

# **PROGRAMMABLE LOGIC CONTROLLER BASED VARIABLE SPEED DRIVES FOR EDUCATIONAL TRAINER**

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A project report submitted in partial  
fulfillment of the requirement for the award of the  
Degree of Master of Electrical Engineering

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**JANUARY, 2013**

## ABSTRACT

The PLC based motor control system is the key area of concerned to relate PLC to the real industrial environment. However, there is no PLC based industrial motor control trainer available in the Automation lab of Politeknik Kota Kinabalu for the practical purposes. This has initiated the need to develop a research and product on the title of “**Programmable Logic Controller Based Variable Speed Drives For Educational Trainer**”. This research focused on *VSD* controlled by PLC conventional programming and Fuzzy Logic based PLC programming. A prototype “Two Conveyors Packaging System” has been constructed. This application is to synchronize two conveyors so that parts and packaging boxes are positioned correctly, regardless of the part and package box positions and the speed of conveyor. Several PLC programs were developed individually for sectionals of the prototype application; the input devices photoelectric part sensors (P004A), motor encoders E1 and E2 (P004B) and output device is *VSD* for box conveyor *M2* (P004E). All these programs can work independently; subsequently to be combined to control the whole prototype application with additional PLC program on conventional basis, and fuzzy logic basis (P004C and P004D). These step by step programming methods contributed to the 10 experiments procedures to achieve the objective to construct the educational trainer procedures. As a conclusion, this research has achieved the objectives to construct the educational trainer procedures to implement PLC conventional and fuzzy logic based programming to control a motor driven by *VSD*, based on the concept of Prototype Two Conveyor Packaging System.

## ABSTRAK

Sistem kawalan motor berasaskan PLC adalah bidang utama menghubungkan PLC kepada persekitaran industri sebenar. Namun demikian, Makmal Automasi & Kawalan, Politeknik Kota Kinabalu tidak mempunyai “Trainer” Kawalan Motor Industri berasaskan PLC untuk tujuan kerja praktikal. Ini telah mencetuskan keperluan untuk membangunkan satu kajian dan produk mengenai tajuk “**Pemacu Kelajuan Bolehubah Pengawal Logik Bolehaturcara (PLC) untuk Alat Bantu Pendidikan**”. Kajian ini memfokuskan kepada Pemacu Kelajuan Bolehubah (VSD) yang dikawal oleh pengaturcaraan konvensional PLC dan pengaturcaraan PLC berasaskan “*Fuzzy Logic*”. Satu prototype “Sistem Pembungkusan Dua Penghantar” telah dibina. Aplikasi ini berfungsi menyegerak dua penghantar supaya bahan dapat dimasukkan tepat ke dalam kotak pembungkusan, tidak dipengaruhi kedudukan bahan dan kotak serta kelajuan penghantar. Beberapa aturcara PLC telah dibangunkan secara berasingan untuk bahagian-bahagian tertentu aplikasi prototype, peranti masukan pengesan bahan *photoelectric PE1* hingga *PE4* (P004A), pengkod kelajuan motor *E1* dan *E2* (P004B) dan peranti keluaran ialah VSD bagi motor penghantar *M2* (P004E). Kesemua aturcara dapat berkendali secara individu, dan kemudian digabungkan untuk mengawal keseluruhan aplikasi prototype dengan aturcara tambahan secara konvensional dan PLC berasaskan “*fuzzy logic*” (P004C & P004D). Pendekatan pengaturcaraan langkah demi langkah menyumbang kepada 10 prosedur praktikal untuk mencapai objektif menghasilkan prosedur “Trainer” pendidikan. Kesimpulannya, kajian ini telah mencapai objektif untuk membina prosedur “*trainer*” pendidikan untuk melaksanakan pengaturcaraan PLC secara konvensional dan berasaskan “*fuzzy logic*” untuk mengawal satu motor yang dikawal oleh VSD, berdasarkan konsep “Sistem Pembungkusan Dua Penghantar”.

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**LIST OF SYMBOLS AND ABBREVIATIONS**

<i>VSD</i>	-	Variable Speed Drive
<i>A</i>	-	Part Conveyor A (fixed speed)
<i>B</i>	-	Box Conveyor B (Variable speed)
<i>E1</i>	-	Encoder 1 (attached to Conveyor A)
<i>E2</i>	-	Encoder 2 (attached to Conveyor B)
<i>PR10</i>	-	Cytron Microcontroller board
<i>MD30B</i>	-	DC brushed Motor Driver
<i>M1</i>	-	Motor 1 that drives Conveyor A
<i>M2</i>	-	Motor 2 that drives Conveyor B.
<i>X</i>	-	Value at position that provides the part/box offset data
$\Delta X$	-	the rate of change of the offset
$X_n$	-	the current offset reading
$(X_{(n-1)})$	-	the previous offset reading

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# CHAPTER 1

## INTRODUCTION

### 1.1 Project Background

Most of the applications involving rotating machinery require a speed controller to govern the speed of the machine. Currently, most speed control problems, either rotational or linear, use a dedicated digital or microprocessor based controller implementing some combination of PID control scheme. PID based controllers are typically very reliable, however, they often have several limitations that can drastically reduce their performance. Most often the PID speed controllers are implemented using a dedicated controller, which can increase the cost of the overall control system.

Proportional-Integral-Derivative (PID) controllers are still widely used in industrial systems, despite the significant developments of recent years in control theory and technology. This is because they perform effectively for a wide class of processes and operating conditions besides provide robust performance. Furthermore, they are easy and remarkable effectiveness and simplicity to implement using analogue or digital hardware and familiar to engineers.

The response of standard PID controllers can be severely limited in applications where the process environment is constantly changing. An example of such an environment is that of a steam turbine / generator, where temperatures, levels, and pressures are constantly changing the dynamics of the system. The PID controllers are often limited in highly nonlinear cases and do not respond with the required accuracy for obtaining acceptable control. The PID controllers require the system designer to develop an extensive mathematical model of the control process, which is not always easily achieved.

The need for a stand-alone device, one of the main downfalls of PID controllers, can easily be eliminated by implementing the control scheme from within a general purpose programmable logic controller (PLC). Utilizing a PLC **as** the primary cerebrum is a common practice in industrial plants. However, in order to accomplish PID control from within a PLC, one frequently needs a PID coprocessor that can be programmed in a language other than the standard PLC ladder logic. These coprocessors, which are often obtained from a company other than the PLC manufacturer, can add a significant amount to the overall PLC cost and therefore work against the goal of reducing the cost of the control system. In addition, the performance of the controller is still hindered by the limitations of PID control.

On the other hand, in highly nonlinear cases where the process is relatively slow (changes take place on the order of milliseconds rather than microseconds), control schemes based on *fuzzy* methods often allow much simpler controller design than their classical PID counterparts. Accurate and responsive control can be achieved using *fuzzy* control methods without the need for highly involved mathematical modeling and an additional PID coprocessor module. Thus the thought is to eliminate the need for these standalone controllers and implement the speed controllers from within the PLC using a control scheme other than PID. Due to the inherently slow nature of most process type applications where a general purpose PLC is being utilized, fuzzy control methods offer a desirable alternative to PID controllers. Fuzzy logic arose from a desire to incorporate logical reasoning and the intuitive decision making of an expert operator into an automated system. The aim is to make decisions based on a number of learned or predefined rules, rather than numerical calculations. Fuzzy logic incorporates rule-base structure in attempting to make decisions.



## 1.2 Problem Statements

Programmable Logic Controller (PLC) is a general purpose controller where by the functions of the controller are custom designed by the user via the programming. Thus the complexity of the controller functions is very flexible and very much dependent on the programmer experty. Learning of PLC-programming is more effective via well structured practical lab works. In the Automation & Control Lab (EAK) of Electrical Engineering Department, Politeknik Kota Kinabalu, there are some 15 sets of industrial standard PLC OMRON CPM2A-40R used to perform basic PLC programming with simple wiring of Input and output devices such as push buttons, light bulbs, relays etc. There are only several PLC trainers to demonstrate the basic application of PLC programming such as simulation conveyor system, traffic light prototype.

PLC is one of the most widely used controllers in the industrial. This is mainly due to the very flexible and easy-to-learn programming features. There are many motors used to build an industrial application. Thus PLC based motor control system is the key area of concerned to relate PLC to the real industrial environment. However, there is no PLC based industrial motor control trainer available in the lab for the practical purposes. This has initiated the need to develop a research and product by the name as follows:

### **PROGRAMMABLE LOGIC CONTROLLER BASED VARIABLE SPEED DRIVES FOR EDUCATIONAL TRAINER**

### 1.3 Project Objectives

The objectives of this project are as follows:

- (i) To construct the application prototype hardware of variable speed drive (*VSD*) to control a motor.
- (ii) To implement the *VSD* controller using Programmable Logic Controller (*PLC*) with the standard instruction.
- (iii) To implement the *VSD* controller with Fuzzy Logic method by *PLC* programming.
- (iv) To develop the educational trainer procedures for motor that to be fed by the *PLC* based *VSD* controller.

### 1.4 Project Scopes

The scopes of the project are as follows:

- (i) The prototype consists of two 12V DC motor driven conveyors with four part sensors and two encoders. The purpose of prototype is to implement variable speed drive (*VSD*) on one of the motors that can be implemented with *PLC* programming.
- (ii) The *PLC* programming is developed with the software of *CX-Programmer* for *PLC* *OMRON CPM2A-40R*. The *VSD* motor is to be controlled with *PLC* conventional programming utilizing the *I/O* devices available in the prototype.
- (iii) The *PLC* programs developed for the *I/O* devices during conventional programming will be added to the sub programs developed based on the fuzzy logic membership as the interface to all the *I/O* devices of prototype.
- (iv) The educational trainer procedures consists of the interface between *PLC* and the motor and *VSD* assembly; lab sheet which includes wiring diagram and practical procedures and the *PLC* program modules.

## CHAPTER 2

### LITERATURE REVIEW

#### 2.1 Introduction

This research, “PROGRAMMABLE LOGIC CONTROLLER BASED VARIABLE SPEED DRIVES FOR EDUCATIONAL TRAINER” consists several important areas of concerned such as PLC, programming, motors, drives, and power electronics. Figure 2.1 shows the block diagram of the area of concerned for this project. The four main objectives to be achieved have outlined the areas of literature review.

- (i) To identify the lab equipment to conduct practical works on Variable Speed Drive (*VSD*) which will includes power electronics and motor. The theory behind this hardware will be obtained from the literature review.
- (ii) PLC (OMRON CPM2A-40R) of the Automation and Control Lab will be used in this project. Thus all the instructions and sample programs need to be explored thoroughly so that an effective program can be developed to supply signals to the *VSD* to control the motor effectively.
- (iii) The *VSD* control will also be implemented via Fuzzy Logic method, thus the theory of fuzzy logic and development of fuzzy relationship algorithm especially on *VSD* Motor control will be focused and specifically in the area of the PLC approach on fuzzy logic method.
- (iv) For the requirement to develop the educational trainer, the important information will be on the interfacing between all the discrete sections of system for the input/output (I/O) requirement in term of amount, type of signals, signal conversion and conditioning.

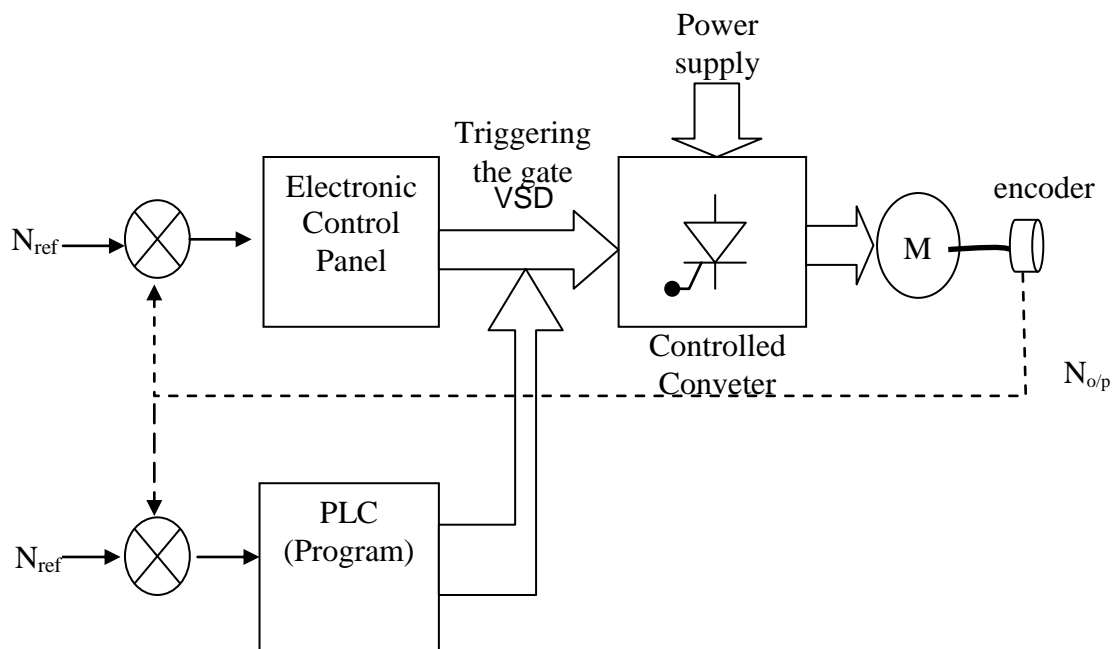


Figure 2.1: Block diagram of project's area of concerned

**Note:** If the control panel and Controlled Converter are unavailable in the lab, the Controlled Converter needs to be fabricated. But the converter will be tested operation by injecting triggering signal to the gate and observing the output waveform at the converter output only.

## 2.2 Experimental of motor drive in the lab setup

The first objective is to setup the experiment of variable speed drive (*VSD*) to control a motor. The experimental setup is based on the lab procedures [1] that come with the Universal motor in the Power Electronic and Machine Lab, complete with the Variable Speed Drive (*VSD*). Figure 2.2 shows the layout diagram for the test module of the “6-fold IGBT Current Converter” which can be connected in various applications for DC and AC motors. Figure 2.3 shows the layout for “Servo-brake Control Unit” used together with the IGBT Current Converter.

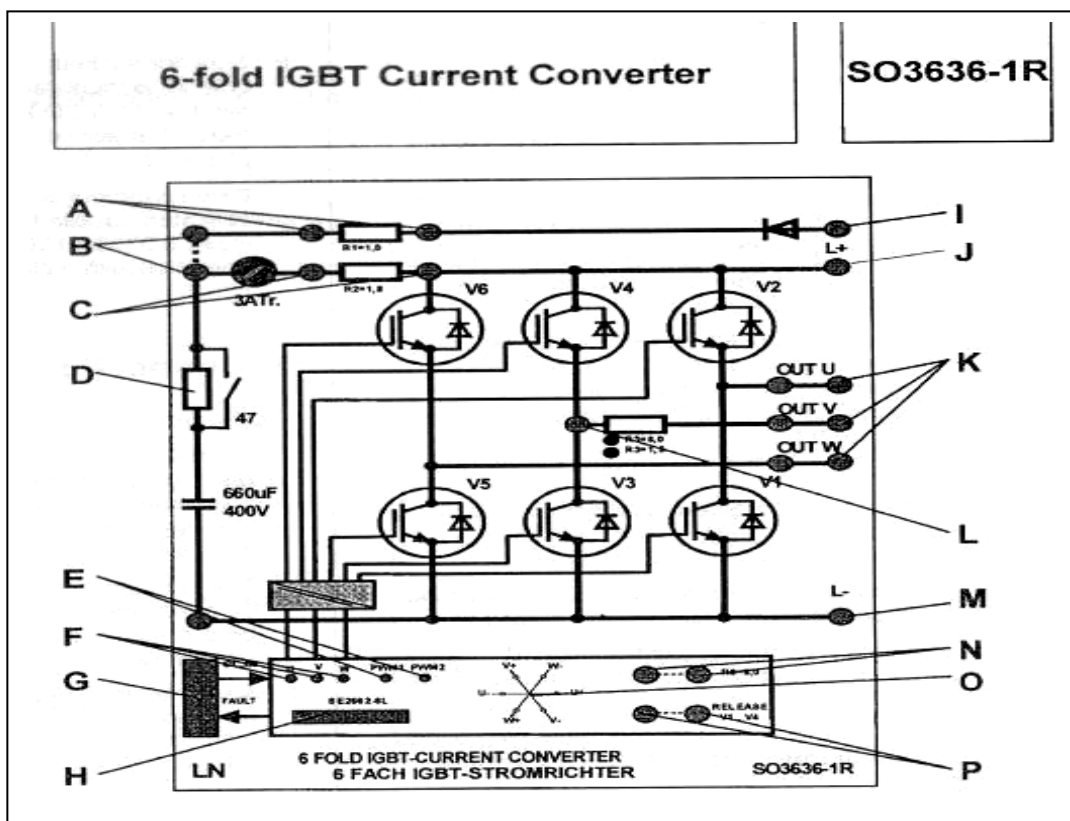


Figure 2.2: Layout for Module 6-fold IGBT Current Converter

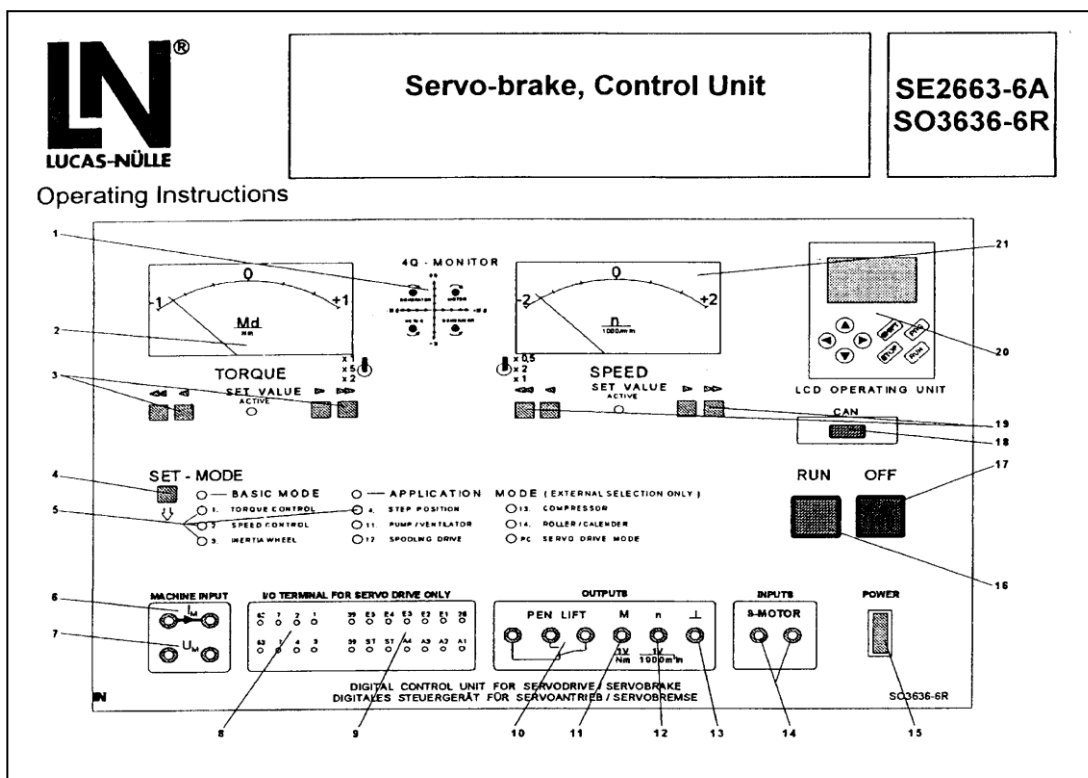


Figure 2.3: Layout of Servo-brake Control Unit

The servo-brake is a digital-controlled 4-quadrant precision drive with excellent control characteristics in all modes of operation. It is a robust unit, easy to operate and combines four functions in one unit, there are brake, 4-quadrant drive, load simulation and positioning drive.

The servo-brake is suitable for static and dynamic loading exercises. The complete equipment consists of the control unit and asynchronous machine with resolver. The connection cables are fixed to the control unit and connected to the machine with polarity-reversal protection. Four basic applications (1-4), all different, can be selected at the operating module.

- (i) TORQUE CONTROL (loading brake)
- (ii) SPEED CONTROL (drive)
- (iii) INERTIA WHEEL (inertia wheel)
- (iv) STEP POSITION (position control)

The 6-fold IGBT Current Converter Module board can be assembled in several experiments. Figure 2.4 illustrates DC Chopper controller for multi-quadrant operation, where four IGBT are connected to supply a load. The four gate signals are supplied by the controller module.

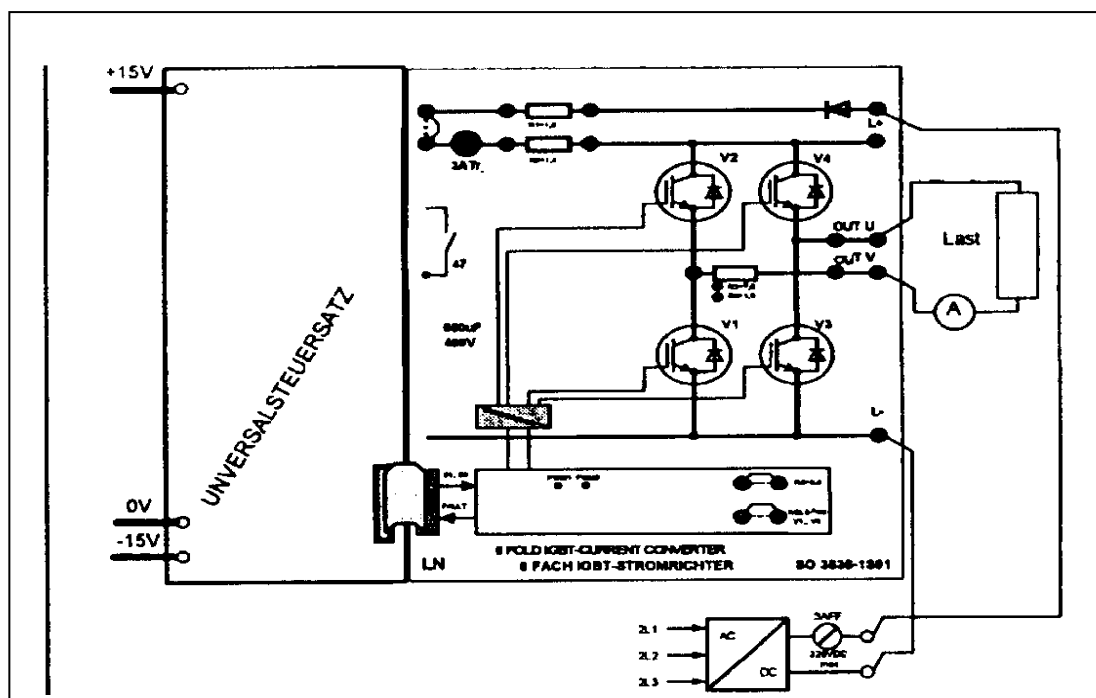


Figure 2.4: DC Chopper controller for multi-quadrant operation

Figure 2.5 illustrates the connection for Single quadrant operation with a DC shunt wound. Only one IGBT is connected to supply a motor and gate signal is supplied by the controller module.

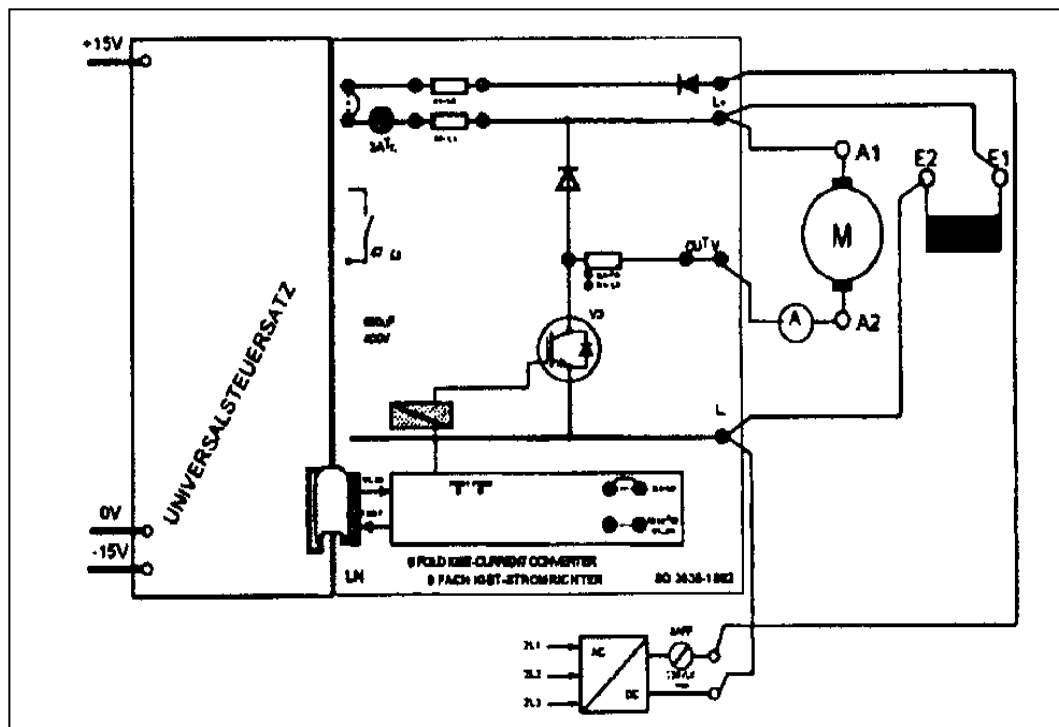


Figure 2.5: Single quadrant operation with a DC shunt wound

Figure 2.6 illustrates the connection for Four quadrant operation with a DC shunt wound machine. Four IGBT are connected to supply a motor armature. The four gate signals are supplied by the controller module. Figure 2.7 shows Three-phase operation with a synchronous machine. Six IGBT are connected in three pairs, each pair will supply each phase of AC motor. The six gate signals are supplied by the controller module

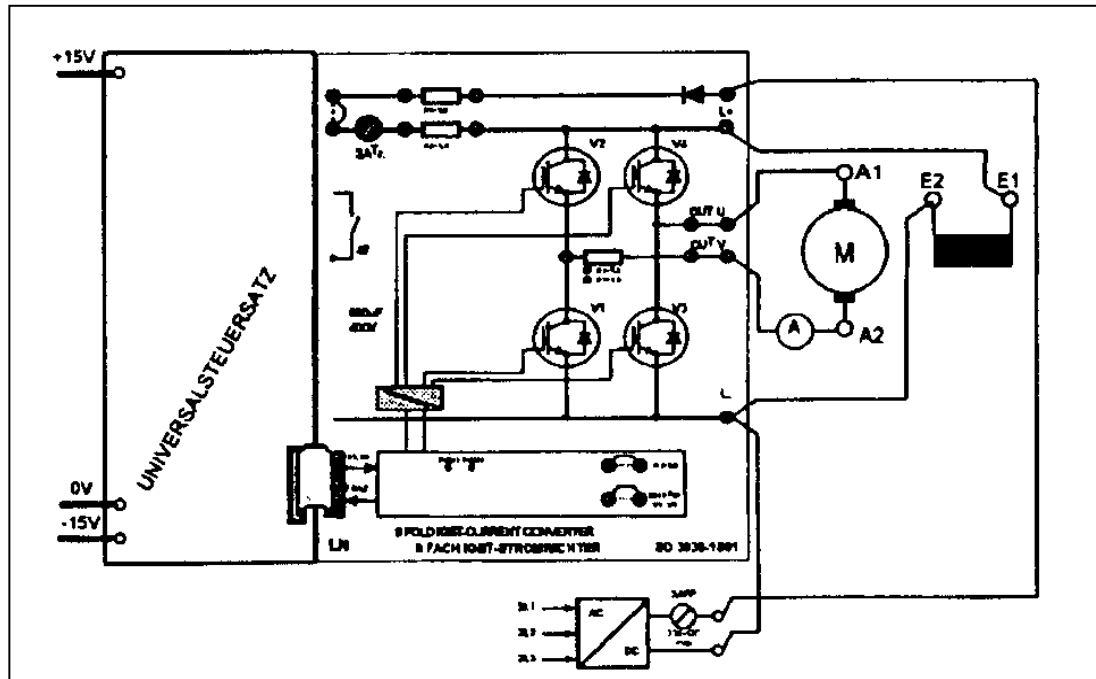


Figure 2.6: Four quadrant operation with a DC shunt wound machine

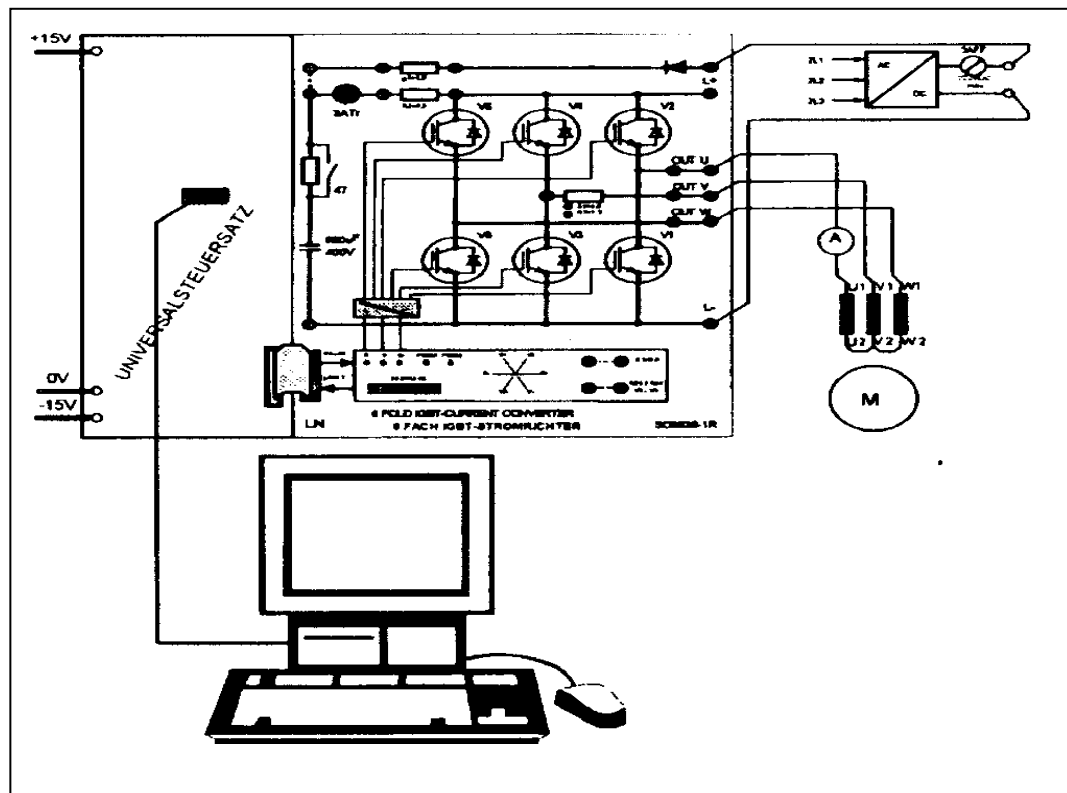


Figure 2.7: Three-phase operation with a synchronous machine



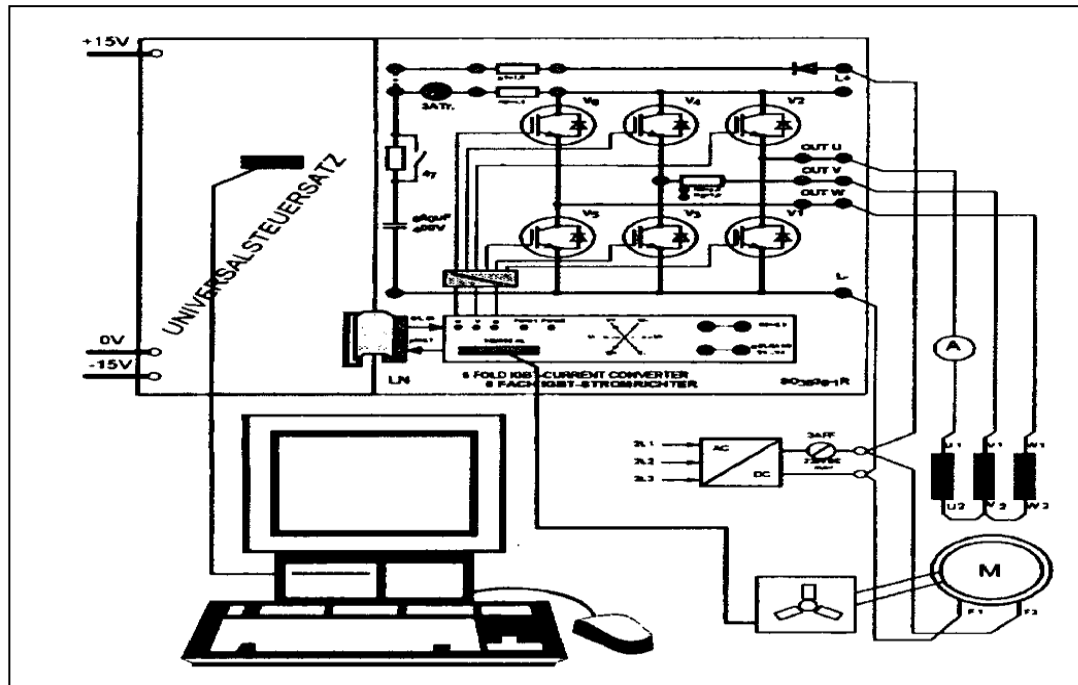


Figure 2.8: Electronic motor with load angle indicator

Figure 2.4 to Figure 2.8 show several experiments setup to be connected on the same “6-fold IGBT Current Converter Module board”, with selected components. The signals to the gate of the IGBT are supplied from the Servo Brake Control Unit as shown in Figure 2.3.

### 2.3 Motor drive

Most of the applications involving rotating machinery require a speed controller to govern the speed of the machine. This device is called Variable Speed Drive (VSD). A typical electric VSD system consists of three basic components, i.e. the electric motor, the power converter, and the control system as illustrated in Figure 2.9. The electric motor is connected directly or indirectly (through gears) to the load. The power converters are usually constructed by power semiconductor switches, basically categorized into two main groups uncontrolled and controlled. The controlled group power semiconductor which have triggering terminal “gate” such as thyristor, IGBT which receive triggering signal from the control system. Whereas the

uncontrolled group usually two terminals such as diode which has no triggering terminal.

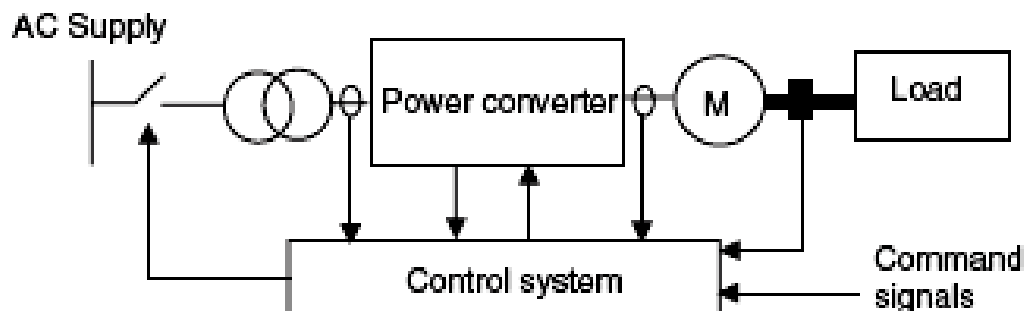


Figure 2.9: VSD Schematic diagram

Speed control of universal motors typically employs two scheme, i.e. Phase Angle Control and PWM Chopper Control [2]. Phase Angle Control is the simplest method to control the speed of a universal motor. Figure 2.10 illustrates schematic diagram of Phase Angle Control of a Universal Motor [2]. Speed control is achieved by the varying the firing angle for the TRIAC. Phase angle control is very cost effective solution but not very efficient and prone to EMI. The Phase Angle Control mechanism typically employed for speed control of the TRIAC. A phase shift of the TRIAC gate's pulses allows the effective voltage, seen by the motor to be varied and hence the speed of the motor. A Zero Crossing Detection circuit is used to establish a timing reference for delaying the firing of the gate pulses.

Figure 2.11 illustrates the schematic diagram of **PWM Chopper Control of a Universal Motor**. It is a more advanced solution for controlling the speed of a universal motor. In this method rectified AC line voltage is switched at a high frequency by a Power MOFSET or IGBT device to generate time varying voltage for the motor. Switching frequency is usually in the range of 10 to 20 KHz so as to eliminate acoustic noise. This method of universal motor control can achieve better current control, better EMI behavior and hence more efficient.

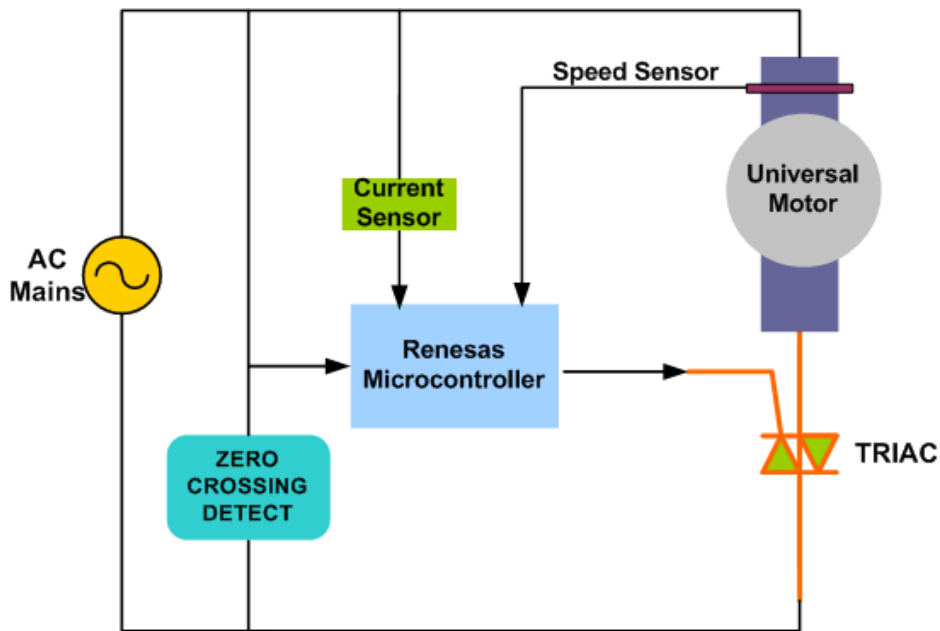


Figure 2.10: Phase Angle Control of a Universal Motor [2]

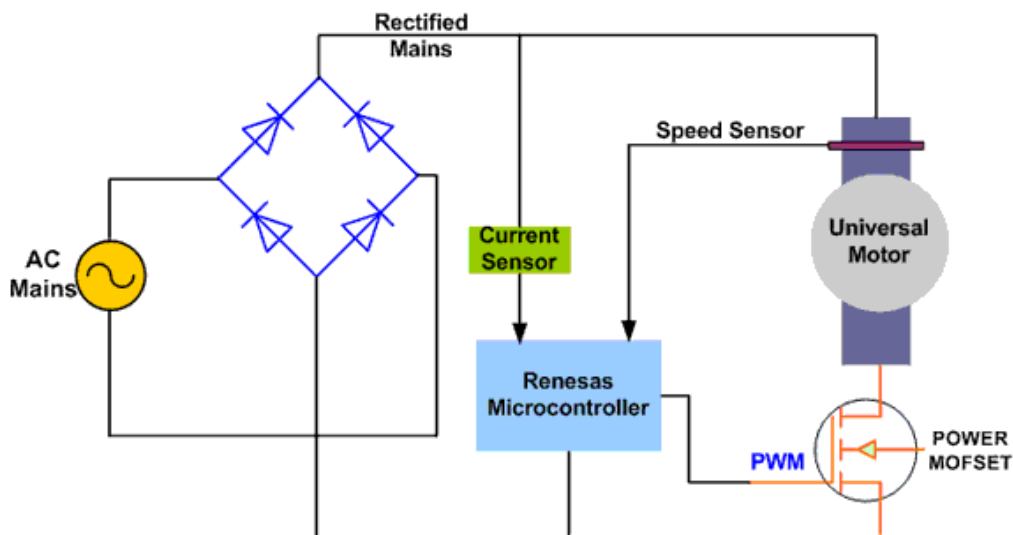


Figure 2.11: PWM Chopper Control of a Universal Motor [2]

Figure 2.12 illustrates the circuit diagram of the unity power factor buck type PWM rectifier for separately-excited dc motor application [3]. The dc motor drives are upgraded by replacing primarily the magnetic amplifiers, Ward Leonard Systems, secondarily old versions of six-pulse line-commutated bridge converters with unity pf buck-type PWM rectifiers.

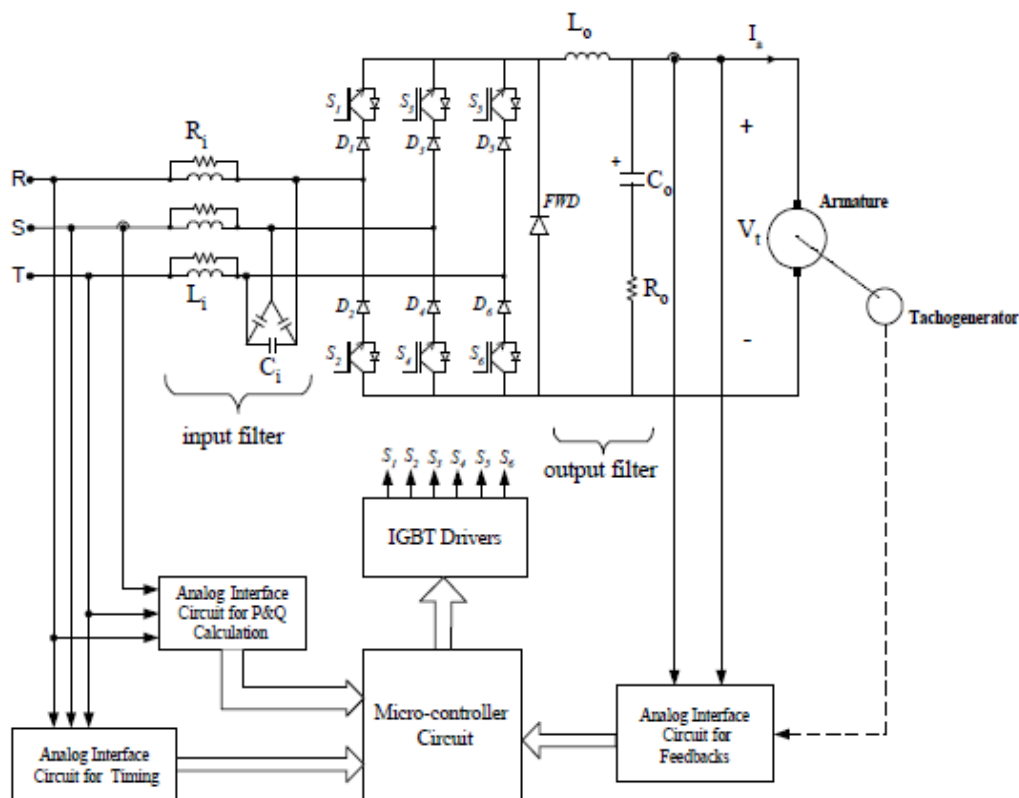


Figure 2.12: The circuit diagram of the unity power factor buck type PWM rectifier for separately-excited dc motor application [3]

The unity pf buck-type PWM rectifier supplies power to the armature circuit of a separately excited dc motor. Each power semiconductor switch consists of an IGBT connected in series with an ultrafast recovery diode, resulting in reverse voltage blocking capability and unidirectional current flow. A low-pass, damped LC filter is connected to the input side of the converter to filter out the switching frequency harmonic components in the line currents. In order to avoid accelerated ageing in motor insulation due to steep voltage wavefronts, and mechanical failure due to circulating bearing currents, the switching frequency harmonics are filtered out with a damped output filter.

The microcontroller block in Figure 2.12 will generate signals to supply the six gates of IGBT Drivers  $S_1$  to  $S_6$  to drive the motor. The microcontroller will receive the feedback signal from the motor speed encoder and also the armature current. Beside that the microcontroller inputs also taken from the P&Q and timing of the incoming three phase supply.

The 2-Q reversible dc motor drives have been designed by the use of a unidirectional unity pf buck type PWM rectifier on the armature side, and a four-

quadrant (4-Q) dc-dc converter on the field side. The 4-Q dc-dc converter in Fig.2.13 allows both reversing the field current rapidly, and keeping it constant at the preset value against supply voltage fluctuations.

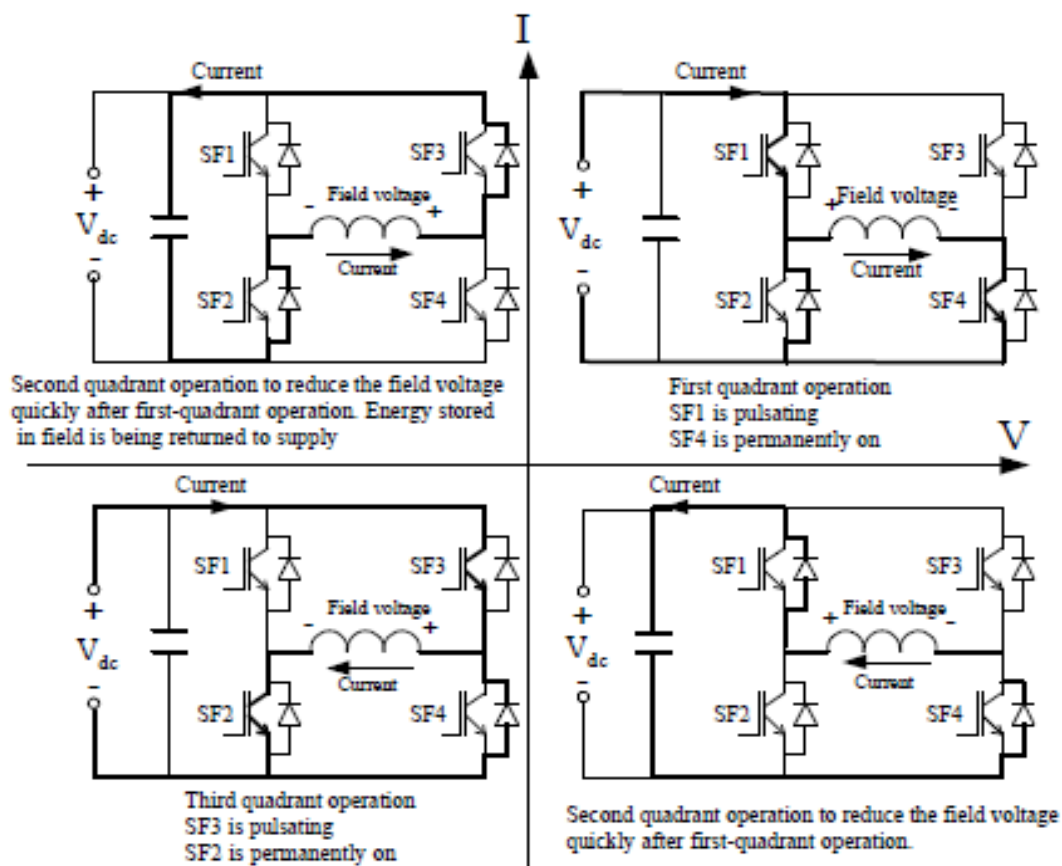


Figure 2.13: Operation modes of 4-Q field exciter [3]

Simplified circuit diagram of a three-phase, current source, buck-type rectifier is as shown in Fig.2.14. Although different PWM techniques have been used for the buck-type rectifier, their operating principles are nearly the same. In this research [3], operating principles will be explained using the six-step PWM technique.

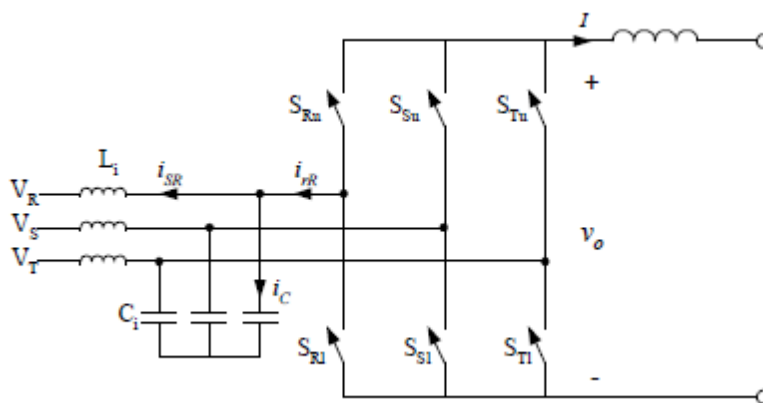


Figure 2.14: Current source buck type rectifier [3]

## 2.4 PID Controller

The data sheet for AVR221: Discrete *PID* controller of Atmel (2006) explain the theory of *PID* controller. This application note describes a simple implementation of a discrete Proportional-Integral-Derivative (*PID*) controller [4].

Figure 2.15 shows the block diagram of a system with a *PID* controller. The *PID* controller compares the measured process value  $y$  with a reference setpoint value,  $y_0$ . The difference or error,  $e$ , is then processed to calculate a new process input,  $u$ . This input will try to adjust the measured process value back to the desired setpoint. The alternative to a closed loop control scheme such as the *PID* controller is an open loop controller. Open loop control (no feedback) is in many cases not satisfactory, and is often impossible due to the system properties. By adding feedback from the system output, performance can be improved.

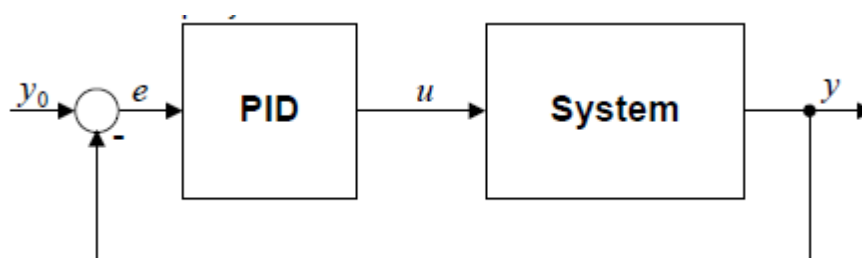


Figure 2.15: Closed Loop System with *PID* controller [4]

Figure 2.16 shows the *PID* controller schematics, where  $T_p$ ,  $T_i$ , and  $T_d$  denote the time constants of the proportional, integral, and derivative terms respectively.

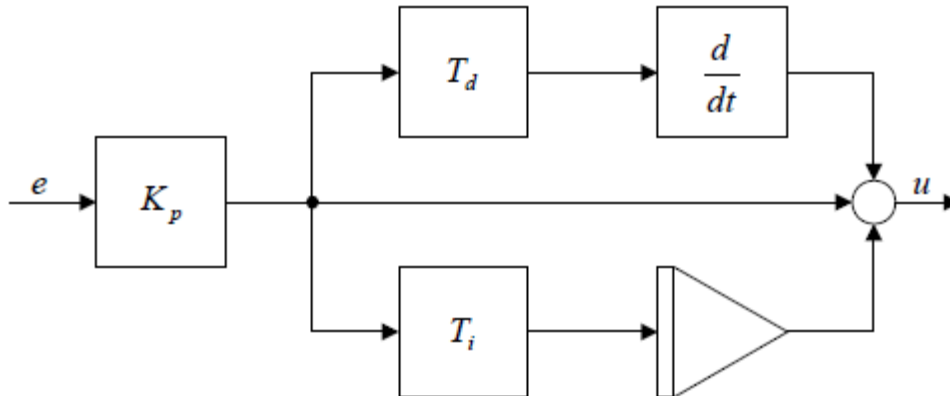


Figure 2.16: *PID* controller schematic [4]

### 2.4.1 Proportional term

The proportional term ( $P$ ) gives a system control input proportional with the error. Using only  $P$  control gives a stationary error in all cases except when the system control input is zero and the system process value equals the desired value. In Figure 2.17 the stationary error in the system process value appears after a change in the desired value (ref). Using a too large  $P$  term gives an unstable system.

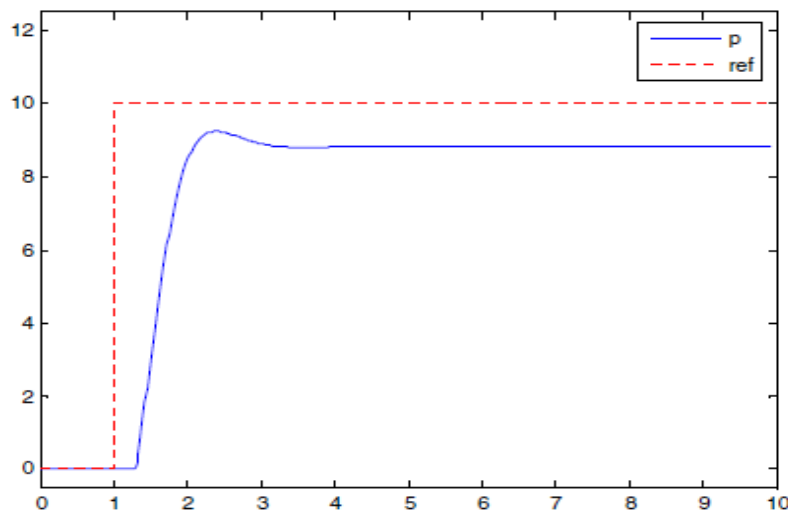


Figure 2.17: Step response  $P$  controller [4]

### 2.4.2 Integral term

The integral term ( $I$ ) gives an addition from the sum of the previous errors to the system control input. The summing of the error will continue until the system process value equals the desired value, and this result in no stationary error when the reference is stable. The most common use of the  $I$  term is normally together with the  $P$  term, called a  $PI$  controller, this will generate a very small overshoot but settled down to steady state level exactly similar to the reference level (shown in green line). Using only the  $I$  term gives slow response and often an oscillating system as shown in the blue line. Figure 2.18 shows the step responses to a  $I$  and  $PI$  controller. As seen the  $PI$  controller response have no stationary error and the  $I$  controller response is very slow.

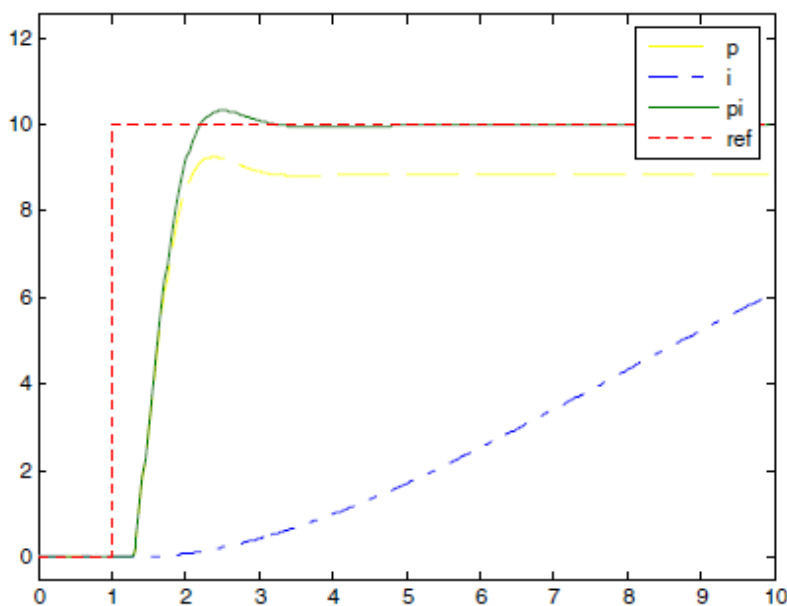


Figure 2.18: Step response  $I$  and  $PI$  controller

### 2.4.3 Derivative term

The derivative term ( $D$ ) gives an addition from the rate of change in the error to the system control input. A rapid change in the error will give an addition to the system control input. This improves the response to a sudden change in the system state or reference value. The  $D$  term is typically used with the  $P$  or  $PI$  as a  $PD$  or  $PID$



controller. A too large  $D$  term usually gives an unstable system. Figure 2.19 shows  $D$  and  $PD$  controller responses. The response of the  $PD$  controller gives a faster rising system process value than the  $P$  controller. Note that the  $D$  term essentially behaves as a highpass filter on the error signal and thus easily introduces instability in a system and make it more sensitive to noise.

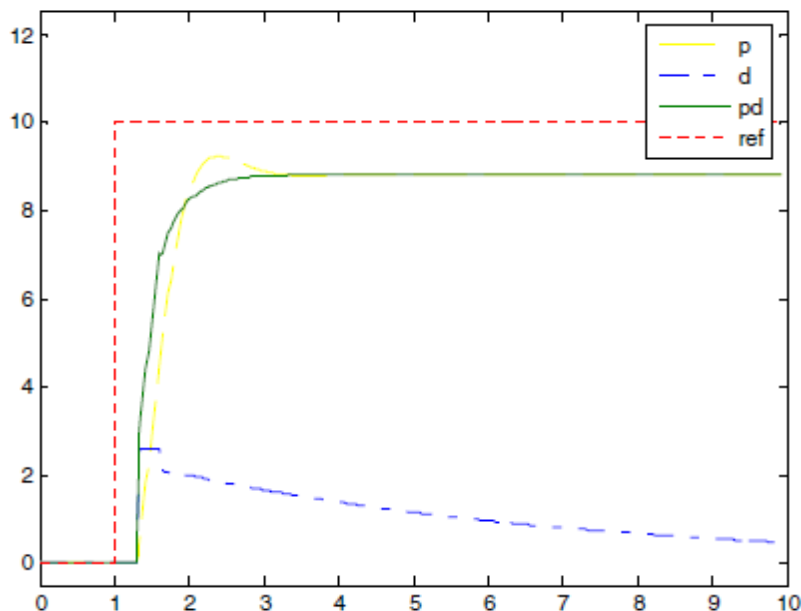


Figure 2.19: Step response  $D$  and  $PD$  controller

#### 2.4.4 PID term

Using all the terms together, as a  $PID$  controller usually gives the best performance. Figure 2.20 compares the  $P$ ,  $PI$ , and  $PID$  controllers.  $PI$  improves the  $P$  by removing the stationary error, and the  $PID$  improves the  $PI$  by faster response and no overshoot. The square wave (in red line) shows the reference signal to be injected. With the  $P$ -controller feature the corrected signal waveform (shown in yellow line) demonstrate reduce in the overshoot but at the same time also reduce the level of steady state level.  $PI$  parameter improve the steady state level but experience some value of overshoot.  $PID$  parameter produce the best response to improve the overshoot, the steady state level and also the faster response to achieve the steady state value.

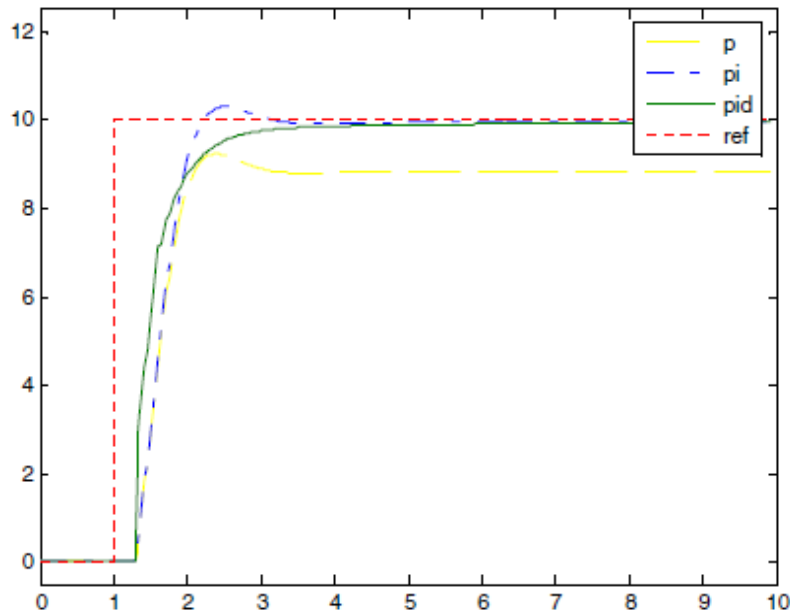


Figure 2.20: Step response  $P$ ,  $PI$  and  $PID$  controller [4]

### 2.4.5 Tuning the parameters

The best way to find the needed  $PID$  parameters is from a mathematical model of the system, parameters can then be calculated to get the desired response [4]. Often a detailed mathematical description of the system is unavailable, experimental tuning of the  $PID$  parameters has to be performed. Ziegler-Nichols method is a well-known online tuning strategy. The first step in this method is setting the  $I$  and  $D$  gains to zero, increasing the  $P$  gain until a sustained and stable oscillation (as close as possible) is obtained on the output. Then the critical gain  $K_c$  and the oscillation period  $P_c$  is recorded and the  $P$ ,  $I$  and  $D$  values adjusted accordingly using Table 2.1.

Table 2.1: Ziegler-Nichols parameters

Controller	$K_p$	$T_i$	$T_d$
P	$0.5 * K_c$		
PD	$0.65 * K_c$		$0.12 * P_c$
PI	$0.45 * K_c$	$0.85 * P_c$	
PID	$0.65 * K_c$	$0.5 * P_c$	$0.12 * P_c$

### 2.4.6 A research on PID controller

Ezwan, M. E. (2008) conducted a research on PID controller as shown in the Figure 2.21. This research involved developing the well-known Ziegler-Nichols tuning algorithms. The error signal,  $e$  represents the difference between the speed command and the speed feedback. The proportional control multiplies the speed error  $e$  by a constant  $K_p$ , the integral control multiplies the  $e$  by a constant  $K_i$ , to correct steady state error; the derivative control reduces the overshoot and the rise time

$$U(t) = K_p e(t) + K_p K_i \int_0^t e(t) dt + K_p K_d \frac{de(t)}{dt} \quad (2.1)$$

where,  $U(t)$  is a control signal,  $K_p$  is a proportional gain,  $K_i$  is a an integral gain,  $K_d$  is a derivative gain,  $e(t)$  is an error, the term  $\int_0^t e(t) dt$  is a summation of all past error over time and  $de(t)/dt$  is rate of change of error term.

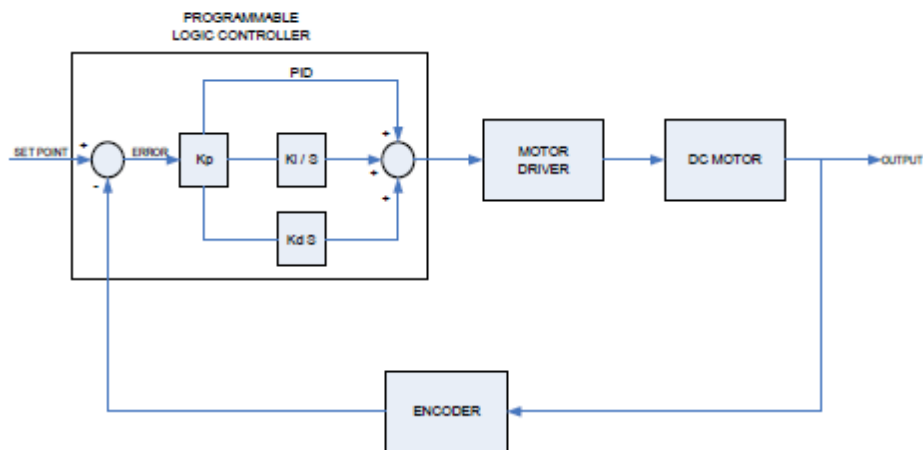


Figure 2.21: A block diagram of speed PID controller

For the basic control system, the controller compares the measured value to a set point or reference voltage to get the error value as expressed in equation above and then the error signal will take the appropriate corrective action. The parameter of PID controller,  $K_p$ ,  $K_i$ , and  $K_d$  can be manipulated to produce various response curves from a motor controller. For this project, we change voltage to speed. It is because we need to know an error of speed.

$$e(t) = r(t) - y(t) \quad (2.2)$$

where,  $r(t)$  is a set point (SP) or reference voltage and  $y(t)$  is a measured value (Process Variable)

Ziegler and Nichols proposed rules for determining values of the proportional gain  $K_p$ , integral time  $T_i$ , and the derivative time  $T_d$  based on transient response characteristics of a given plant. For the Ziegler-Nichols Frequency Response Method, the critical gain,  $K_{cr}$  and the critical period,  $P_{cr}$  have to be determined first by setting the  $T_i =$  and  $T_d = 0$ . Increase the value of  $K_p$  from 0 to a critical value,  $K_{cr}$  at which the output first exhibits sustained oscillation. Table 2.2 displayed the Ziegler-Nichols tuning rule. The step-by-step calculations based on the algorithm given in equation 2.1 & 2.2 are shown below. Table 2.3 shows the tuned PID controller values.

Table 2.2: Ziegler-Nichols tuning rule based on  $K_{cr}$  and  $P_{cr}$  [5]

Type of Controller	$K_p$	$T_i$	$T_d$
<b>P</b>	$0.5 K_{cr}$	$\infty$	$0$
<b>PI</b>	$0.45 K_{cr}$	$P_{cr}$	$0$
<b>PID</b>	$0.6 K_{cr}$	$0.5P_{cr}$	$0.125P_{cr}$

$$\begin{aligned}
 K_{cr} &= 16 \\
 P_{cr} &= 8.324 - 8.321 \\
 &= 0.003
 \end{aligned}$$

*Tuning the PID controller:*

$$G(s) = K_p (1 + 1/T_{is} + T_{ds})$$

**iii. P Mode**

$$\begin{aligned}
 K_p &= 0.5 K_{cr} \\
 &= 0.5 (16) \\
 &= 8
 \end{aligned}$$

**ii. PI Mode**

$$\begin{aligned}
 K_p &= 0.45 K_{cr} \\
 &= 0.45 (16) \\
 &= 7.2
 \end{aligned}$$

$$\begin{aligned}
 K_i &= 1 / T_i \\
 &= 1 / (P_{cr}/1.2) \\
 &= 1 / (0.003/1.2) \\
 &= 400
 \end{aligned}$$

**i. PID Mode**

$$\begin{aligned}
 K_p &= 0.6 K_{cr} \\
 &= 0.6 (16) \\
 &= 9.6 \\
 \\
 K_i &= 1 / T_i \\
 &= 1 / (0.5 P_{cr}) \\
 &= 1 / [0.5(0.003)] \\
 &= 666.67 \\
 \\
 K_d &= 0.125 P_{cr} \\
 &= 0.125 (0.003) \\
 &= 0.000375
 \end{aligned}$$

Table 2.3: Tuned PID controller value

Type of Controller	$K_p$	$K_i$	$K_d$
<b>P</b>	8	0	0
<b>PI</b>	7.2	400	0
<b>PID</b>	9.6	666.67	0.000375

The PID can be implemented by PLC program instruction. PLC OMRON CPM2A-40R implements PID function with the instruction PID(--). The operands of the instruction and the set values are discussed in detail in Appendix A1.

## 2.5 PLC Programming based of VSD

Brushed DC motors (BLDCM) have been used in industry due to their linear characteristics and the ease of adjusting their speed through a simple power electronic circuit. Tawadros et al. investigated the possibility of using a PLC (Programmable Logic Controllers) to control such motors rather than microcontrollers [6]. Maria G. I. (2004) [11] conducted a research of the induction motor system driven by inverter and controlled by PLC prove a higher accuracy in speed regulation as compared to a conventional V f control system. The efficiency of PLC control is increased at high speeds up to 95% of the synchronous speed. Thus, PLC proves themselves as a very versatile and effective tool in industrial control of electric drives..

Figure 2.22 shows the block diagram of BLDCM drive system. The driving circuit (Figure 2.23) is implemented to drive six power MOSFETs controlling the BLDCM. Only two MOSFETs are switched on at a time receiving the driving signal from the transistor outputs of the PLC. The circuit is built with six dual input NAND gates, where two CD4011BCN chip are used. The upper half utilizes three NAND gates, where one pin of each NAND gate is common to the PWM and the second pin receives 1 or 0 based on the rotor position.

The PLC takes an action to switch only two NAND gates at any moment driving the output transistors to be switched off which makes the signal to the NAND gate to be high (15V). The effect on the upper half is that the PWM signal will appear on the output on the NAND gate which is applied to the optocoupler. When the optocoupler is on the MOSFET is driven to the off state and vice versa. In the lower half, the MOSFET will be on at all times (no PWM) during the off period of the PLC transistor output. Once the rotor moves and the PLC receives the new position from the feed back sensors, the current off transistor output is activated (switched on) and new one is switched off to drive a different MOSFET (from the upper or lower half based on the BLDCM sequence of operation). All resistors are selected based on the maximum current consumption of each component.

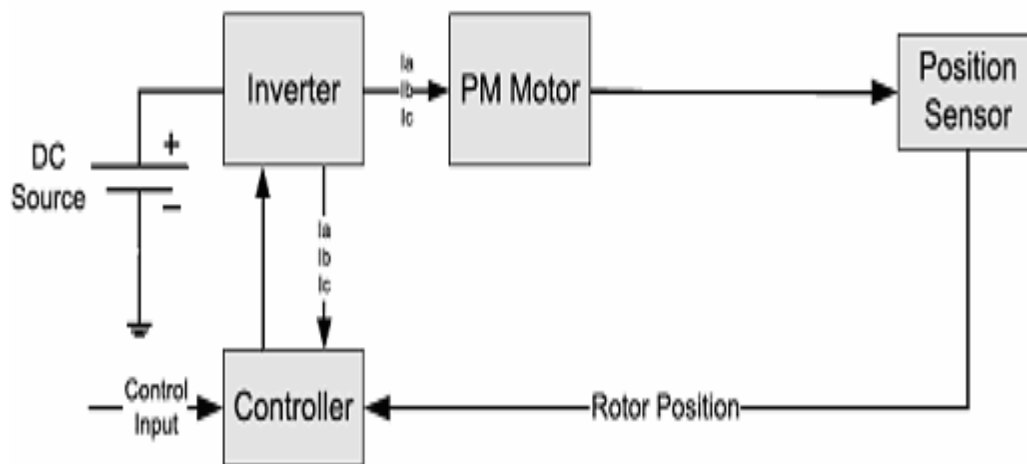


Figure 2.22: Block diagram of BLDCM drive system

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