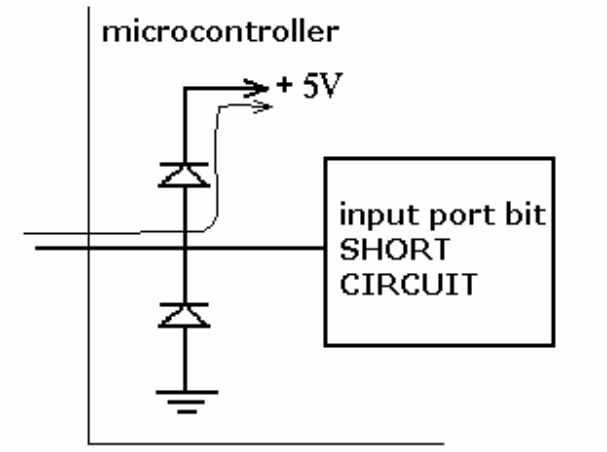


Figure 4-12 Microcontroller input

When current overload occurs or when ENABLE signal changes it state to logical "0" output transistor of fourth comparator will turn off. ITRIP signal will rise very rapidly, time constant value is

$$T = \frac{R_{50} \parallel R_6 * C_{25}}{2 * \pi} \cong 160\mu s \qquad (4.2)$$

approximately. ITRIP will rise until it reaches 5V, because in that moment, protection diode of input port pin SHORT_CIRCUIT will start to conduct and limit pins voltage to

5V – shown on the second figure. This will happen in about $50\mu s$ from triggering of the fourth comparator. ITRIP will stay at 5V until ENABLE signal becomes high or until software reset is applied, depending on what was the cause of ITRIP in the first place. Diode D18 turns off, C25 starts emptying. After a time interval of something like $200\mu s$ logical level of ITRIP will be "0", since time constant in this case is approximately double than the one in the first case, and exponential streaming to the final voltage, which s 0V is much slower than in the first case, when it was practically linear. When ITRIP befalls logical "0", IRAMS will be operating again. Holdup of 200 microseconds in IRAMS turn off will grant us additional safety. Transition process can be observed in software, by reading the value of voltage converted on pit AN2 (figure {}).

RS232 serial link

With intention to connect our IRADK to PC standard RS232 serial link is used. While IRADK is functioning diverse information will be exchanged between PC and microcontroller on IRADK. From PC to microcontroller we can transfer speed, torque/current or voltage/PWM command, as well as any other command, and from microcontroller to PC we can transfer various bits of information that will allow us to monitor execution of microcontrollers program and debug. In addition we can observe all the values that A/D converters have captured: motor current, DC bus voltage etc. Baud rate of our serial link can go up to 2400 baud/s. This is usually sufficient for the communication between microcontroller and PC.

The problem that arose here is galvanic isolation of serial link. As we have seen in previous section, our power supply is not isolated from power grid reference, since we used buck converter that has no transformer in its structure. Voltage on the ground of IRADK, the one marked as a ground on all schemes will be hovering between 0 and something like 300V comparatively to the ground voltage of power grid, while the ground of serial link cable is the same as grids. That is why we will have to apply circuit for signal separation. IRADK solution is application of two opto-transistors, one for each transfer direction. On the subsequent figure is a part of IRADK circuit responsible for information transfer between PC and microcontroller.

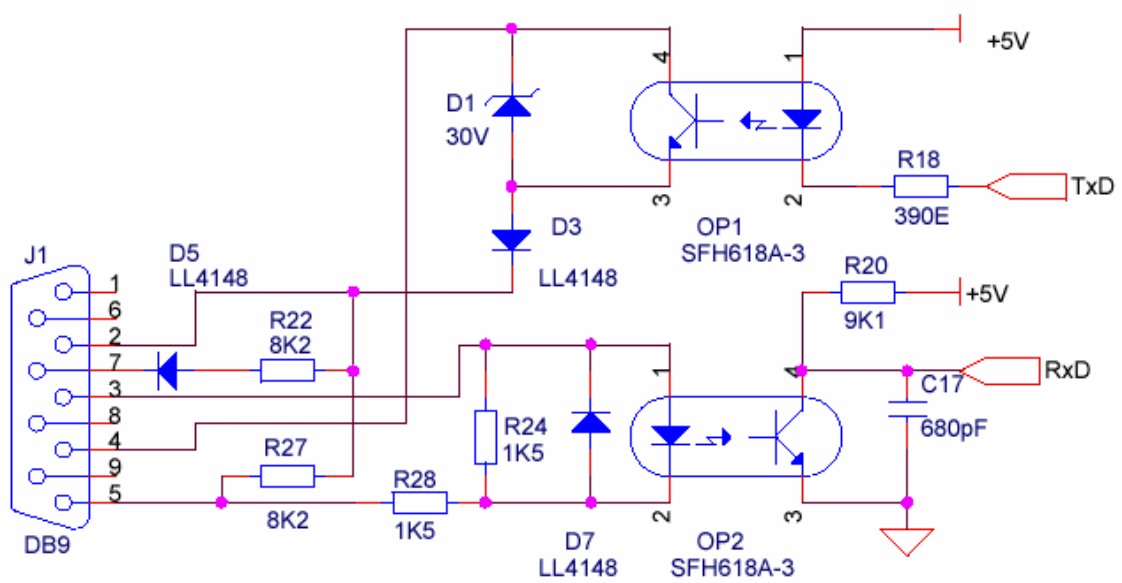


Figure 4-13 Serial link galvanic isolation circuit

TxD and RxD are transfer and receive pins of microcontroller, correspondingly. Power to left part of this circuit is supplied through pins 4 – DTR (Data terminal ready) and 7 – RTS (Request to send) of RS232 bus. For data signals (the ones we are transmitting and receiving) the "on" state occurs when the received signal voltage is more negative than -3 volts, while the "off" state occurs for voltages more positive than 3 volts. For control signals (DTR and RTS in our case) the "on" state occurs when the received signal voltage is more positive than 3 volts, while the "off" state occurs for voltages more negative than -3 volts. The voltage between -3 volts and +3 volts is considered to be the transition region, and the signal state is undefined. DTR signal must be “on” if we want our communication to function. It is desirable that RTS signal be set to “off”. Communication will function with RTS set to “on”, but if a cable that connects IRADK to PC is longer we could have faults, due to noise induced in cable. Values of control signals are set in PC program responsible for PC-IRADK communication.

I personally used DOS program, written in Borland turbo C because that was the simplest way to ensure data transfer which in my case was not a problem, considering low data amount that needed to be transferred. For more advanced use it is recommendable that we use GUI (graphical user interface) that is provided with IRADK system.

Our serial communication can work with speeds up to 2400 baud/sec. That is 2400 baud/sec is a highest standard baud rate communication that will function (next one is at 9600). We can have a higher receive rate, but we cannot have higher transmit rate because of resistor R20 and capacitor C17 which will damage higher frequencies of our data signal. Problem could be solved by lowering the values of these components, though they are SMD.

Additional features

LED – There are three light emitting diodes: red, yellow and green on IRADK which can be used for various signaling purposes. Red could indicate some fault, green that everything is all right etc. They are in a common anode configuration therefore will light up when logical "0" is applied to corresponding pin.

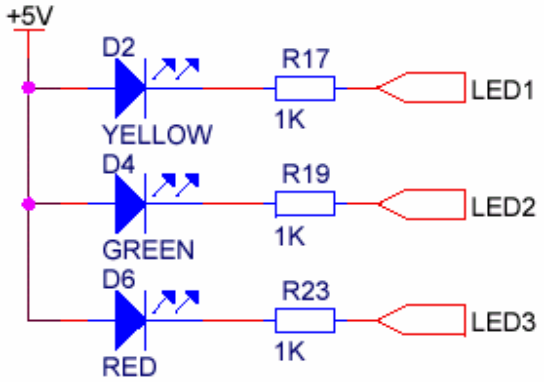


Figure 4-14 LED on IRADK

Button – One button is sited on IRADK. It can be very useful as we will see later. Pressing of button will cause low logical level on related pin, which is normally on high level. This button needs to be debounced in software, since pin signal will oscillate after being pressed.

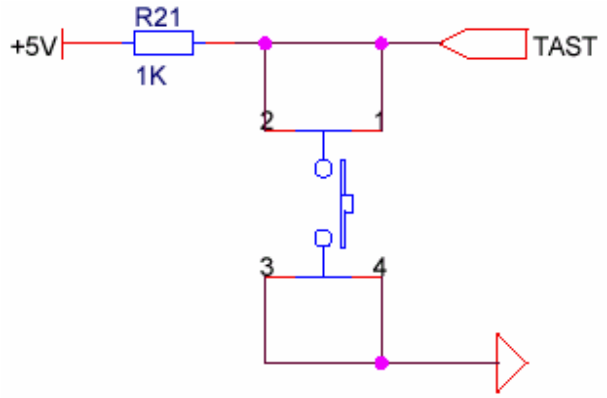


Figure 4-15 Button on IRADK

Working with button in interrupt mode can be unreliable, nevertheless that is the mode we will use.

Additional analog input – Via this feature we can pass one external signal or a voltage from variable resistor to analog input of microcontroller. This is done by putting a drop of tin on a G1 or G2 tin slots. We should not put it at both slots because we can cause short circuit and damage the device that we are taking signal from.

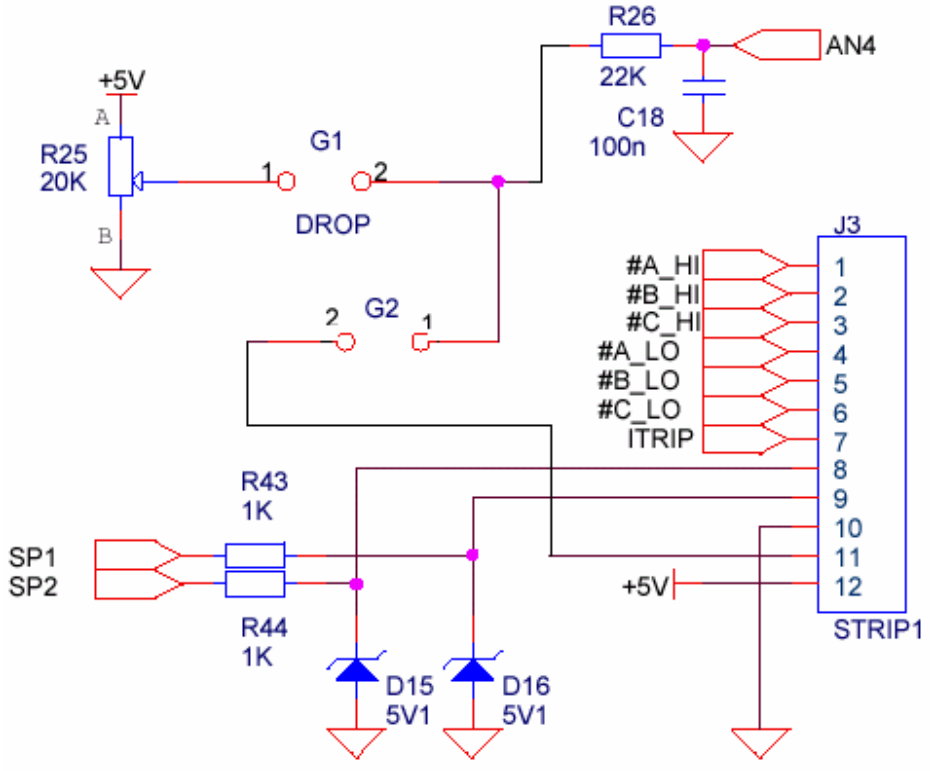


Figure 4-16 Strip1

Passing a voltage from variable resistor can be very useful in situations when we want our IRADK to function without PC command. This could be the way to apply speed command, for example.

Additional digital inputs (SP1,2 stands for spare input) are shown on the same figure as analog (above). External digital signal should be TTL compatible. Resistors R43 and zener diodes D15 and D16 are placed with the aim of protection.

Both analog and digital inputs will be passed to microcontroller via **strip.** Using the same strip output PWM signals and ITRIP can be transferred to outside of IRADK. This is useful if we want to observe wave diagrams of this signal on oscilloscope.

High voltage signals strip and power connections

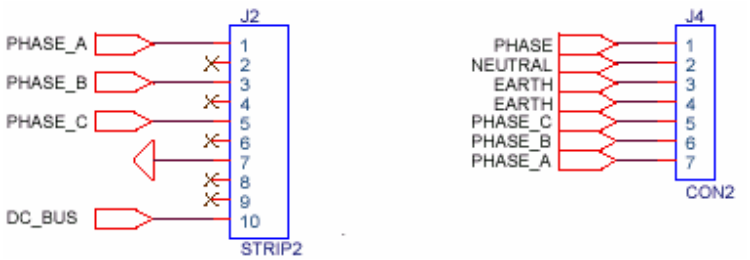


Figure 4-17 High voltage signals strip and power connection

High voltage signals are present on strip2 of IRADK (figure, left image). They can be passed to various analog circuits that can extract information from them. Our information will contain rotor position of brushless DC electromotor.

Power connections of IRADK are shown on the figure (right image). Voltage from the power grid should be connected to the first three pins of CON2. Special care has to be taken when connecting IRADK to European power grid as its connections are not polarized that is we cannot tell the difference between phase and neutral connections. IRADK would function either way but with phase voltage connected to neutral connection, we would have high voltage on IRADK even when switch is shut down. To prevent this I suggest that we connect it randomly and than measure voltage between power grid ground and stabilizer cooler while switch is off. If there is voltage, we should swap neutral and phase connections.

I should emphasize again that IRADK has no galvanic isolation, hence **should not be touched while in function**. This may be problem during the phase of development of our project. But when project is done (hardware and software) we can place IRADK in a box which will be connected to the ground thus completely harmless.

Microcontroller slot on IRADK

IRADK is supposed to work 8-bit microcontroller. On the following figure we can see slot with microcontroller PIC16C72. We will be using PIC16F873 microcontroller in this project which is pin compatible to this one. In this section possibilities for connecting other microcontrollers to IRADK will be considered as well. If we have needs for higher processing powers we could use DSP that would be connected to IRADK by the use of an adapter. Task of adapter task would be to bypass required pins of DSP to matching pins of microcontroller slot.

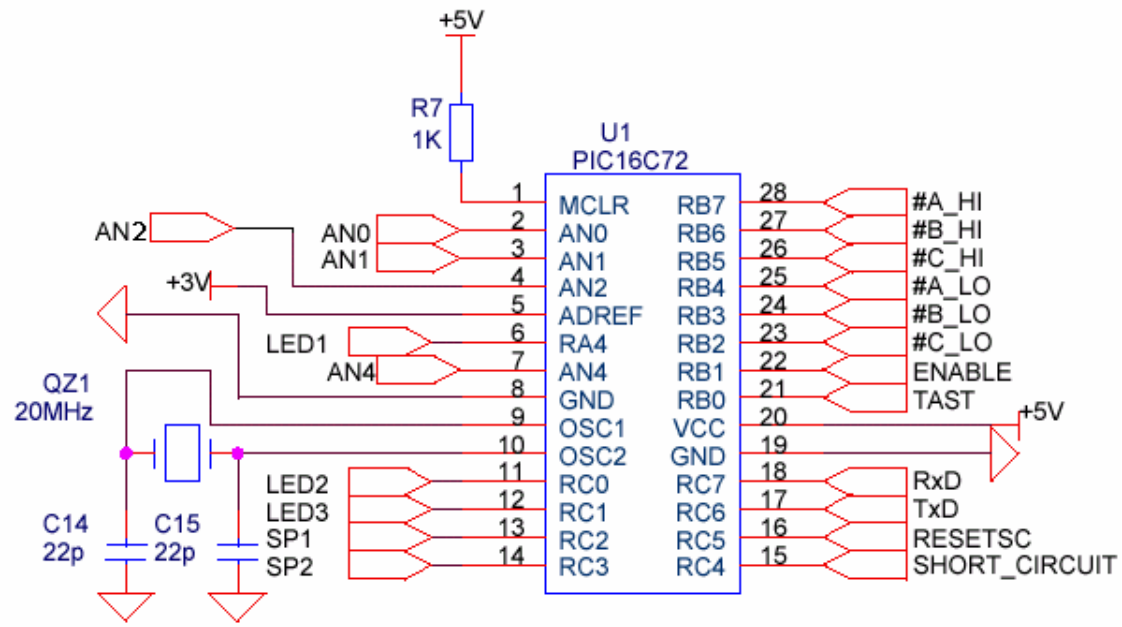
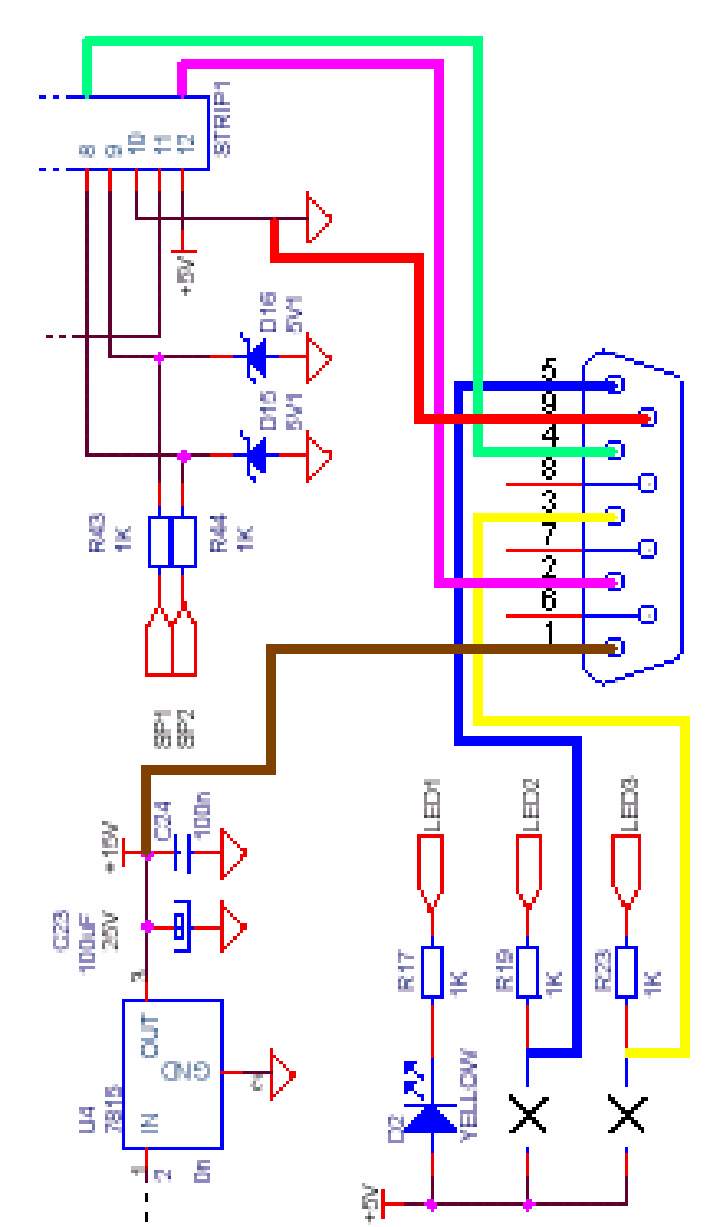


Figure 4-18 Microcontroller slot on IRADK

On the figure we can see the microcontroller connections to the circuits from previous sections. Analog input AN2 is connected to analog signal from ITRIP circuit – take a look at protection circuit section. Quartz crystal is connected to its corresponding pins in order to provide oscillating frequency of 20MHz. If we use DSP or some other microcontroller that is connected to IRADK via adapter it is most probable that it will use its own oscillator so the structure on the picture is only for PIC16C872 pin compatible microcontrollers. MCLR – Master clear pin is also only for PIC – when 12V is on it will be in programming mode, when 5V is on it will be in operating mode. 5V power is supplied to the slot as its most common power supply for microcontrollers. 3V supply is used as A/D converter reference, when using non PIC microcontroller this voltage can be used only for reference functions as its current capacity is very low. All other pins are connected to input or output ports of PIC thus when using non PIC microcontroller should be connected to its ports via adapter.

IRADK modifications, position detecting circuit connection

In order to connect position detection circuit we will need three digital inputs. Only two are available. One of the two available digital inputs is connected to RC1 pin, which is connected to PWM block, thus will have to be output pin thus can not be input pin. Since LED are not very important, we will take out two diodes and put two digital input wires in their place.

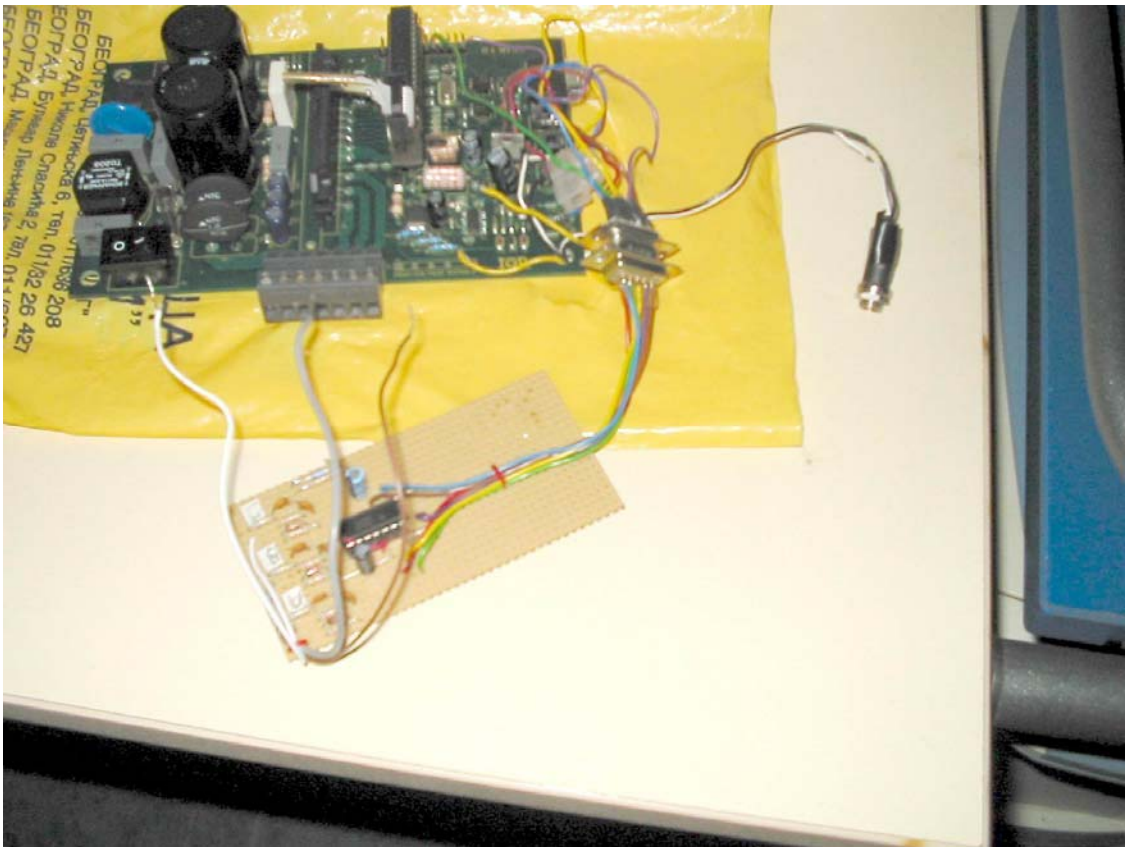


Scheme 4-1 Position detecting circuit connection to IRADK

On the previous figure we can see IRADK modification, as well as its connection to female DB9 connector, to which position detector will be connected later. Green and red LEDs are taken of the board in order to connect inputs from position detector (X marks their anterior location). We chose them because they are connected to PORTC, just like digital input SP2, so we will be able to read states of all digital inputs in one instruction cycle (i.e. software will be simplified).

Auxiliary power inputs are also added to IRADK. They are attached between 15V linear regulator input and the ground. 25V galvanic isolated power source is connected here. The purpose of this is to supply voltage for microcontroller programming. I used them also in the first phase of project to test my program, as connecting IRADK to power

grid voltage can be problematic, an error in software can damage IRADK, while it probably will not damage it if it is connected to 25V. In addition there is a wire added that can connect via connector auxiliary input source (25V) directly to DC bus, since we need a source that will supply motor. This wire **has to be disconnected** when connecting IRADK to power grid, in order to avoid short circuit that could cause severe damage to IRADK.



Picture 4-1 Position detecting circuit connected to IRADK

Chapter 4 IRADK motor drive

Picture 4-2 IRADK board

5. PIC16F873 microcontroller

Introduction

PIC16F873 is a 28-Pin 8-Bit CMOS FLASH general purpose microcontroller. It has 4Kb of flash memory. In subsequent sections most important features of PIC will be discussed. More information can be found on internet, in file:
http://www.microchip.com/download/lit/pline/picmicro/families/16f87x/30292c.pdf

Ports

PIC has three input/output ports: PORTA (6 bit), PORTB (8b) and PORTC (8b). Every port has some special features adjoined.

PORTA is a six-bit wide, bidirectional port. Pins of this port are passed to the input of A/D multiplexer Corresponding data direction register is TRISA. Setting a TRISA bit (= 1) will make the corresponding PORTA pin an input (i.e., put the corresponding output driver in a Hi-Impedance mode). Clearing a TRISA bit (= 0) will make the corresponding PORTA pin an output (i.e., put the contents of the output latch on the selected pin).

Reading the PORTA register reads the status of the pins, whereas writing to it will write to the port latch. All write operations are read-modify-write operations. Therefore, a write to a port implies that the port pins are read, the value is modified and then written to the port data latch. Pin RA4 is multiplexed with the Timer0 module clock input to become the RA4/T0CKI pin. The RA4/T0CKI pin is a Schmitt Trigger input and an open drain output. All other PORTA pins have TTL input levels and full CMOS output drivers. Other PORTA pins are multiplexed with analog inputs and analog VREF input. The operation of each pin is selected by clearing/setting the control bits in the ADCON1 register (A/D Control Register1). The TRISA register controls the direction of the RA pins, even when they are being used as analog inputs. The user must ensure the bits in the TRISA register are maintained set when using them as analog inputs.

PORTB is an 8-bit wide, bi-directional port. The corresponding data direction register is TRISB. It works the same way as TRISA. Three pins of PORTB are multiplexed with the Low Voltage Programming function: RB3/ PGM, RB6/PGC and RB7/PGD. Microcontroller can be programmed with 5V voltage, by using this function. Furthermore we can program our controller using only boot loader, a small program in microcontroller memory that would accept data via serial bus and place it in adequate locations of program memory. Of course boot loader would previously have to be programmed to microcontroller by a real programmer.

Each of the PORTB pins has a weak internal pull-up. A single control bit can turn on all the pull-ups. This is performed by clearing bit RBPU of OPTION register.

Four of the PORTB pins, RB7:RB4, have an interrupt-on-change feature. This interrupt can wake the device from SLEEP.

RB0/INT is an external interrupt input pin and is configured using the INTEDG bit (OPTION_REG<6>).

In this project, IRAMS control signals are attached to PORTB (7..2). ENABLE control signal is attached to RB1. Button is attached to RB0/INT, and it works with interrupt.

PORTC is an 8-bit wide, bidirectional port. TRISC register functions in the same manner as TRISB and TRISA. PORTC is multiplexed with several peripheral functions. PORTC pins have Schmitt Trigger input buffers. When enabling peripheral functions, care should be taken in defining TRIS bits for each PORTC pin. On the following table we can see what can be functions of each and every pin.

PORTC FUNCTIONS

Name	Bit#	Buffer Type	Function
RC0/T1OSO/T1CKI	bit0	ST	Input/output port pin or Timer1 oscillator output/Timer1 clock input.
RC1/T1OSI/CCP2	bit1	ST	Input/output port pin or Timer1 oscillator input or Capture2 input/ Compare2 output/PWM2 output.
RC2/CCP1	bit2	ST	Input/output port pin or Capture1 input/Compare1 output/ PWM1 output.
RC3/SCK/SCL	bit3	ST	RC3 can also be the synchronous serial clock for both SPI and I^2C modes.
RC4/SDI/SDA	bit4	ST	RC4 can also be the SPI Data In (SPI mode) or data I/O (I^2C mode).
RC5/SDO	bit5	ST	Input/output port pin or Synchronous Serial Port data output.
RC6/TX/CK	bit6	ST	Input/output port pin or USART Asynchronous Transmit or Synchronous Clock.
RC7/RX/DT	bit7	ST	Input/output port pin or USART Asynchronous Receive or Synchronous Data.

Legend: ST = Schmitt Trigger input

Table 5-1 PORTC functions

As we can see all communication to the outside world would go through PORTC, since all communication modules are attached to it. Modes that can be used are: I^2C, SPI and USART.

Capture/Compare/PWM functions also use PORTC. In addition we can pass Timer1 clock input to this port as well as make Timer1 oscillator output of it.

In this project we will use some pins of PORTC as digital inputs – from position detecting circuit. Pins RC6 and RC7 will be used for asynchronous communication with PC. PWM feature will be used also, but only as a reference, to put it more precisely, PWM signal will be copied to desired PORTB pin by software.

Timers

Our microcontroller has three programmable timers.

Timer0 timer/counter module can be found in all PIC devices. Interrupt control bits of this timer are in INTCON register, as it is not considered as peripheral of our microcontroller. It has the following features:

- 8-bit timer/counter

- Readable and writable
- 8-bit software programmable prescaler
- Internal or external clock select
- Interrupt on overflow from FFh to 00h
- Edge select for external clock

Timer0 module functioning is defined through OPTION register. Timer mode is selected by clearing bit T0CS (OPTION_REG<5>). In Timer mode, the Timer0 module will increment every instruction cycle (without prescaler). If the TMR0 register is written, the increment is inhibited for the following two instruction cycles. The user can work around this by writing an adjusted value to the TMR0 register

There is only one prescaler available, which is mutually exclusive shared between the Timer0 module and the Watchdog Timer. A prescaler assignment for the Timer0 module means that there is no prescaler for the Watchdog Timer, and vice-versa. Prescaler assignment is defined in PSA (OPTION_REG<5>). If PSA is 0 prescaler is assigned to the timer0 module, otherwise it is assigned to the watchdog timer. Prescaler value is defined by three least significant bits of OPTION_REG <PS2..PS0> using the following table:

Bit Value	TMR0 Rate	WDT Rate
000	1 : 2	1 : 1
001	1 : 4	1 : 2
010	1 : 8	1 : 4
011	1 : 16	1 : 8
100	1 : 32	1 : 16
101	1 : 64	1 : 32
110	1 : 128	1 : 64
111	1 : 256	1 : 128

Table 5-2 Prescaler value table

Timer0 interrupt control functions via two bits of INTCON register, T0IE – Timer0 interrupt enable, and T0IF – Timer0 interrupt flag. When timer0 wraps over (FFh->00h) T0IF will be set, in the same moment if T0IE is set interrupt procedure will be called. T0IF is indication that timer0 interrupt occurred, and should be cleared at the end of timer0 interrupt procedure.

In this project timer0 will be used a reference time base source of our system.

Timer1 module is a 16-bit timer/counter consisting of two 8-bit registers (TMR1H and TMR1L), which are readable and writable. The TMR1 Register pair (TMR1H:TMR1L) increments from 0000h to FFFFh and rolls over to 0000h. Flag pair TMR1IF (PIR1<0>) and TMR1IE (PIE1<0>) functions in the same manner as timer0 flag pair, only here this flags are bits of peripheral interrupt flag/enable registers respectively. Timer1 operation is defined by Timer1 control register (t1con).

Timer1 can operate in one of two modes, as a timer and as a counter. The operating mode is determined by the clock select bit, TMR1CS (T1CON<1>). When in timer mode, Timer1 increments on every instruction cycle. In counter mode, it increments on every rising edge of the external clock input. When the Timer1 oscillator is enabled (T1OSCEN is set), the RC1/T1OSI/CCP2 and RC0/T1OSO/T1CKI pins become inputs. That is, the TRISC<1:0> value is ignored, and these pins read as ‘0’.

Bits T1CON<5,4> are prescale bits. By choosing them to be 00, 01, 10, 11, we will get prescale values 1:1, 1:2, 1:4, and 1:8 correspondingly.

Timer1 can be enabled/disabled by setting/clearing control bit TMR1ON (T1CON<0>).

In this project Timer1 will be used in accelerating of Brushless DC motor, since position detecting circuit will not work if rotor is not moving or if it moves slowly.

Timer2 is an 8-bit timer with a prescaler and a postscaler. It can be used as the PWM time-base for the PWM mode of the CCP module(s). The TMR2 register is readable and writable, and is cleared on any device RESET. T2CON is the register that determines its operation. The input clock (FOSC/4) has a prescale option of 1:1, 1:4, or 1:16, selected by control bits T2CKPS1:T2CKPS0 (T2CON<1:0>). The Timer2 module has an 8-bit period register, PR2. Timer2 increments from 00h until it matches PR2 and then resets to 00h on the next increment cycle. PR2 is a readable and writable register. The PR2 register is initialized to FFh upon RESET. The match output of TMR2 goes through a 4-bit postscaler (which gives a 1:1 to 1:16 scaling inclusive) to generate a TMR2 interrupt (latched in flag bit TMR2IF, (PIR1<1>)). Timer2 can be shut-off by clearing control bit TMR2ON (T2CON<2>), to minimize power consumption. Timer2 scheme is revealed on the following figure.

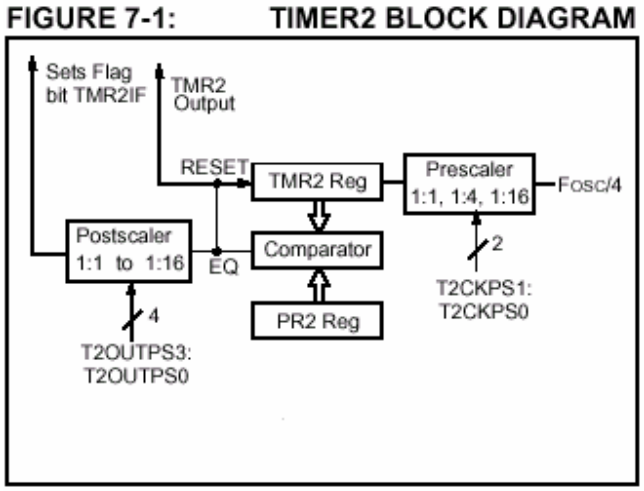


Figure 5-1 Timer2 block diagram

In this project Timer2 will be used in **CAPTURE/COMPARE/PWM module** in order to provide reference PWM signal. Block scheme of mentioned module (when it functions as PWM) can be seen on subsequent figure. Registers related to this module are CCP1CON and CCP2CON (2 modules). In Pulse Width Modulation mode, the CCPx pin (RC2) produces up to a 10-bit resolution PWM output. Since the CCP1 pin is multiplexed with the PORTC data latch, the TRISC<2> bit must be cleared to make the CCP1 pin an output. If we want our module to function as PWM, bits <3..2> of CCP1CON register have to be set. PWM period is defined be PR1 register of Timer2 by formula: PWM period = [(PR2) + 1] • 4 • TOSC • (TMR2 prescale value).

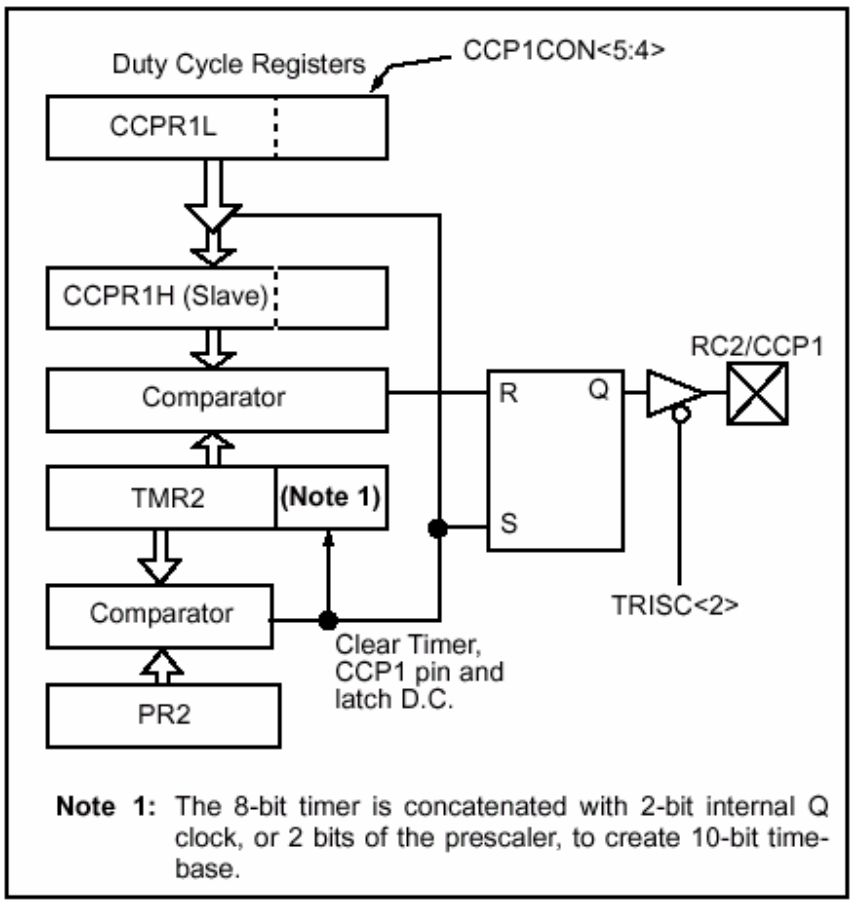


Figure 5-2 PWM mechanism

The PWM duty cycle is specified by writing to the CCPR1L register and to the CCP1CON<5:4> bits. Up to 10-bit resolution is available. The CCPR1L contains the eight MSbs and the CCP1CON<5:4> contains the two LSbs. This 10-bit value is represented by CPR1L:CCP1CON<5:4>. The following equation is used to calculate the PWM duty cycle in time:

PWM duty cycle =(CCPR1L:CCP1CON<5:4>) •TOSC • (TMR2 prescale value)

CCPR1L and CCP1CON<5:4> can be written to at any time, but the duty cycle value is not latched into CCPR1H until after a match between PR2 and TMR2 occurs (i.e., the period is complete). In PWM mode, CCPR1H is a read-only register. The CCPR1H register and a 2-bit internal latch are used to double buffer the PWM duty cycle. This double buffering is essential for glitch-free PWM operation.

Asynchronous communication module

PIC has integrated USART (Universal synchronous asynchronous receiver transmitter) module. Here will be discussed aspects of asynchronous communication (full

duplex), as it is the one used in the project. In addition, it is the most frequently used form of communication. Full duplex means that both communication entities transmit data via one line and receive via the other. Data that is being transferred has a ten bit format. While idle, communication lines are in high state (logical "1"). Device begins transfer with start bit. This is a bit with logical level "0". By changing the state of communication bus, it is "informing" the other device that information is about to be sent. Then it sends eight data bits – one byte and finishes with stop bit, which is "1" of course.

Parameters of data transmission are defined in register TXSTA (Transfer status and control) register. Relevant bits of this register are:

-TX9, nine bit transmit enable bit – enable=1, bit 7
-TXEN, transmit enable bit – enable=1, bit 6
-SYNC, synchronous/asynchronous mode select, synchronous=1, bit
-BRGH, high baud rate select bit, high baud rate=1
-TX9D, value of ninth bit in nine bit communication, can be parity bit

Data reception parameters are located in register RCSTA. Relevant ones are:

-SPEN, Serial Port Enable bit, should be set, bit 7
-RX9, toggles 9/8 bit transfer modes, set for 9 bit communication, bit 6
-CREN, continuous receive enable, bit 4
-ADDEN, Address Detect Enable bit, enable=1, bit 3
-FERR, Framing Error bit, if set, framing error can be updated by reading RCREG register and receive next valid byte, bit 2

-OERR, Overrun error bit, overrun error=1 (can be cleared by clearing CREN bit), bit 1
-RX9D: 9th bit of Received Data (can be parity bit, but must be calculated by user firmware), bit 0

Both devices have to be set at the same communication baud rate. Baud rate is determined by SPBRG register of Baud rate generator. It can be calculated from the equation: Baud Rate = FOSC/(16(X+1)) if BRGH=1, or Baud Rate = FOSC/(64(X+1)), if BRGH=0, where BRGH is a bit of transmit status register, X is a value of SPBRG register (0..255).

Communication registers are RCREG and TXREG. RCREG receives incoming data. Data that we want to send should be written to TXREG, transfer will start as soon as data is written.

There are two interrupts that can be adjoined to asynchronous communication: receive and transmit interrupt. Flag pair that serves receive interrupt is RCIE, RCIF from registers PIE1 and PIR1 respectively. RCIF is set when byte is received, and is cleared when RCREG is read.

If we need to send large amount of data, we will use transmit interrupt. Interrupt flag pair will be TXIE, TXIF from registers PIE1 and PIR1 respectively. TXIF is set when transfer is over, and can be cleared only by writing new value to TXREG. This will

maximize our transfer rate, as our software will enable us that new byte is written as soon as anterior one is sent.

In this project we will use asynchronous communication via receive interrupt.

Interrupt system, interrupt on button press

PIC16F873 has a non-vectored interrupt system. That way, every interrupt that occurs will cause the execution of the same interrupt procedure. Determining which interrupt occurred is a task for interrupt procedure. Procedure will poll interrupt flags in order to determine interrupt cause. Every interrupt has two flags. One for enabling it, and other which is set whenever interrupt occurs (this one is polled in the procedure), as we have already seen (timer0 – section 2).

Beside the timer and USART interrupt in this project interrupt from the button is used also. Button is attached to RB0 bit of PORTB. This interrupt flags are INTE and INTF (external interrupt). Both are the bits of INTCON register. Interrupt will occur on rising or falling edge of the signal on RB0 pin, depending of the state of INTEDG flag of OPTION register.

Microcontroller programming

Programming of PIC microcontroller can be done by a programmer device. In that case we would place our microcontroller in the programmer, program it, and then get it out of the programmer and place it in IRADK (or any other device). This technique has great drawbacks. It takes a lot of time to move microcontroller from one slot to another, and if we do it many times, it is very probable that we will damage pins of our microcontroller, which would make it unusable. Solution of these problems can be found in in-circuit programming, that programming without getting our microcontroller out of IRADK.

In-circuit programming can be applied by the use of boot loader. It is a small program that is programmed in high program locations of the microcontroller by a regular programmer. Afterwards, that program will receive program via serial bus and place it in microcontroller memory. This is known as programming via change of configuration. In order to function this programming method, low voltage programming has to be enabled when programming boot loader, as our microcontroller functions with 5V voltage. There is a PIC downloader program on PC side that is responsible for the communication with boot loader that is microcontroller. When reset, microcontroller will wait some time (0.2s for example) to receive program from PIC. If this fails to occur it will start with execution of program. The disadvantage of this method is use of higher memory locations of microcontroller, less resources. Besides, it is possible to write program over a boot loader by mistake. In that case, boot loader would have to be programmed again, and then we must have the programmer.

The other form of in-circuit programming is to add an adapter to microcontroller slot on IRADK and place a microcontroller in it. In programming mode we will connect programmer cable to it and program. In program execution mode we will place one jumper on a programmer connection. This is the method I used. The only difference is that I used ICD (In Circuit Debugger) instead of programmer. It is a device that can do

everything that programmer can do, plus it can be connected via serial bus to microcontroller, while it is functioning, and then it could read the states of microcontroller registers, display them on the screen, change them, etc. These features will not be used in the project.

If we want our ICD to function we have to connect it to pins RB6, RB7, MCLR, +5V, GND to it. Communication will be realized via serial link through pins RB6 and RB7. ICD will get a power supply from +5V and ground pins. This voltage will be used for ICD functioning, as well as for a conversion to 12V via boost converter that is integrated on ICD. 12V supply is sent back to controller via MCLR pin for programming purposes. In programming mode RB6, RB7, MCLR pins of microcontroller will be disconnected from their corresponding pins on IRADK microcontroller slot, while in functioning mode these pin would connect via jumper.

5V voltage source mentioned in previous paragraph is provided through IRADK circuitry. 25V voltage source is connected at input of 15V stabilizer. The switcher is turned off. 25V voltage is supplied from a small isolated transformer. We cannot use voltage from switcher i.e. power grid, neither from non isolated transformer (auto transformer, for example), since ICD has its own reference that could be fatal to it.

MPLAB integrated development environment and HI tech C

MPLAB is microchip development environment which is used with all PIC microcontroller types. It is a user friendly program. It has built in assembler compiler and linker. Programmer support is also provided, as well as ICD software, so we can program the chip and debug directly from MPLAB. Program that is written can be simulated in the simulator. Simulator executes program line by line, while values of registers and other variables are monitored in watches. External interrupts can be simulated by using a pin stimulus. Serial communication can not be simulated.

Hi-tech C for PIC programming is user friendly tool that can be added to MPLAB development environment, so programs can be written and compiled without changing working environment. Hi-tech C for PIC microcontroller family is completely compatible with regular ANSI C, from the programming point of view. All statements, commands and syntax are the same. Even include libraries are the same (they have the same functions implemented). Since interrupt system is not vectored, that, there is only one interrupt procedure, we can define only one function that will be interrupt adjoined: interrupt void isr() {…}. Values of microcontroller registers are accessed by their name, for example PORTB, TMR1H, etc. To them we can access from any part of program. This method of programming is very simple, as there is not much new for an engineer to learn in order to start programming PIC. There are also specialized functions that are used to modify and read values of microcontroller registers. These functions will enable more organized program development, but will not affect program function (these functions are not used in this project). Mathematical operations of multiply, divide, and even more complicated like log, sin etc. (from math.h include file) should be used carefully or avoided. Time of their execution can be very long, so they are not suitable for real time, or any other time critical applications. In this project they are avoided. Majority of variables that are used in this project are 8 bit variables. There is only one 16 bit variable. It is natural to use 8 bit variables when working with 8 bit microcontroller.

Regards on simulation are the same, whether we are using assembler or Hi-tech C. The difference is only at the beginning of program execution, there is a code inserted by linker that has to be executed prior to our program.

6. Sensorless mechanism software resources

Introduction

In chapter 2, position detecting circuit was presented. At the end of the third chapter circuit connection to IRADK was depicted (IRADK modification section). The theme of this chapter is software integration of our system. Software resources located on PC will be described here also (this is referring to serial communication program). There are several functions that microcontroller software has to implement.

Our motor needs to be accelerated to some speed in order to produce BEM forces sufficient for position detector functioning. Brushless DC acceleration is achieved though open loop control, i.e. timer determines commutation moments.

When accelerated, motor should commutate on regular angle intervals, thus signals from position detecting circuit should be read, and depending of their values commutation moments should be determined. I can say that this is the most important software function, although other software functions are indispensable.

Each one of two previously mentioned functions has a mode of functioning that is adjoined to it. On the following block diagram we can see association of those two modes. When functioning, our system is always in one of these two modes.

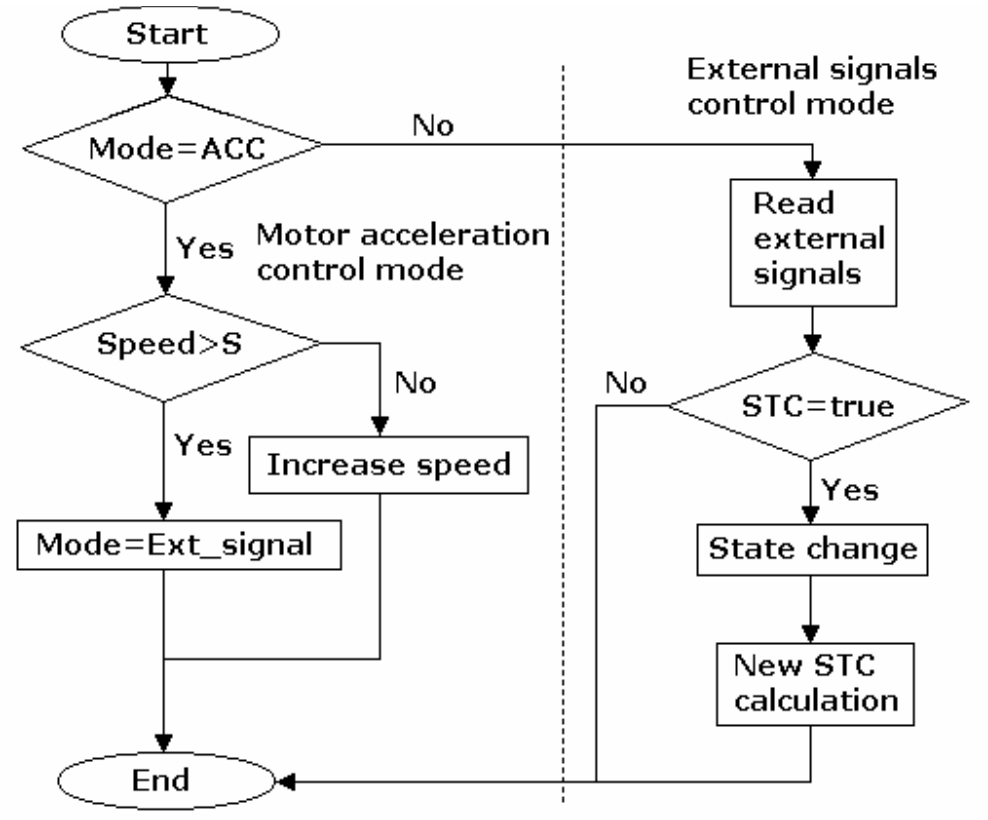


Figure 6-1 Software resources block diagram

STC stands for **S**tate **T**ransition **C**ondition. Blocks on the diagram will be coded in interrupt service routine and their execution will be invoked by timer interrupt.

Pulse Width Modulation has to be implemented, as our desire is to control values of phase voltages.

One part of software has to be dedicated to the reset of IRADK. When IRADK signal ITRIP becomes high, due to high current or on startup, it need to be reset to low level if we want IRADK to function. This function is implemented on the button press interrupt.

Change of direction of motor rotation is also implemented on button interrupt. When motor is not blocked (ITRIP=0), button press will cause change of rotation direction, otherwise it will unblock the motor.

One part of program is in charge of communication with PC, as voltage command has to be accepted from PC, and current position has to be sent in the other direction in order to monitor program execution. Microcontroller communicates with PC at the rate of 2400 baud/sec. When byte is received from PC, interrupt will occur.

All previously defined functions are realized in interrupt service routines, except PWM. It is normal to realize PWM via interrupt, but this is not the case in this project, since there are some efficiency reasons that will be discussed later. Beside PWM, main program is also in charge of variable initialization just like in all microcontroller systems.

In this chapter all previously mentioned software functions will be discussed in subsequent sections, thus program will be analyzed part by part. In appendix A entire program can be found. But before we get to the analysis of microcontroller program we will take a brief look at the advantages and drawbacks of C/ASM programming, and also serial link program on PC side.

Hi-tech C Vs regular PIC assembler programming

It is well known that advantages of comfort program writing in C are followed by sluggish execution of program, and we know that speed is crucial to real time applications. In this section we will see that C program execution is sufficiently fast for this application by comparing one simple program written in C and assembler.

Following program has interrupt routine that toggles the value of Boolean variable <var> In the main program a value of PORTB bit 0 is toggled (oscillator on RB0). There are three listings: C code, assembler code produced by program in C and then independently written assembler code that has the same function.

C program:

```
#include <pic1687x.h>

interrupt void isr() {
 static int var;

  if (T0IF)
        {if (var) var=0;
```

```
                else var=1;
            }
  T0IF=0;
}

main() {
  TRISB=0;     //  PORTB is output

  OPTION=0X11;
  T0IE=1;

  GIE=1;       //  Global interrupt enable

  while (1) if (RB0) RB0=0;
                  else RB0=1;
  };
```

Compiled C program:

```
0000  0183  poweru  clrf   0x3
0001  3000          movlw  0x0
0002  008A          movwf  0xA
0003  2827          goto   exit
0004  00FF  intlev   movwf  0x7F
0005  0803          movf   0x3,W
0006  0183          clrf   0x3
0007  00A2          movwf  0x22
0008  080A          movf   0xA,W
0009  00A3          movwf  0x23
000A  018A          clrf   0xA
000B  1D0B  int_fu  btfss  0xB,0x2
000C  280E          goto   0xE
000D  280F          goto   0xF
000E  281D          goto   0x1D
000F  0821          movf   0x21,W
0010  0420          iorwf  0x20,W
0011  1903          btfsc  0x3,0x2
0012  2814          goto   0x14
0013  2815          goto   0x15
0014  2818          goto   0x18
0015  01A0          clrf   0x20
0016  01A1          clrf   0x21
0017  281D          goto   0x1D
0018  1283          bcf    0x3,0x5
0019  1303          bcf    0x3,0x6
001A  01A0          clrf   0x20
```

```
001B  0AA0          incf   0x20
001C  01A1          clrf   0x21
001D  110B          bcf    0xB,0x2
001E  1303          bcf    0x3,0x6
001F  1283          bcf    0x3,0x5
0020  0823          movf   0x23,W
0021  008A          movwf  0xA
0022  0822  int_re  movf   0x22,W
0023  0083          movwf  0x3
0024  0EFF          swapf  0x7F
0025  0E7F          swapf  0x7F,W
0026  0009          retfie
0027  3020  exit    movlw  0x20
0028  0084          movwf  0x4
0029  3022          movlw  0x22
002A  2031          call   clear_ram
002B  0183          clrf   0x3
002C  118A          bcf    0xA,0x3
002D  2FEA          goto   main
002E  0604          xorwf  0x4,W
002F  0180          clrf   0x0
0030  0A84          incf   0x4
0031  0604  clear_  xorwf  0x4,W
0032  1D03          btfss  0x3,0x2
0033  282E          goto   0x2E
0034  3400          retlw  0x0
0035  3FFF  isr     addlw  0xff

07EA  1683  main    bsf    0x3,0x5
07EB  1303          bcf    0x3,0x6
07EC  0186          clrf   0x6
07ED  3011          movlw  0x11
07EE  0081          movwf  0x1
07EF  168B          bsf    0xB,0x5
07F0  178B          bsf    0xB,0x7
07F1  2FFD          goto   0x7FD
07F2  1283          bcf    0x3,0x5
07F3  1303          bcf    0x3,0x6
07F4  1C06          btfss  0x6,0x0
07F5  2FF7          goto   0x7F7
07F6  2FF8          goto   0x7F8
07F7  2FFA          goto   0x7FA
07F8  1006          bcf    0x6,0x0
07F9  2FFD          goto   0x7FD
07FA  1283          bcf    0x3,0x5
07FB  1303          bcf    0x3,0x6
```

```
07FC  1406            bsf    0x6,0x0
07FD  2FF2            goto   0x7F2
07FE  118A            bcf    0xA,0x3
07FF  2827            goto   exit
0800  3FFF            addlw  0xff
07FC  1406            bsf    0x6,0x0
07FD  2FF2            goto   0x7F2
07FE  118A            bcf    0xA,0x3
```

Assembler program:

```
#include "p16f873.inc"
__CONFIG _CP_OFF & _WDT_OFF & _PWRTE_ON & _XT_OSC

   org 0x00
   goto Main

   org 0x04
   goto ISR

   Cblock 0x0C
    var
    w_temp
    status_temp
    pclath_temp
   endc

bank1 macro
   bsf STATUS,RP0
endm

bank0 macro
   bcf STATUS,RP0
endm

Main
   bank1

   movlw 0
   movwf TRISB

   movlw b'00010001'
   movwf OPTION_REG

   bsf INTCON,T0IE
   bsf INTCON,GIE
```

```
    bank0

lo   btfss PORTB,0
     goto loi
     bcf PORTB,0
     goto lo
loi  bsf PORTB,0
     goto lo

ISR
     movwf w_temp ;
     swapf STATUS,w ;
     clrf STATUS ;
     movwf status_temp ;
     movf PCLATH, w ;
     movwf pclath_temp ;
     clrf PCLATH ;

      decfsz var
      goto ilo
      movlw 0
      movwf var
      goto ied
ilo   movlw 1
      movwf var

ied  movf pclath_temp, w ;
      movwf PCLATH ;
      swapf status_temp,w ;
      movwf STATUS ;
      swapf w_temp,f ;
      swapf w_temp,w ;
      retfie
end
```

In the third program (assembler original) the entire context is saved upon entering in interrupt service routine. C program automatically saves the context. We can see that program written in C is similar to its assembler equivalent thus in many cases will not produce holdup in execution. Context saving, as well as some other processes may be unnecessary, in that case we may choose to write our program in assembler or add some lines of assembler code in C. In high speed real time systems it is recommendable to write interrupts in assembler while specific routines called from interrupt can be easily written in C.

We can insert assembler code lines into C program by using directives #asm and #endasm:

```
#asm
   code
#endasm
```

In code section we can use all variables active in that part of C program. We can also use predefined variable _RETURN_ to store C function result in it.

Serial link program on PC

Serial communication program on PC side that is used in this project is written in ansi C. This program will not be listed here as it is unnecessary. This program is adjoined to this project. It consists of two ansi C files: DOSP.C and DOSF.C (dos is because they work in dos). In DOSF.C all constants are defined, and usartcomm function is implemented. DOSP.C is a user of DOSF program. In it we can change parameters of asynchronous communication: parity bits, baud rate, communication port (COMM1, COMM2…), etc. Compilation of this program will produce executable program version that can be transferred to every computer. It is important to have source code of this program so we can change parameters and recompile it when needed.

When started, this program will automatically write on the screen all values received from the microcontroller. Write is accomplished by typing a number we want to send to microcontroller while holding ALT.

This is DOS program, so it may not work in windows NT, and later DOS independent operating systems. It is the simplest form of PC communication program, but its performances are sufficient.

Serial link on microcontroller side

Main program initializes serial communication through the following code lines:

```
TXSTA=0X23;  //   Serial link configuration

    RCSTA=0X90;
    SPBRG=129;      (*)
    RCIE=1;          (**)
    PEIE=1;          (***)
    CREN=0;          (****)
    CREN=1;
```

Non-parity, one start, one stop bit, asynchronous, non-addressing communication is the meaning of first two lines. Communication baud rate is set at 2400 baud/sec (*). Receive interrupt is enabled (**, ***). Lines (****) clear the OERR flag, that may be set due to previous overrun error occurrence. Next code lines will enable PWM duty ratio modification via serial link:

```
 if (RCIF) {
   dutyR=RCREG;
```

```
TXREG=dutyR;
CCPR1L=dutyR;  }
```

When a value is received from PC, it is automatically placed in CCPR1L register, echo is returned to PC. During the program analysis and debug, in some places of program, some values are sent to PC. All this is accomplished by a simple write to TXREG.

Button press functions

IRADK button is used for two purposes: reset of IRADK over current protection latch and changing of motor direction. When button is pressed interrupt is generated. Button **is not debounced**, so it may happen that one button press causes two interrupts. Debouncing is avoided because it would use a timer, and would be too complicated, and as we will see it will not be necessary. Following part of interrupt service routine is meant to work with button:

```
if (INTF) {
  if (RC4) {temp=TRISC;            (*)
        TRISC=TRISC & 0xdf;       (**)
        RC5=1;                    (***)
        TRISC=temp;}              (****)
  else if (inc) inc=0;else inc=1;  (*****)
  INTF=0;
  }
```

When button is pressed INTF flag is set. Pin RC5 is connected to reset of protection circuit. Information of this circuit state is on the pin RC4. If over current protection latch is set RC4 is on high logical level. In order to reset a latch RC5 is made an output, and logical “1” is placed on it for a short amount of time, roughly 1us (*, **, ***). Then a circuit is returned to its previous state (****) – RC5 is an input, thus has no effect on protection circuit functioning. If interrupt occurs more than once, due to fault of undebounced button, everything will work normally, since there is no big difference if signal is set at logical “1” 1 or 2 microseconds.

Changing of motor direction is accomplished by changing a value of interrupt service routine variable <inc>. If a protection latch is not set, than a user must have been pressed a button because he wants to change a direction of motor rotation. Value of <inc> variable is complemented (*****). Following section will reveal functioning of our program with this variable. INTF flag is reset at the end of the procedure for the reason mentioned in previous chapter. Due to the fault of undebounced button, it may happen that our motor does not change direction – if interrupt occurs twice or any even number of times nothing will happen. In that case we should press it again. This poses little inconvenience. Its solution would be far too complicated, so I decided simply not to solve it.

Init of this interrupt is done in main() program. Interrupt on rising edge of the RB0 signal is set and enabled. We could work with falling edge, there would be no difference.

Pulse **W**idth **M**odulation

Beside PWM this section will deal with toggling on/off of inverter switches generally. PWM is realized on high side switches of our IRAMS inverter for the reasons mentioned in previous chapters. There are six states of inverter: 1) C->A 2) B->A 3) B->C 4) A->C 5) A->B 6) C->B. Since there are three phases, A, B and C, letter on the left side of the arrow is the phase that the current is running into, and a letter on the right side is the phase that current is running from. Bits 7..2 are in charge of toggling on/off inverter switches, so a simple write to PORTB will turn on/off desired transistors. PORTB<7..2>=A#hi, B#hi, C#hi, A#low, B#low, C#low. Pin 1 is ENABLE, "1" should be written to it. Pin 0 of PORTB is input, thus values that are written to it are ignored. Every state has two assigned vectors – one for impulse and one for pause of PWM period. They are defined by following tables:

```
const unsigned TableOn [7] = {0xff, 0xce, 0xae, 0xba, 0x7a, 0x76, 0xd6};
const unsigned TableOff[7] = {0xff, 0xee, 0xee, 0xfa, 0xfa, 0xf6, 0xf6};
```

First hexadecimal number in parenthesis is never used, as it has index zero, and there is no state zero. It is there because an array in C has to start with index zero. Value of state zero vectors is FF, which guarantee that all switches will be off if this state occurs.

When written to PORTB, value from TableOn will turn on two- switches of inverter, one on the high side, and one on the low side. Corresponding TableOff vector will turn off high side switch.

During state change, values of new state vectors are written in variables OnVector and OffVector:

```
OnVector=TableOn[state];
OffVector=TableOff[state];
```

These code lines are repeated two times throughout the program, since there are two modes of function, thus two modes of state changing. Switch toggling, i.e. PWM, is realized by consecutive forwarding of On/OffVector values to PORTB.

PWM module of our microcontroller has its output on RC2 pin of PORTC. This module is used here indirectly. RC2 output is read by software (and only by software), and then depending of its value, OnVector or OffVector is forwarded to PORTB:

```
if (RC2) PORTB=OnVector;
        else PORTB=OffVector;
```

These lines should be executed as often as possible in order to have high quality PWM, especially if impulses are narrow. In our program they are in main(), and in some parts of interrupt service routine, thus will be executed whenever there is no interrupt, and in some parts of interrupt procedure. Main program (without initializations) looks like this:

```
while (1) if (RC2) PORTB=OnVector;
                  else PORTB=OffVector;
```

As we can see main program only executes PWM while waiting for interrupts to occur. This is not the usual way of PWM realization, but it has some important advantages. The other way would be to use timer and interrupts, but then we would have to calculate pause period (or impulse period, if pause is defined). More important, some parts of interrupt service routine of this project can take a lot of processor time, halting that way our PWM.

At the end of this section, we are dealing with necessary program fraction, initialization (PORTB and PWM). PORTB pins 7..1 have to be outputs, and pin 0 input:

```
TRISB=0X03;
PORTB=0XFF;
TRISB=0X01;
PORTB=0XFC;
```

These may look complicated as there is a simpler way to initialize PORTB, but it will provide additional security, as we must not allow two transistors from the same phase to be turned on. First two lines will ensure that all transistors are off, and ENABLE signal is an input, thus inverter is out of function. Last two lines will make ENABLE signal an output on high logical level (i.e. enable).
PWM init is done through the following lines:

```
TRISC=0XBB;
  . . .
PR2=0XFF;
CCPR1L=5;
T2CON=0X05;
CCP1CON=0X0F;
```

First line configures pins of PORTC, at this point, important is that it configures RC2 to be an output, otherwise PWM would not function. Lines that follow are not written as their purpose is not related to PWM (three dots). Lines that follow those lines configure period register at maximum value (FF=255), and set initial value of PWM impulse at 5 – it is a low level that will not cause high current protection reaction. PWM impulse width can be increased/decreased by a data received from serial bus (this will be discussed later). Last two lines configure a timer2 to work adjoined to PWM module, as well as a frequency of a clock that drives it. Frequency of a clock is set to 1.25Mh ($=F_{oscillator}/16$). One quarter of processor clock is prescaled by a factor 4. PWM frequency is $F_{PWM} = 1.25MHz/256 = 4882Hz$. Resolution of PWM is 8 bits, two additional PWM bits (located in CCPRL1 register) are not used.

Motor acceleration mode

As it is already mentioned, motor has to be accelerated to a speed at which BEM forces will be strong enough that motor position can be extracted from their values. In order to accelerate motor, commutation moments will be determined by timer. To put it

briefly, value written in timer register will increase until it reaches maximum. When it reaches maximum interrupt will occur. Commutation will be executed through interrupt procedure. Then, new value is written into timer register and so on. Values that will be written to timer register should increase. That way period of commutation will decrease and frequency i.e. motor speed will rise.

In this mode of control there is absolutely no feedback, so we will not know the angle between rotor and stator flu. The idea is to let a high current through motor windings (higher than nominal), that will produce high electromagnetic torque, which will force rotor to follow stator field, i.e. angle between stator and rotor flux will be small. High current and torque guarantee that our motor will move. Current in motor windings will be: I=U/2R-2E, where U is phase voltage (produced by PWM), R is resistance of one phase of motor and E is BEMF of one phase of motor. This expression is approximate, as we neglected existence of inductivity and transient processes, but it is sufficiently precise, since we do not practically want to control current here – we only want to limit it. In addition, we can not measure current during the motor startup, since PWM impulses are very narrow.

Acceleration rate has to be limited. As we know:

$$M = J * \alpha$$

M is resultant torque, α is acceleration and J is polar moment of inertia. Resultant torque is available electromagnetic torque diminished by the value of load torque. If our acceleration is too high, term on the right side of the equation can get higher than the one on the left which will cause our motor to block, thus value of acceleration should be chosen to be reasonable.

In order to implement the acceleration of motor Timer1 timer/counter module is used. I chose this module because it has two 8 bit registers (tmr1h, tmr1l), when used with prescaler it can provide longer periods, i.e. lower speeds which are necessary for acceleration. In addition, resolution is higher, and it is possible to accomplish linear speed augment more easily. The following portion of software will configure Timer1:

```
T1CON=0X31;  //  TMR1 configuring
TMR1IE=1;
```

First line places hexadecimal value 31 in T1CON register, 0X31=00110001. Bits 7, 6 and 2 are irrelevant. Bits 5 and 4 (11) define prescale value at 1:8 (maximal value). Bit 3 shuts-off oscillator, since we are using internal clock. Bit 1 selects internal clock. Bit 0 enables timer1. Second line of code enables interrupt on timer1. This initialization is placed in the main procedure, like the most of initializations, though there is a portion of code in interrupt procedure that will reconfigure this timer when needed. Maximum period of timer1 configured in manner described above is:

$$T = \frac{8 * 2^{16}}{F_{oscillator} / 4} = 0.104\text{s } (\sim 9.53\text{Hz}), \qquad (6.1)$$

Frequency of oscillator is 20Mhz. Frequency in parenthesis is the minimal frequency of state shifting. Divided by 12 it gives us a number of rotations per second – 0.79Hz (case of 4 pole motor), as we can see it is sufficiently low frequency, that is, speed. Subsequent block of code is the one in charge of motor acceleration. 16 bit variable t1Control contains the number that is written to timer1 registers at the end of interrupt procedure. Increasing of this variable in every cycle (i.e. interrupt occurrence) obviously accelerates the motor.

```
interrupt void isr() {
  static unsigned state=1;                  //  Variable definitions;
  static unsigned dutyR=0;
  static unsigned int tStep=637;
  static unsigned int t1Control=0;
  static signed direction=1;
  static unsigned inc=0;


  static unsigned sending=0;
;
    . . .
 if (TMR1IF)
          {state+=direction;                                    //  changing of state
          if (state==0) state=6;else if (state>6) state=1; // state overflow ctrl      (*)
          OnVector=TableOn[state];   //
          OffVector=TableOff[state];  //
          if (!inc) {t1Control+=tStep;
                  tStep-=5;}
          else {t1Control-=tStep;
               tStep+=5;}

          if (t1Control<637) {inc=0;
                          if (direction==1) direction=-1;else direction=1;
                          tStep=637;
                          TXREG=100;}

          if (t1Control>40000)    {OPTION=0X11;           //    (**)
                                    T0IE=1;
                                    if (state && 0x01) test=0; else test=1;
                                    if (direction) testVector=testTable1[state];
                                    else testVector=testTable_1[state];
                                    TMR1ON=0;
                                    TMR1IE=0;}

          if (tStep<10) tStep=10;
          TMR1H=t1Control>>8;          // (***)
          TMR1L=t1Control;             // (***)
```

```
TMR1IF=0;
sending=PORTC & 0x0B;
TXREG=sending;
};
```

Let us suppose now that we want to move motor that is standing still. Initial value of variable t1Control is 0, which means that initial speed of our motor will be 0.79 rounds per second (as discussed above). On every interrupt occurrence state will increase/decrease (*) depending on the variable direction (+/-1). Motor will start to move in desired direction.

When the motor is starting to move, interrupts (i.e. state changes) are less frequent, therefore step should be smaller in order to obtain linear speed augmentation. Current step value is contained in variable tStep. Now let us take a look at the program presented above supposing that value of variable inc is zero (inc=0;) and t1Control is less than 40000. As we can see, on every interrupt come to pass following events: state changes in desired direction, tStep decreases by a fixed value, previous value of t1Control is increased by tStep value, t1Control is written to timer1 registers (TMR1H, TMR1L). tStep value is decreased by 5 in every cycle, its initial value is 637. Motor accelerates until t1Control value reaches 40000. These values (5, 637, 40000) are more or less empirical, that is, they are the result of testing, not a precise calculation. The calculation that is used was only approximate, and it only yielded the first results, that I changed later through experimenting. Though, the motor will not be accelerating ideally linear. In the following graph we can see the acceleration characteristic.

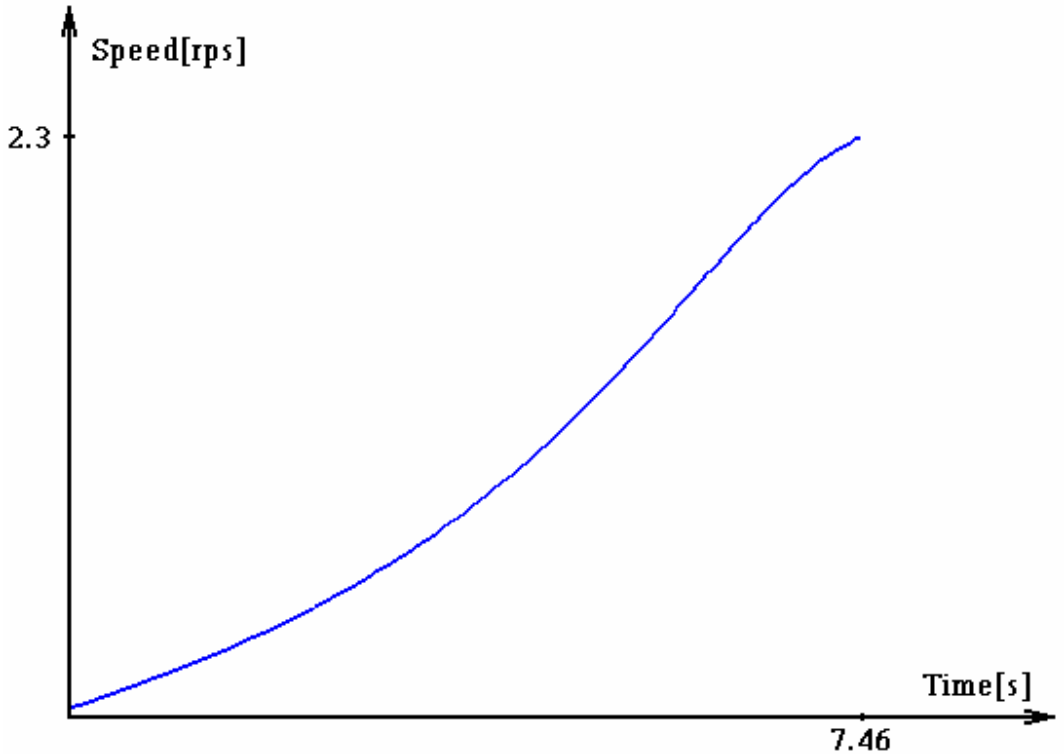


Figure 6-2 Acceleration characteristic

Although we do not have linear speed augmentation, this type of acceleration will preserve a processor time and resources significantly. Any other, more linear type would have to use one more timer and/or operations like getting a square root, reciprocal value, multiplication etc., and their execution is very slow.

When t1Control value reaches 40000 our system shifts to the other mode of control – control by digital input signals. Value of 40000 written to TMR1H: TMR1L register pair is correlated to motor speed of 2.3 rpm-for a 4 pole motor (4.6 for 2 pole motor). When motor gets to revolve at this speed, we are changing a control mode. Change of control mode is done by stopping a timer1 and turning on timer0 (**). More comprehensive control mode change discussion is in next section.

Variable <inc> serves for a direction change. <inc> is "0" in normal circumstances. When we press the button <inc> will become "1", motor will start to slow down following the same steps that are followed when it was accelerating, i.e. tStep value will be increasing. When t1Control drops below 637 – maximal step value, direction is changing, <inc> is back at "0" and motor starts to accelerate again (in opposite direction of course).

Value from t1Control is written to timer1 registers in two lines (***), since t1Control is a 16 bit variable – there is an eight bit shift that allows us to write higher byte of t1Control to TMR1H. Last two lines of code presented in this section are for debugging purposes, they have no effect on program execution.

External signals control mode

When motor reaches certain speed (anterior section), BEM forces become significant, as a result position can be detected via position detecting circuit. As it is discussed in the second chapter, in order to provide high quality torque and speed control, motor has to be commutated at precise positions. Motor position is reflected in BEM forces. On subsequent images we can see motor circuit circumstances throughout six commutation states (states are defined in PWM section of this chapter).

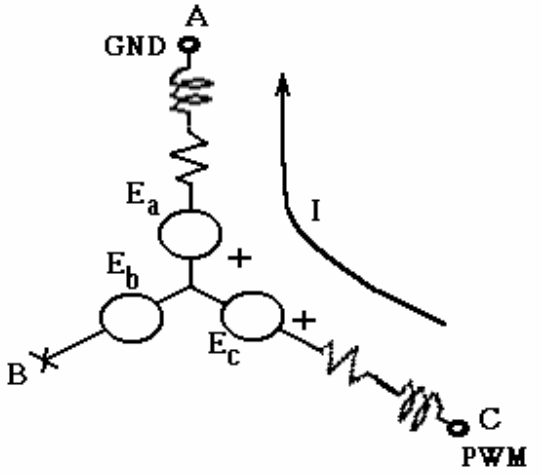


Figure 6-3 State 1 electric model

External signals condition: B>A=1, C>B=1, A>C=0
Transition to state 2 should occur when C>B becomes "0" – positive direction.

Transition to state 6 should occur when B>A becomes “0” – negative direction.

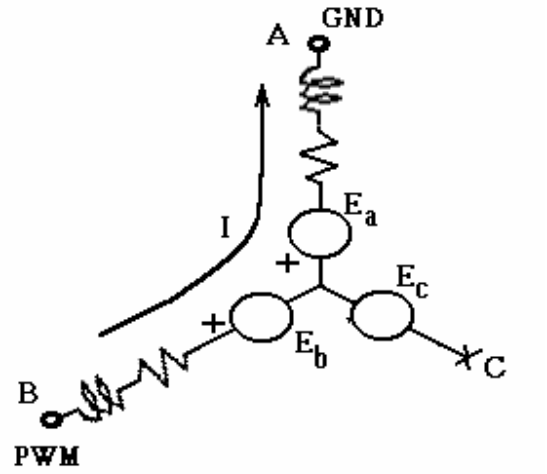


Figure 6-4 State2 electric model

External signals condition: B>A=1, C>B=0, A>C=0
Transition to state 3 should occur when A>C becomes “1” – positive direction.
Transition to state 1 should occur when C>B becomes “1” – negative direction.

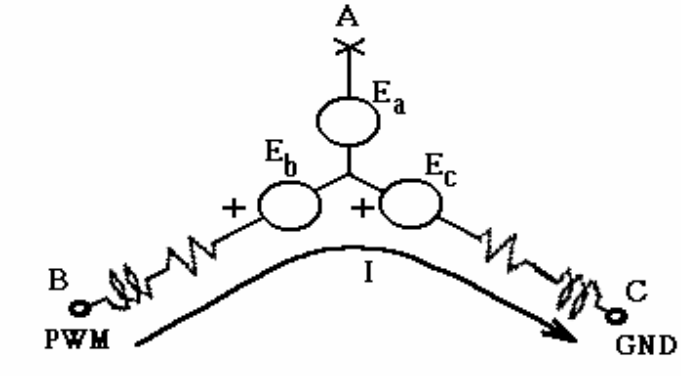


Figure 6-5 State 3 model

External signals condition: B>A=1, C>B=0, A>C=1
Transition to state 4 should occur when B>A becomes “0” – positive direction.
Transition to state 2 should occur when A>C becomes “0” – negative direction.

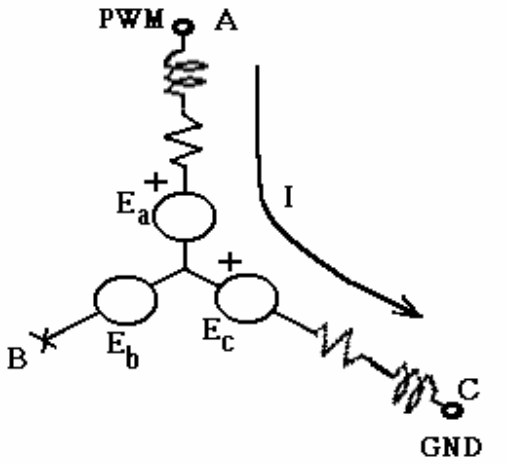


Figure 6-6 State 4 model

External signals condition: B>A=0, C>B=0, A>C=1
Transition to state 5 should occur when A>C becomes "1" – positive direction.
Transition to state 3 should occur when C>B becomes "1" – negative direction.

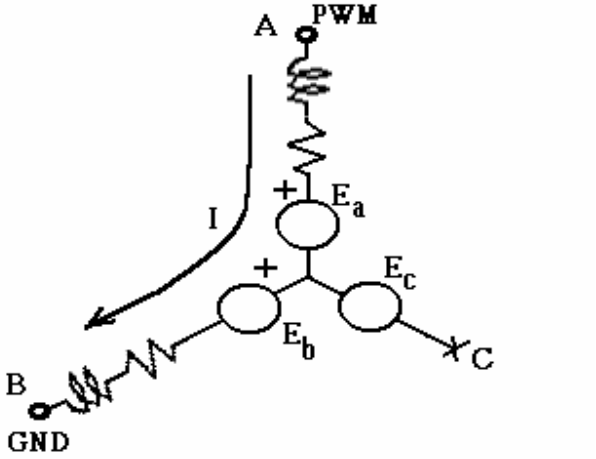


Figure 6-7 State 5 model

External signals condition: B>A=0, C>B=1, A>C=1
Transition to state 6 should occur when A>C becomes "1" – positive direction.
Transition to state 4 should occur when C>B becomes "1" – negative direction.

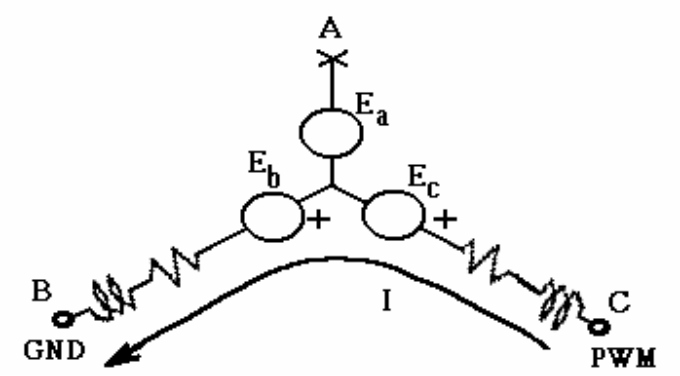


Figure 6-8 State 6 model

External signals condition: B>A=0, C>B=1 , A>C=0
Transition to state 1 should occur when B>A becomes "1" – positive direction.
Transition to state 5 should occur when A>C becomes "1" – negative direction.

Position detecting circuit which produces digital signals is discussed in section Practical realization Summary of external signal values and transition conditions through states is presented in the following table (6-1, next page). Our program task is to read external signals (B>A, C>B, A>C) on distinct time intervals, that are much shorter than duration of one state, and execute state change when a preferred external signal changes its state. Timer0 is configured to generate interrupts on every ~200us (4882Hz). This configuration is done upon entering in this control mode – in interrupt procedure of timer1 (code from previous section, when t1Control variable gets higher than 40000, marked with (**)). Timer1 oscillator is shut down and timer0 interrupt is enabled, simultaneously.

STATE	B>A	C>B	A>C	Positive direction condition	Negative direction condition
1	1	1	0	(C>B)=0	(B>A)=0
2	1	0	0	(A>C)=1	(C>B)=1
3	1	0	1	(B>A)=0	(A>C)=0
4	0	0	1	(C>B)=1	(B>A)=1
5	0	1	1	(A>C)=0	(C>B)=0
6	0	1	0	(B>A)=1	(A>C)=1

Table 6-1 External signals and state transition conditions through states

Next block of code will be executing on timer0 interrupt occurrence.

```
interrupt void isr() {
 . . .
 static unsigned test=0;
```

```
static unsigned testVector=0;
static unsigned waitState=3;
static unsigned temp
.  .  .
if (T0IF)
        {if (waitState>0) waitState--;
         if (RC2) PORTB=OnVector;
              else PORTB=OffVector;

         if (waitState==0)                    //    (*)
         if (((testVector & PORTC)!=0 && (test)) ||                    //  (**)
            ((testVector & PORTC)==0 && !(test)))
                  {state+=direction;                                          //     (***)
                   if (state>6) state=1;else if (state<1) state=6;
                   OnVector=TableOn[state];
                   OffVector=TableOff[state];
                   if (state & 0x01) test=0; else test=1;                //        (****)
                   if (direction==1) testVector=testTable1[state];else  //      (*****)
                              testVector=testTable_1[state];
                  waitState=3;       //    (******)
                  }
        T0IF=0;
        TXREG=state;}

}
```

External signals A>C, C>B and B>A are connected to PORTC pins 3, 2 and 0 respectively. Their values are determined by a logical AND test. Bits that are to be tested are determined by a two tables, one for each direction:

```
const unsigned testTable_1 [7] = {0, 2, 1, 8, 2, 1, 8};
const unsigned testTable1 [7] = {0, 1, 8, 2, 1, 8, 2};
```

Values 8, 2, 1 correspond to bits RC3, RC1, RC0 (8=00001000 – RC3, 2=00000010 – RC1, 1=00000001 – RC0). Values 0 from the table are never used. Table testTable1 refers to positive direction of rotation, while testTable_1 refers to negative direction. If we take a look at the Table 6-1 which summarizes signals that should be tested for every state, we can notice that it corresponds to a definition of these two tables. During the commutation adequate value from these tables is placed in variable testVector - code line (*****).

Variable <test> contains anticipated value of external signal, that is, when external signal which is monitored becomes equal to test value, commutation should be executed. Code line (****) calculates the value of test. If state is even test is 0, if state is odd test is 1. This can also be explained by Table 6-1.

Condition check is done by a code line (**). This is the most important code line of this part of program. One should note that both logical and bitwise AND operations are

used here. Lines that follow are a commutation execution. Line (***) and following are the same as for the acceleration mode (previous section). Lines (****) and (*****) calculate test and testVector values respectively.

Variable waitState is introduced in order to prevent untimely commutation. When a commutation is executed, it is necessary to wait until a current from the phase that is detached decays through diode, as external signals may have incorrect values during this decay. This effect is notable only at low speeds, since BEMF is small and PWM impulse is narrow. Also, problem exists only if decay is realized through diodes on inverters low side. If PWM impulses are narrow, we can suppose that the situation is like the one in the following image.

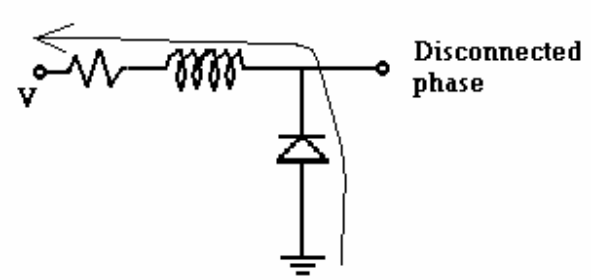


Figure 6-9 Current decay from disconnected phase

V is voltage in the wye. It is near to zero volts, as BEM forces are low and voltage is zero on both connected phases (PWM pause). For those reasons, voltage on inductivity will be low, and current will decay vary slowly. If we analyze decay throughout states, we can notice that this type of decay will occur in following state transitions: 2->3, 4->5, 6->1 for positive direction, and 3->2, 5->4, 1->6 for negative direction of rotation. This will cause states 1, 3 and 5 to be skipped at positive direction, and states 2, 4 and 6 at negative direction. In chapter 3 when filter was presented it was supposed that decay is instantaneous. This only refers to low speeds and PWM periods (there is a correlation between these two entities). Variable waitState will solve this problem.

Value of waitState variable determines how many idle cycles after commutation there should be. Evidently this will cause a limit in maximum speed that we can obtain, as it will limit the rate of state shifting. In our case this maximum speed will be higher than nominal, so it is not really a limitation. On every commutation, i.e. state change, waitState is set to 3 (******). On every next interrupt this value is decreased by 1. Only when this value reaches 0 (*) our program will start to read external signals and decide whether or not a commutation should be executed.

I will mention here that when analyzing a filter function in chapter 3, decay is supposed to be instantaneous. From the point of view of filter analysis this approximation is fine, considering that current decay time is only a fraction of one state duration time.

At the beginning of this routine we can see two lines that refresh PWM state. These lines are here in order to prevent harming of PWM quality, since procedure that follows can take to much time to execute. Last line of code will write a current state number on PC screen, enabling us to monitor a program execution. Naturally it will not affect a program execution.

7. Conclusion

System performance

In order to test the quality of this drive, two brushless motors connected to the same shaft are used. Both motors are of Italian company moog. First is FAST K2, nominal speed 3000 rpm, with 2 pair of poles. Second is FAST T1, with 3 pairs of poles, nominal speed is 4500 rpm. Our drive can work with both motors, though significantly better with the first one, as BEMF to winding resistance ratio is much higher, for the same load (chapter 3). While one of these motors is connected to the drive, the other is connected to variable resistors. By decreasing the resistance we are increasing the load and vice versa. Loading motor can be connected to one resistor via 3 phase Graz junction. This is much simpler than using three variable resistors.

When working with a bigger motor (FAST K2), maximum load that it can support at speeds lower than 2000 rpm is higher than the maximum that we can apply (short circuit). At this speed BEMF effective value of the other motor is around 38V. When we apply maximum load at this speed, speed drops to 1660 rpm. One phase current through short circuit of other motor is 3,8A. Power conversion is:

$$P_{conv} = 3 * 3\Omega * (3.8A)^2 = 130\text{W}. \qquad (7.1)$$

Three ohms is resistance of one phase. 130W corresponds to loading torque M=0.77Nm

There is a limitation in PWM duty ratio change dynamic. At low speeds PWM duty ratio has to be changed gradually, otherwise motor will block. This occurs because sudden rise of PWM impulse causes noise in our system that prevents our position detection circuit to work properly. As speed gets higher BEM forces rise and this noise becomes insignificant. Practical results show that the following sequence of duty ratio command is the most rapid that does not block the rotor: 5, 12, 20, 50,…(of 255). To those who work with this system this may seem a very serious restriction because the only way to control PWM duty ratio is by a serial link, and they have to type every single value from the array (5,6...). But if we have the software that will smartly increase/decrease duty ratio, this limitation would be practically insignificant. In addition, this testing is done on very light shaft with practically no inertia. If we had some weight added to the shaft a rotation would be more stabile and PWM ratio change dynamic would be more liberated.

Possible system upgrades

Speed control is a logical upgrade to this system. In order to implement speed control we have to measure speed. Speed measurement will be implemented in software, as any other type of measurement would be impractical – it would demand mounting of sensor on the shaft, and all this work is about avoiding that. Speed would be measured by measuring time between two consecutive state shifts – for lower speeds, or by counting state shifts in a determined amount of time – for higher speeds. If a precision of speed measurement is unsatisfying, a software observer can be implemented. PI type of speed

regulator will be applied. Output of this regulator is torque that should be applied to the shaft. In order to obtain high quality torque control, current has to be controlled.

Current control can be implemented by using one PI regulator, since there is only one current that we are controlling here. Special care has to be taken a propos state transition, since current peaks in these time intervals are inevitable. Current measurement can be problematic, as discussed in chapter 4 (IRADK). Hardware peak detector can be added in order to obtain current value that is valid during the entire PWM period. Current measured this way would have a PWM ripple. This problem could be solved by synchronizing PWM with current measurement. Synchronization usually requires both PWM and current measurement to have the same timer reference. Hence PWM would have to be on interrupt, this implies lower quality of PWM. Some hybrid solution would probably be the best.

Dynamical breaking (recuperation) can be implemented by a simple software intervention. States should be shifted in the manner that stator flux follows rotor flux. Practically two tables similar to testTable_1 and testTable1 (previous chapter) should be added. Two tables for PWM should be added also. While breaking dynamically DC link voltage has to be measured, since voltage of the link will rise. When DC link voltage gets too high, breaking has to be halted otherwise link capacitors can be damaged. Dynamical breaking probably would not have any practical value – in fact it would only serve us if there is a high inertia on the shaft, but we must bear in mind that its implementation demands only some software interventions.

Serial communication can be improved. Graphical user interface can be used in order to communicate more comfort with IRADK microcontroller. In addition we can assign an address to our microcontroller, so it can serve as a part of a complex system which is controlled using one central PC. In that case software has to be changed, both on PC and microcontroller side.

Manual control can be implemented if we want our system to perform simple tasks. Variable resistor can be placed on IRADK. Voltage from this resistor can be our speed command. On button we can implement direction control and/or toggle computer/manual control. This could be useful when validating system functioning.

Possible applications

This system, without upgrades has a transfer function of DC motor with fixed excitation – permanent magnet. It has no mechanical commutator, and it is a great advantage because there are no parts that could wear out, there is no speed limit and it is more ecological – since mechanical commutator usually contains lead that is very hard to dispose. Brushless DC motors also have better power to volume ratio. It is possible that in near future brushless DC motors will completely substitute regular DC motors.

A propos our system, it can be used whenever a continual speed change is required. We can use scalar controlled asynchronous motor as a cheap solution, but if we need quicker response, this system is superior. Disadvantage is its use in systems that require frequent direction change, since every direction change implies mode change i.e. time. I suppose here that we have a simple speed control implemented – without current sensing.

With the upgrades from previous section our system can be considered as a high quality drive. In this case it is competitive to a drive with regular synchronous motor.

Brushless DC can not reach the speed of synchronous motor because the gradient of current slope is higher at the same speed, and it has a problem of current peaks through commutation, but price of this drive will always be significantly lower. We also must bear in mind that motor price will be also lower, as sinusoidal distributed winding motors that are required for a regular drives with synchronous electromotor and they are more expensive than the ones with linear distribution (i.e. trapezoidal BEMF)

Appendixes

Appendix A Source code

```
        #include <pic1687x.h>

unsigned OnVector=0xce;
unsigned OffVector=0xee;

const unsigned TableOn [7] = {0xce, 0xce, 0xae, 0xba, 0x7a, 0x76, 0xd6};
const unsigned TableOff [7] = {0xee, 0xee, 0xee, 0xfa, 0xfa, 0xf6, 0xf6};
const unsigned testTable_1 [7] = {0, 2, 1, 8, 2, 1, 8};
const unsigned testTable1 [7] = {0, 1, 8, 2, 1, 8, 2};

interrupt void isr() {
  static unsigned state=1;
  static unsigned dutyR=0;
  static unsigned int tStep=637;
  static unsigned int t1Control=0;
  static signed direction=1;
  static unsigned inc=0;
  static unsigned test=0;
  static unsigned testVector=0;
  static unsigned waitState=3;
  static unsigned sending=0;
  static unsigned temp;

  if (INTF) {
     if (RC4) {temp=TRISC;
               TRISC=TRISC & 0xdf;
               RC5=1;
               TRISC=temp;}
     else if (inc) inc=0;else inc=1;
     INTF=0;
     }

  if (RCIF) {
    dutyR=RCREG;
    TXREG=dutyR;
    CCPR1L=dutyR;
     }

  if (TMR1IF)
          {state+=direction;
           if (state==0) state=6;else if (state>6) state=1;
           OnVector=TableOn[state];
           OffVector=TableOff[state];
           if (!inc) {t1Control+=tStep;
```

```
            tStep-=5;}
        else {t1Control-=tStep;
             tStep+=5;}

        if (t1Control<637) {inc=0;
                        if (direction==1) direction=-1;else direction=1;
                        tStep=637;
                        TXREG=100;}

        if (t1Control>55000)    {OPTION=0X11;
                           T0IE=1;
                           if (state && 0x01) test=0; else test=1;
                           if (direction) testVector=testTable1[state];
                           else testVector=testTable_1[state];
                           TMR1ON=0;
                           TMR1IE=0;}

        if (tStep<10) tStep=10;
        TMR1H=t1Control>>8;
        TMR1L=t1Control;
        TMR1IF=0;
        sending=PORTC & 0x0B;
        TXREG=sending;
        };

if (T0IF)
        {
        if (waitState>0) waitState--;
        if (RC2) PORTB=OnVector;
              else PORTB=OffVector;

        if (waitState==0)
        if (((testVector & PORTC)!=0 && (test)) ||
           ((testVector & PORTC)==0 && !(test)))
                    {state+=direction;
                     if (state>6) state=1;else if (state<1) state=6;
                     OnVector=TableOn[state];
                     OffVector=TableOff[state];
                     if (state & 0x01) test=0; else test=1;
                     if (direction==1) testVector=testTable1[state];else
                                       testVector=testTable_1[state];
                     waitState=3;
                    }

        T0IF=0;
        TXREG=state;}
```

```
}

main() {
  TRISB=0X03;    //  PORTB setup
  PORTB=0XFF;  //
  TRISB=0X01;    //
  PORTB=0XFC; //

  TRISC=0XBB;   //  C register is used for serial communication

  T1CON=0X31;  //  TMR1 configuring
  TMR1IE=1;

  INTE=1;            //  Interrupt enable on button press

  TXSTA=0X23;  //  Serial link configuration
  RCSTA=0X90;
  SPBRG=129;
  RCIE=1;
  PEIE=1;

  PR2=0XFF;
  CCPR1L=5;
  T2CON=0X05;
  CCP1CON=0X0F;

  GIE=1;             //    Global interrupt enable

  CREN=0;          //     OERR reset
  CREN=1;

  while (1) if (RC2) PORTB=OnVector;
                  else PORTB=OffVector;


};
```

Appendixes

Appendix B Project making and compilation in Hi-tech C for PIC

Every program (i.e. file) written in Hi-tech C for PIC has to adjoined to some project in order to function. A simple one file project creation and compilation. will be described here. On Mp-lab menu project we chose the new project. We chose some name for project – testing, for example. Then we go to edit project option and set a tool HI-TECH, we also set desired microcontroller type.
Then we should click at testing.hex, when it gets blue (after a click) we should click edit. Following options should be set:

Language tool: PIC C linker
Info messages: quite (desirable)
Hex format: Intel
Compile for Mp-lab: enabled (checked)
All other options should be unchecked

Then we should return to previous menu and click add node. Testing.c file should be added (name should match to hex file name) with following settings:

Language tool: PIC C compiler
Generate debug info (desirable)
Floating point: 24 bit
Error file (desirable)
Assembler list – checked
Retain local symbol – checked

Next step - click at Build project (project menu). Errors that occur will be reported in dos window. If there is no errors object file will be built, and linker will automatically produce hex file from it. It may occur that linker does not start automatically as compiler window (One that is finished) needs to be closed manually.
Hex file can be programmed to microcontroller by using programmer. There is enable programmer option – Pic Start Plus menu. I used ICD instead of programmer. It can do all that programmer can do and more. In order to program microcontroller with ICD, development mode has to be changed to ICD (options menu). Upon mode changing ICD control box will appear. On this box options menu microcontroller and crystal types (xt in our case) should be set. All other options should be disabled. Program button will program our microcontroller.

References

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