A CONTROL STRATEGY FOR PWM INVERTER-INDUCTION MOTOR DRIVE

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UNIVERSITY OF SASKATCHEWAN

BY

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A CONTROL STRATEGY FOR PWM INVERTER-INDUCTION MOTOR DRIVE

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The rapid development of the microprocessor and the software associated with it has contributed significantly towards the modernisation of control systems. The developments in solid state technology have already made it possible for ac induction machines to be considered as alternatives to dc machines in adjustable speed applications. Considering the present trend in microprocessor technology, the replacement of solid state controllers by software based controllers is inevitable.

The work reported in this thesis involved the development of a microprocessor based control strategy for a pulse width modulated inverter induction motor drive. The switching sequence for the SCRs of an auxiliary impulse commutated McMurray inverter are described. The development of the control strategy is the highlight of the thesis.

The basic concepts of the control strategy are explained. The harmonics analysis of the simulated output voltage waveform and the advantages of the new control strategy over the existing methods are given.

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1.INTRODUCTION

1.1 GENERAL

Variable speed drives of electrical machines are used frequently in many industrial applications and for mass transportation systems such as traction motors for electric locomotives. The speed control can be achieved by both AC and DC machines. The speed of a DC machine is varied by controlling the armature voltage up to the base speed and beyond base speed the speed is controlled by varying field current. This is accomplished by using AC to DC thyristor converters for armature and field voltage control or by the Ward-Leonard system. The speed-torque characteristics for a DC machine are shown in Figure 1.1. These are nearly "ideal" characteristics for many applications and form the basic objectives for ac motor control schemes.

The method of speed control proposed in this thesis is to use a software controller to generate firing pulses for the SCRs in a pulse width modulated inverter which would, in turn, provide controlled frequency and voltage power supply for an induction motor.

The emphasis of the work reported in this thesis is on the development of the algorithm and appropriate software for the controller. The control algorithm developed and described in subsequent sections of this thesis was established and tested in two phases.

The computer program development was done on a VAX-11/780 with VMS operating system. The program was written using FORTRAN-77. The simulation program is discussed in detail in the third chapter.

The algorithm was tested on a LSI-11/23 microcomputer system. The main program to calculate the pulse widths was written in FORTRAN-77. The program to generate the clock signals was written using MACRO-11. The implementation details are given in the fourth chapter.

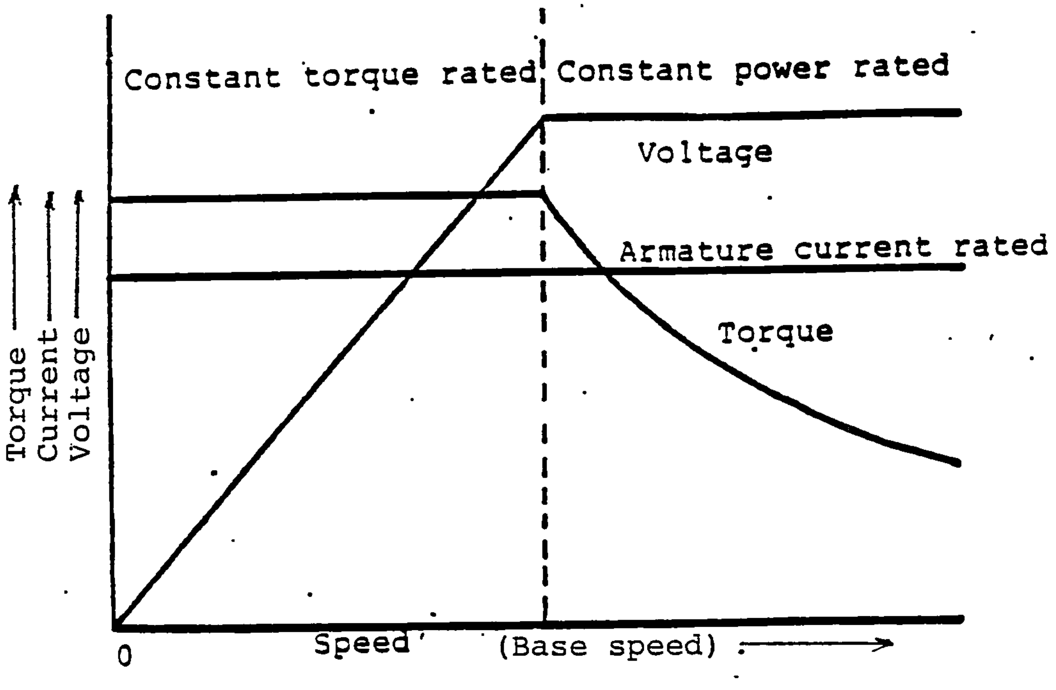

Figure 1.1: Speed-torque characteristic of DC shunt motor

The simulated switching sequence generated by the VAX-11 simulation was used to trigger the SCRs for the SPICE simulation. This was done on a VAX-11/780 with VMS operating system. This is explained in detail in the fifth chapter.

1.2 REVIEW OF PUBLISHED LITERATURE

1.2.1 General

Pulse width modulated inverter control of ac drives is the best alternative to variable speed dc drive. The research work in this field started in the early sixties. However most of the published literature deals with the inverter power circuit, harmonic analysis and improvement of the existing sine wave triangulation technique for pulse width modulation. The improved modulation schemes are intended to improve the harmonic content and the inverter output. Some of the published articles are reviewed briefly in the following paragraph.

In the sixties, the paper published by McMurray[1] introduced the concept of using an auxiliary impulse to turn off the conducting SCR. Most of the pulse width modulation control strategies are developed for the McMurray auxiliary impulse commutated inverter. The paper published by Casteel and Hoft[2]. deals with optimization of PWM output waveforms. The scheme suggested by the above uses an IBM 370 to do the necessary calculations and this is rather impractical. This scheme would still have all the drawbacks of the "sine wave triangulation method" as illustrated in a paper published by Zubek, Abbondanti and Norby[3] . In the recent publications, the trend is towards use of microcomputers and other digital circuits to improve the performance of the PWM strategies. Buja and Fiorini[4] introduced a concept of storing the switching patterns relative to a number of levels of the first harmonics of the inverter output voltage and of computing online the actual pattern by interpolating the stored values. This technique has two major drawbacks. First, the use of interpolation would need fast floating point processors and second, it would still require minimum pulse width clamp circuitry[3] , as it deals only with performance improvement of the sine wave triangulation method. Dwyer and Ooi[5] have published an article on similar principles to implement a PWM control strategy on a system using a Z-80 processor.

This thesis deals with a different concept called the "sine wave area equivalence method" to accomplish pulse width modulation control of the existing inverter power circuits. The proposed technique is fundamentally different from the existing schemes. It does not have the overhead of interpolation and the drawbacks of the sine wave triangulation method. The development of fast, accurate microprocessors makes the proposed scheme simple to implement.

1.2.2 Speed Control Of AC Induction Motor

The speed control of an AC machine requires more complex control logic compared to that of DC machines, but lower cost and less maintenance of ac machines has inspired more research on speed control of AC induction machines. There are various methods of controlling the speed of an AC induction motor as follows:

1. Variable voltage constant frequency control
2. Variable current variable frequency control
3. Slip power recovery control
4. Variable voltage variable frequency control

This thesis describes a new concept for a control system for variable voltage, variable frequency induction motor control scheme using pulse width modulation. The following section places this in context by giving a brief explanation of the four alternative control schemes referred to above.

1.2.3 Variable Voltage Constant Frequency Control

In the variable voltage constant frequency control method, the stator voltage is controlled with a constant line frequency. A typical phase controlled ac power supply using antiparallel SCRs is shown in Figure 1.2.

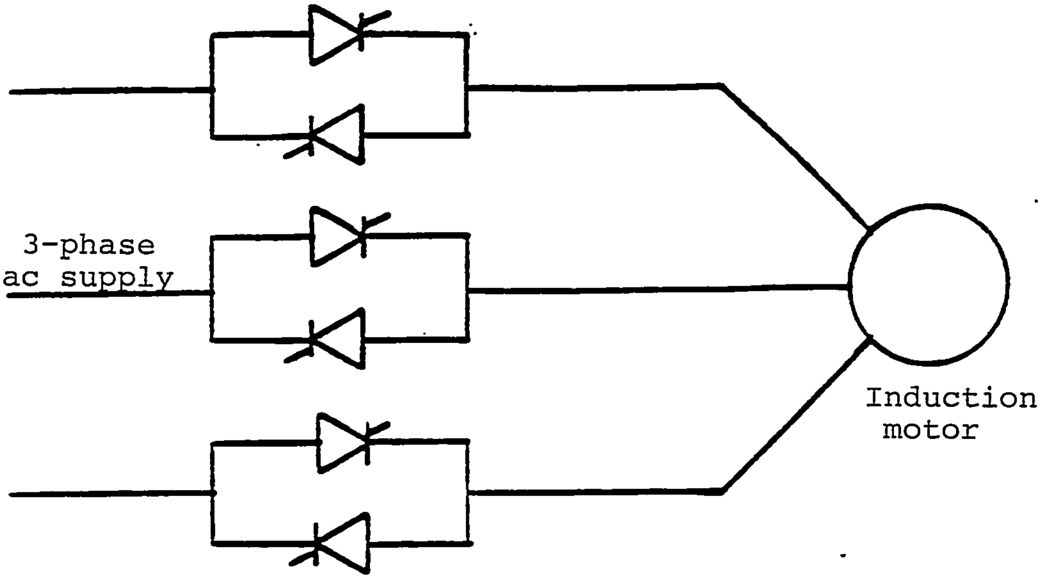

Figure 1.2: Schematic diagram of phase voltage controlled rectifier

Although it is not shown in systems illustrated in this section, each SCR requires an appropriate trigger pulse operating system and auxiliary circuit elements such as surge suppressors to function properly. The supply voltage to the motor can be controlled smoothly by controlling the triggering angles of the SCRs. This is a simple method of speed control, but the supply voltage carries large harmonics at integral frequencies. The supply-side power factor is poor due to the additional reactive power taken by the phase controlled converter. The speed control is relatively good for a limited range as indicated by the torque/speed curves shown in Figure 1.3.

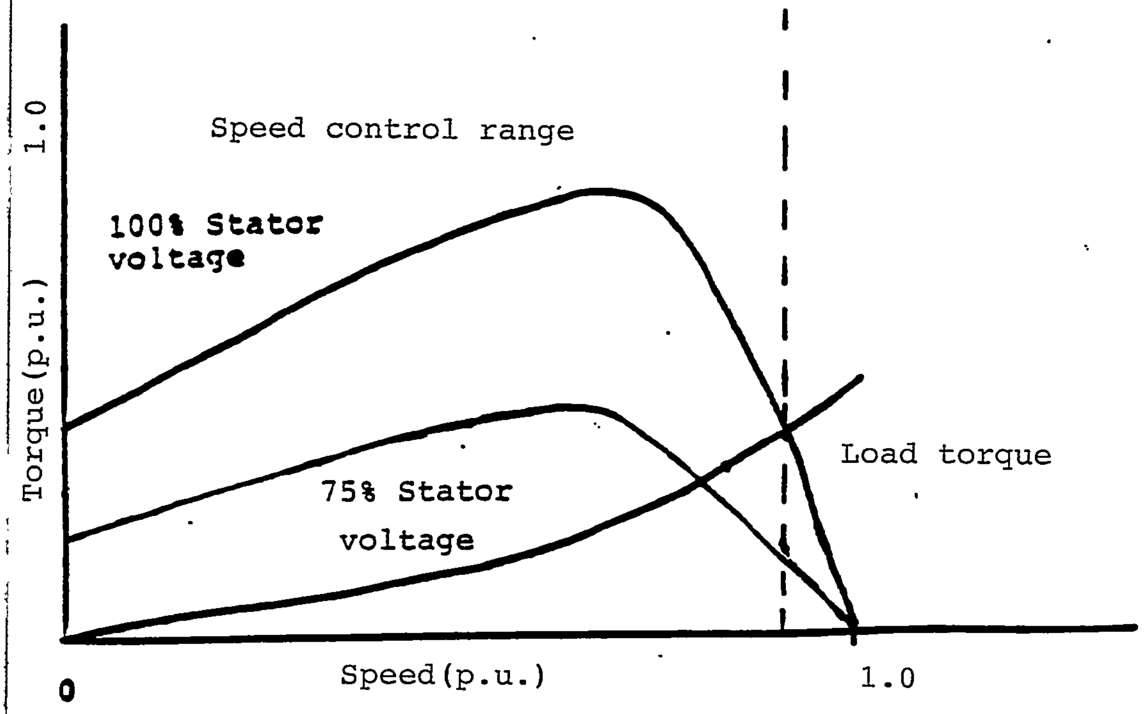

Figure 1.3: Speed-torque curves of induction motor with phase voltage control

This method of speed control is used for low to medium power drives where low initial cost is preferred over high efficiency. In this method the ratio of voltage to frequency decreases at reduced voltage causing reduced airgap flux in the machine. Thus, the magnitude of current goes up for the same amount of torque at reduced voltage. The machines with higher slip have a larger range of speed control as shown in Figure 1.3.

1.2.4 Variable Current Variable Frequency Control

The variable current, variable frequency method of speed control requires an inverter to generate a variable frequency, six-stepped current wave. This is done by generating a variable DC voltage from a phase controlled rectifier. This voltage is then converted to a current source by connecting a large inductor in series. The current source is then used as input to the inverter to generate the six stepped variable frequency current wave. The schematic diagram for such a current fed inverter is shown in Figure 1.4. The typical current and voltage waves for such an inverter are shown in Figure 1.5.

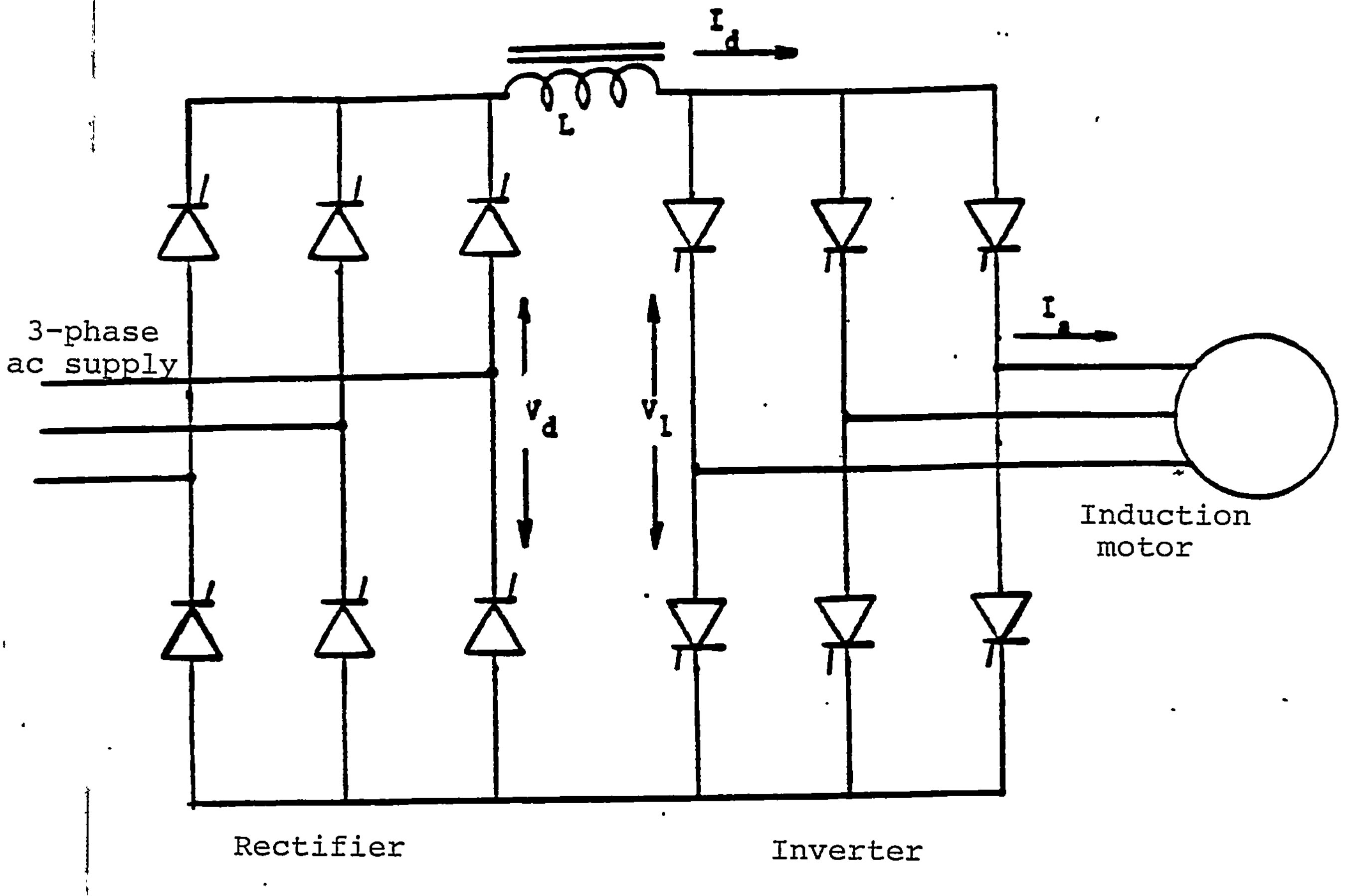

Figure 1.4: Schematic diagram of current controlled induction motor drive

This inverter has to supply an induction motor which is a lagging power factor load. This requires that the SCRs of the inverter be force commutated. There are various methods of force commutation. The auto sequentially commutated inverter is one of those commonly used and is shown in Figure 1.6.

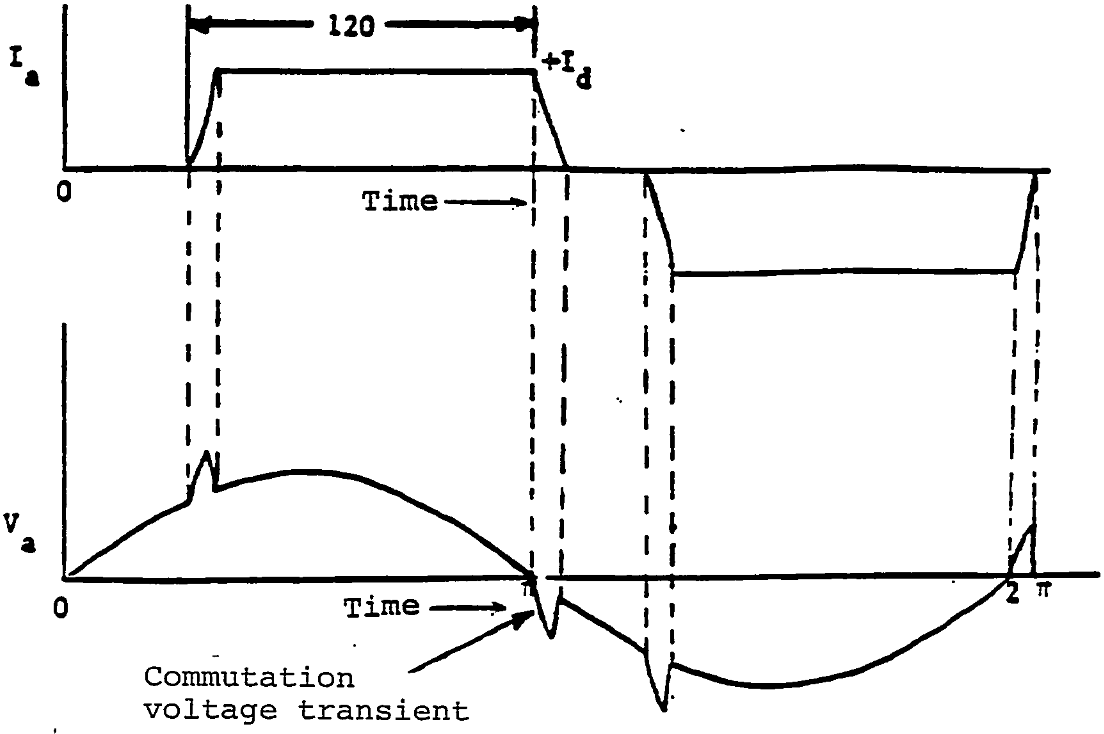

Figure 1.5: Phase voltage and current waveforms

The six capacitors and six diodes constitute the commutation circuit. The diodes allow the capacitors to store energy for commutation. This stored energy is then used to commutate the conducting SCRs. For example, if SCR1 is conducting, then capacitor C1 is charged with polarity as shown. To commutate SCR1, SCR3 is fired which reverse biases the conducting SCR1 and turns it off.

The current fed inverter requires a minimum load current to commutate the inverter. The frequency range of this inverter is relatively low. This is generally used in medium to high power drives.

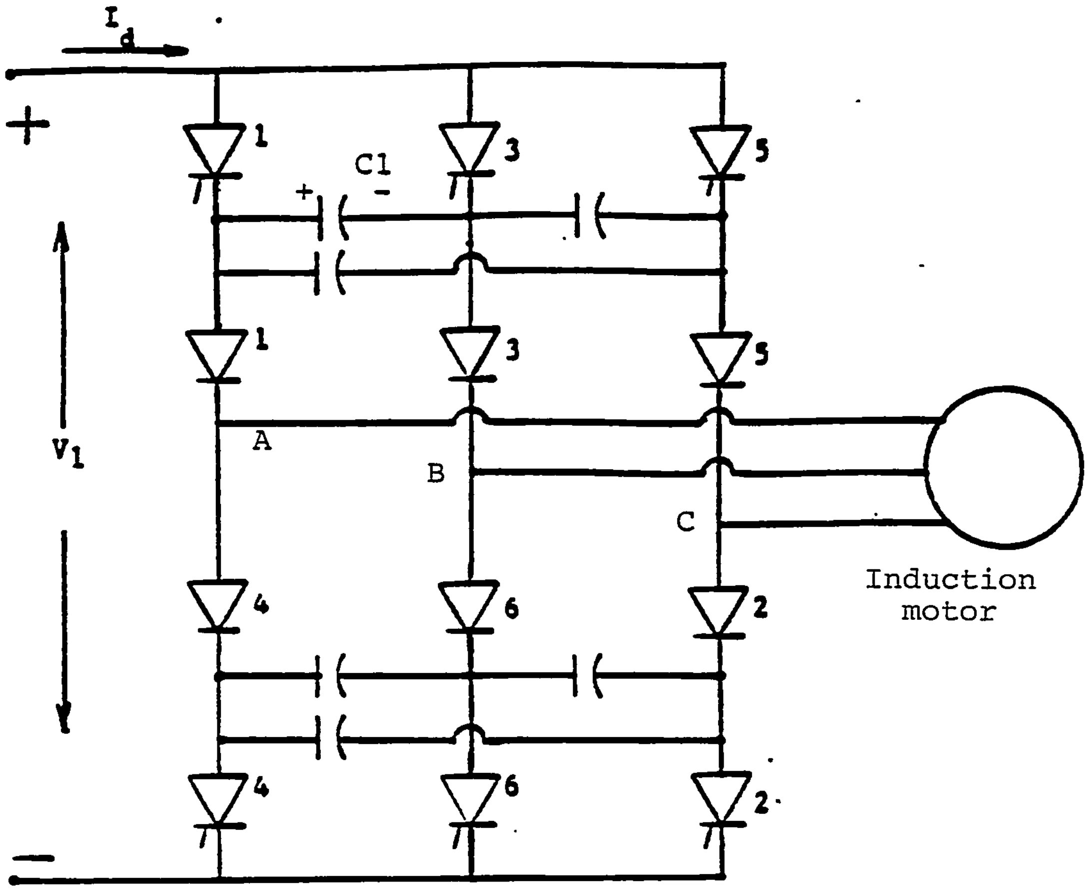

Figure 1.6: Auto sequentially commutated inverter

1.2.5 Slip Power Recovery Control

The slip power recovery method of speed control involves the control of equivalent rotor resistance to control the speed of a wound rotor induction motor. The schematic diagram for such a speed control system is shown in Figure 1.7. In this scheme, the slip power of the rotor is rectified and fed back to the ac line through a line commutated inverter. The power factor of the machine can be improved by force commutating the

SCRs as in the case of the current fed inverters. As shown in the Figure 1.7, the slip power is rectified by diodes. This permits the flow of power in only one direction, thereby restricting the control of speed to the sub-synchronous region. If the diode rectifiers were replaced by SCR's, slip power could flow in either direction. Such a doubly fed machine can be controlled in both subsynchronous and supersynchronous regions. This scheme is used to control the speed of large power pumps and blower type drives.

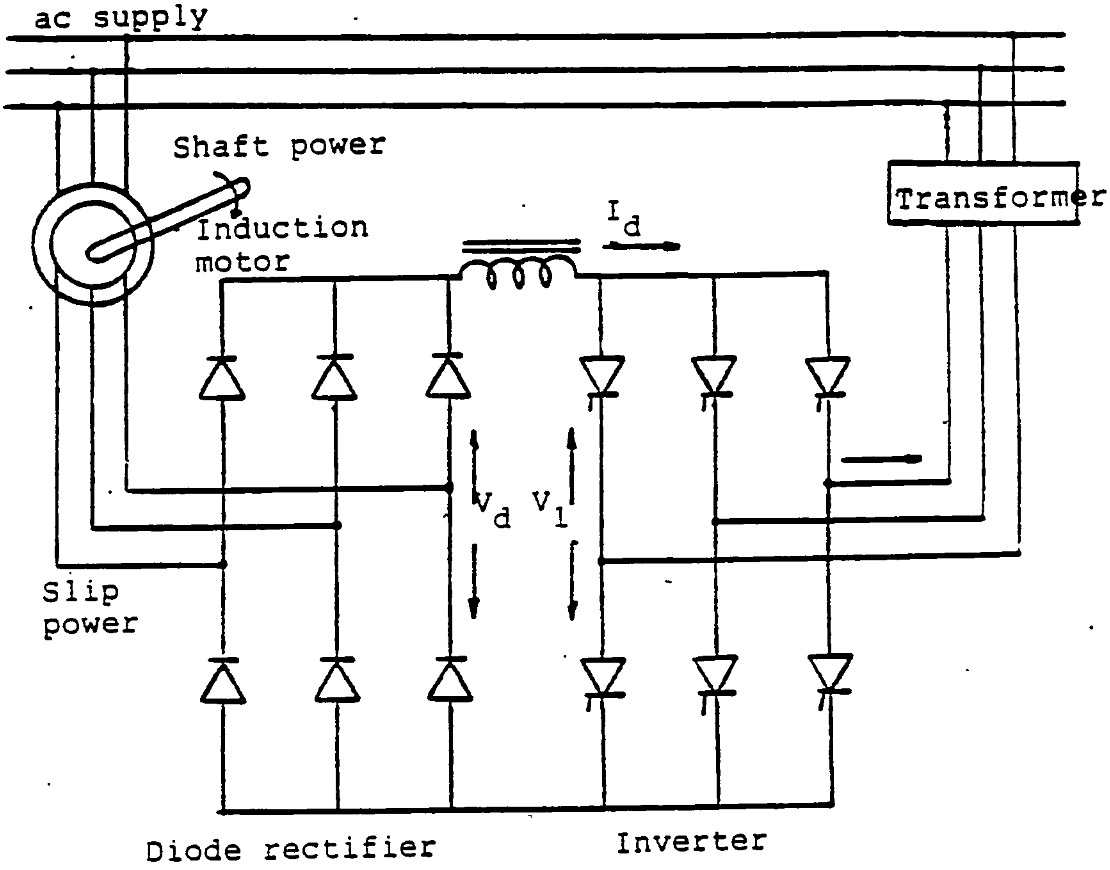

Figure 1.7: Speed control by slip power recovery

1.2.6 Deficiencies Of The Existing Systems

The systems described briefly in sections 1.2.2 to 1.2.5 above suffer from several shortcomings as follows:

1. The output voltage is rich in harmonics.
2. It has a limited speed range, particularly a very limited lower speed.
3. Application is limited due to limited speed range.

Many of the deficiencies can be overcome using the method described in section 1.3 following. This is the method exploited in the techniques described subsequently in this thesis.

1.3 VARIABLE VOLTAGE VARIABLE FREQUENCY CONTROL

The variable voltage variable frequency inverters, which are the systems of prime concern in this thesis, can be classified into two types:(1)square wave inverters , and (2)pulse width modulated inverters.

1.3.1 Square Wave Inverter

In a square wave inverter, the voltages applied to the motor are essentially square waves, with one pulse per half cycle. This type of inverter requires a variable dc voltage as input which is generated by an SCR bridge rectifier. This is shown in Figure 1.8. The SCRs require forced commutation as the induction motor constitutes a passive load. This problem is caused due to the complex behavior of the SCR; once conducting, the forward current through the SCR must fall below the holding current of the SCR to turn it off. This problem can be eliminated by use of power transistors instead of SCRs. However, the power output of the inverter using power transistors is limited by this lower voltage ratings.

This method is used for induction motors with low slip where the speed of the motor is close to synchronous speed. The synchronous speed of the motor can be controlled by varying the stator supply frequency; however the voltage has to vary with frequency to maintain constant airgap flux. The output voltage for a square wave inverter is rich in harmonics.

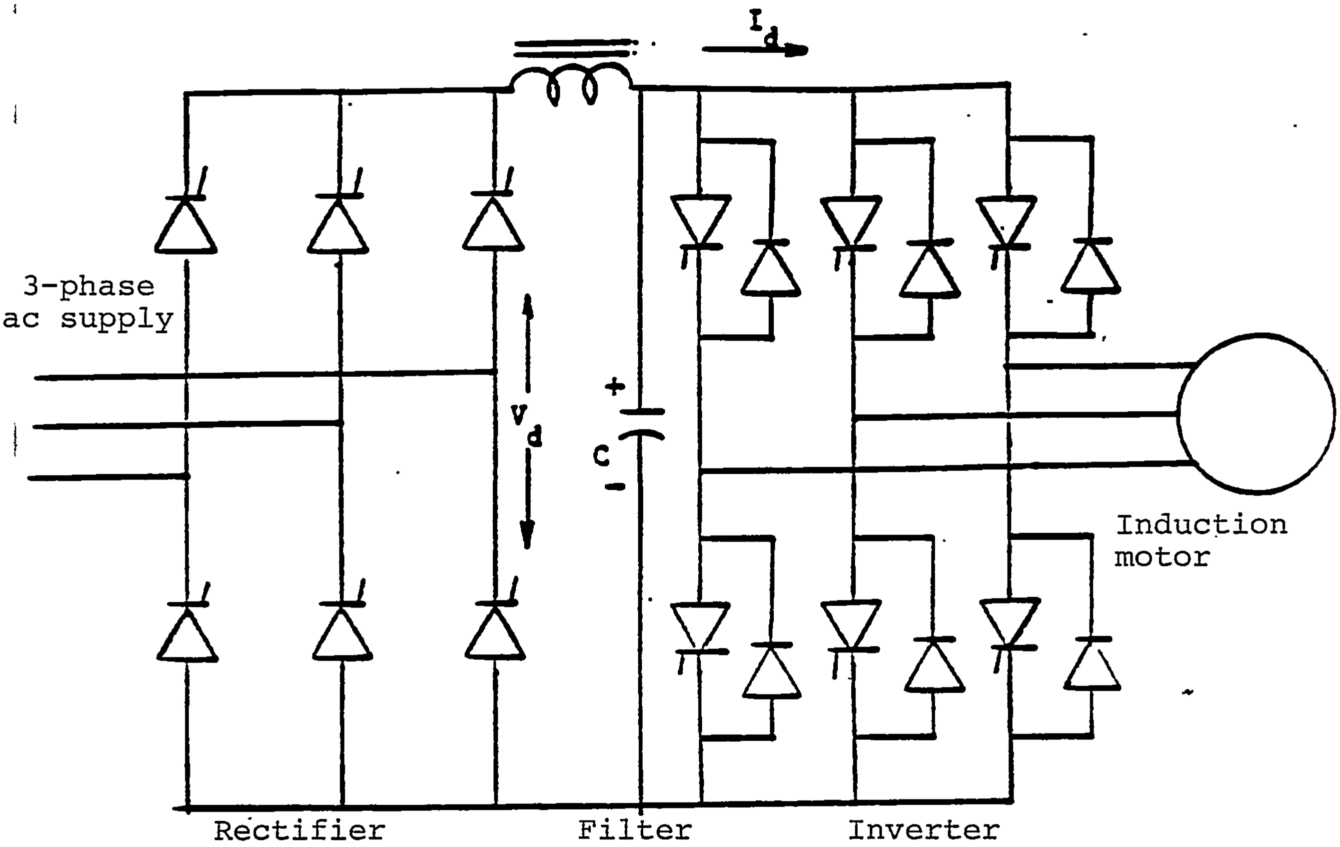

Figure 1.8: Schematic diagram of square wave inverter

The volts/Hertz ratio must be constant to maintain constant airgap flux for constant torque below the base frequency except at lower frequencies when the resistance of the stator becomes significant compared to its reactance. Then additional voltage has to be added to compensate the effect of the resistive voltage drop. This is explained in detail in the third chapter. Above base frequency, the motor runs as a constant power drive with reduced torque due to reduction of airgap flux as the frequency increases.

This voltage-frequency relation is shown in Figure 1.9. The torque-speed curve for constant torque and constant power regions for different frequencies is shown in Figure 1.10. This type of inverter is used for low to medium power drives.

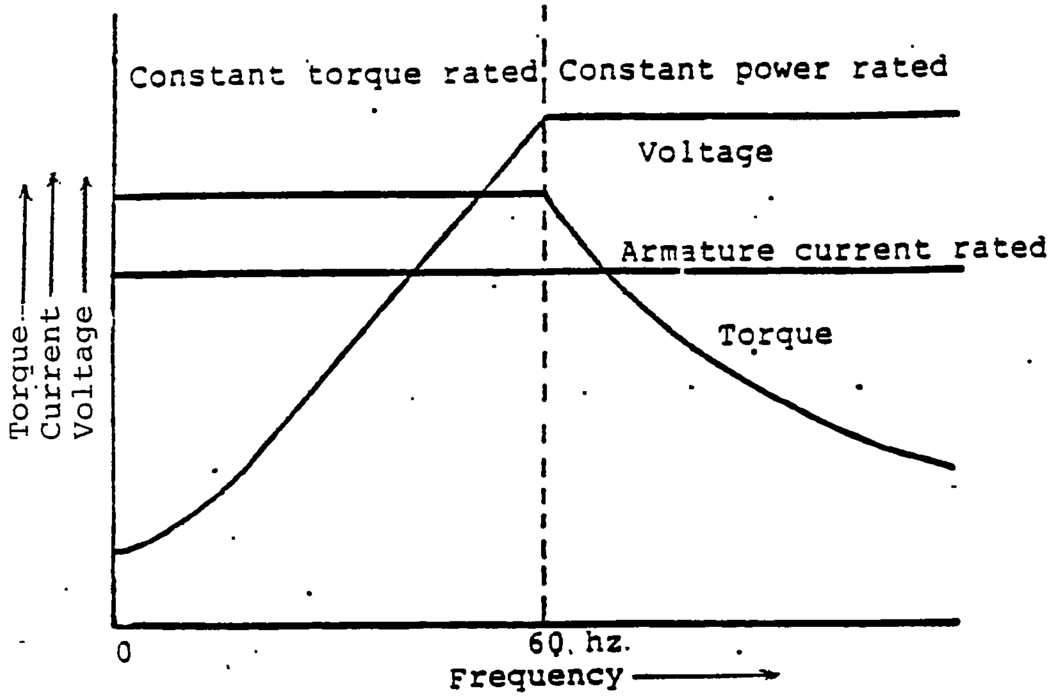

Figure 1.9: Voltage-frequency relation of induction motor(PWM)

1.3.2 Pulse Width Modulated Inverter

The efficiency and performance of a variable voltage variable frequency inverter is improved over the square wave inverter by the pulse width modulation(PWM) technique.

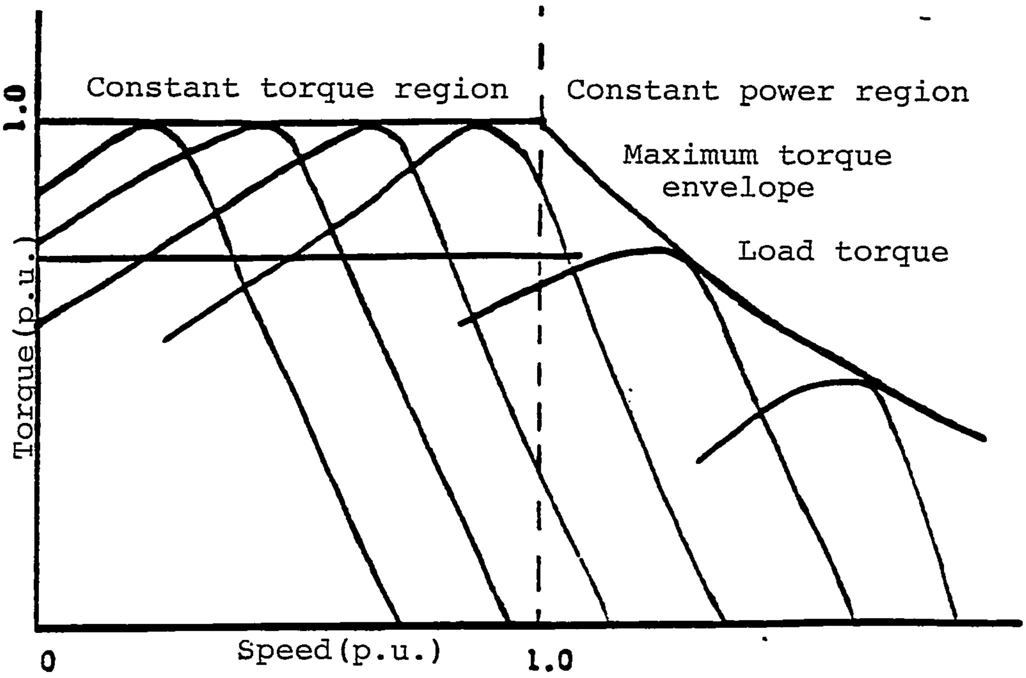

Figure 1.10: Torque-speed relation for various frequencies

In the pulse width modulated inverter, the SCRs are switched on and off to generate a train of square wave voltage pulses for each half cycle; the average voltage over the half cycle is equal to that of a half cycle of sine wave. The width and period of the square wave train is controlled electronically within the inverter circuit, to control the amplitude and frequency of the inverter output. There are various PWM inverter circuits available but the particular control strategy employed and the commutation circuit used, lead to differences in implementation and performance. In each case, the output is a train of square wave pulses with quarter wave symmetry. This is shown in Figure 1.11.

The PWM inverter can be designed to eliminate selected harmonics by generating the points of commutation appropriately. This involves a complex control logic which can be implemented in various ways. Sinusoidal pulse width modulation is one of the commonly used methods. In this method, an isosceles triangular carrier wave is compared with the reference sine wave signal and the points of crossover determine the points of commutation. This method is explained in detail in the third chapter of this thesis.

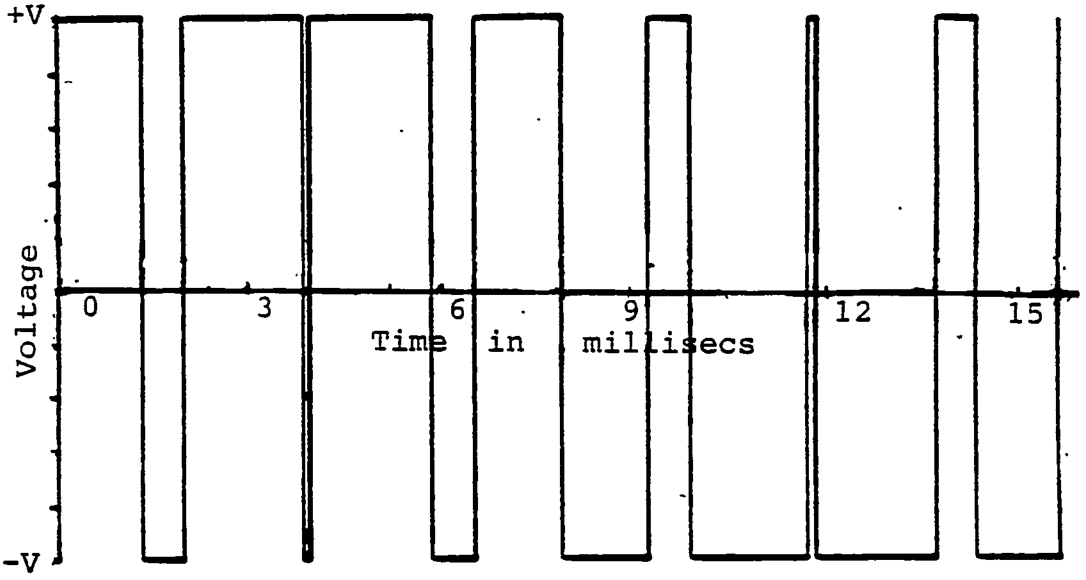

Figure 1.11: Ideal output voltage of a PWM inverter

1.4 PROPOSED CONTROL STRATEGY

This thesis illustrates a uniquely different control strategy for generating the pulses which has been implemented on a microcomputer.

In this method the points of commutation are calculated by a "sine-area equivalence" approach. The half sine wave period is divided integrally into equal segments. Then a square wave of area equal to each sine wave segment is calculated. The zero crossover points of the square wave train determine the points of commutation. This is explained in detail in the third chapter of the thesis. This control scheme is fast and independent of the operating frequency unlike the sinusoidal PWM where it takes time equal to the time period of the operating frequency to determine the switching instants.

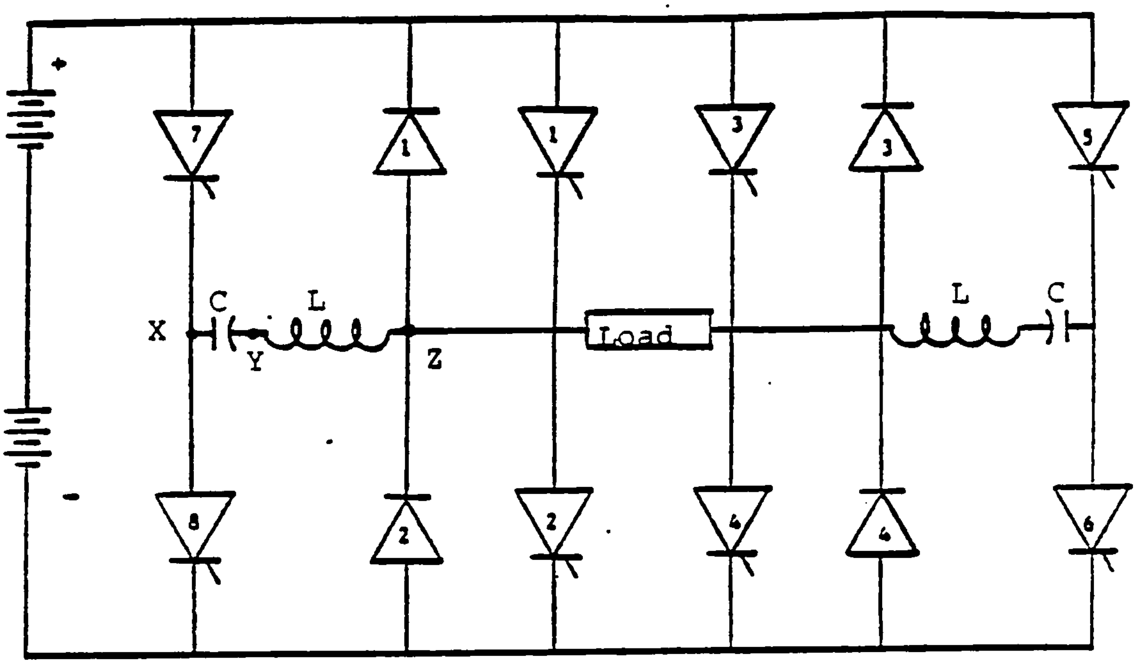

Figure 1.12: McMurray-Bedford auxiliary commutated inverter

As mentioned in section 1.3.1, a constant airgap flux must be maintained for operation below base frequency. This is accomplished using a simple technique which is explained in the third chapter. The inverter circuit used for analysis is an auxiliary commutated inverter as shown in Figure 1.12. This circuit has four main SCRs(1,2,3,4) which carry the load current and four auxiliary SCRs(7,8,5,6) to turn off the main SCRs respectively. The LC oscillatory circuit is used to store the commutating energy which is passed on through the auxiliary SCRs to commutate the main SCRs. The polarity of the voltage across the load alternates as the pair of main SCRs conducting changes from (1,4) to (2,3).

1.5 LAYOUT OF THE THESIS

This thesis describes a number of the existing modulation strategies and analyses the performance of these strategies with reference to the auxiliary impulse commutated inverter shown in Figure 1.12. A new digital technique is proposed to eliminate some of the drawbacks of the previous methods. The performance of the new control strategy is analysed with reference to the auxiliary impulse commutated inverter. These concepts are presented in the thesis in the following order.

The second chapter describes the basic features of an auxiliary impulse commutated inverter. The theory of operation of such an inverter is explained in detail. The importance of commutation elements in reference to the triggering sequence of the SCRs is explained in this chapter.

The third chapter deals with the basic concept of pulse width modulation strategy for power inverters using SCRs. The drawbacks of the sine wave modulation scheme are discussed in this chapter. The improved digital technique for pulse width modulated inverters is explained with reference to the constraints imposed by the power circuit.

The fourth chapter covers the modifications made to the control strategy for nonlinear voltage/frequency characteristic at low frequency. The actual implementation of the scheme on a LSI-11/23 microcomputer is discussed.

The fifth chapter consists of the evaluation of the control strategy for changes in parameters; switchings per cycle, different utility factors for dc to ac gain and the change in harmonic pattern for the change in parameters for steady state. The inverter circuit is simulated with the simulated control signals generated by the new control algorithm. The circuit is simulated using SPICE(simulation program with integrated circuit emphasis). SPICE was originally developed at the University of California, Berkeley. It is a general purpose circuit simulation program for nonlinear dc, nonlinear transient and linear ac analysis of circuits. More details of SPICE are given in Appendix A. A generalised derivation for harmonic analysis of steady state inverter output is given in this chapter.

The sixth chapter presents conclusions based on the complete study. This chapter explains the universality of the control strategy regarding the inverter power circuits. The extension of the single phase control strategy to three phase control strategy is explained.

2. ANALYSIS OF THE POWER CIRCUIT

2.1 GENERAL

The control scheme used in any inverter operation is based upon the power circuit used for generating the ac output. In the system of concern in this thesis, an auxiliary impulse commutated inverter is used. The theory of operation and analysis of the power circuit for such an inverter is given in this chapter.

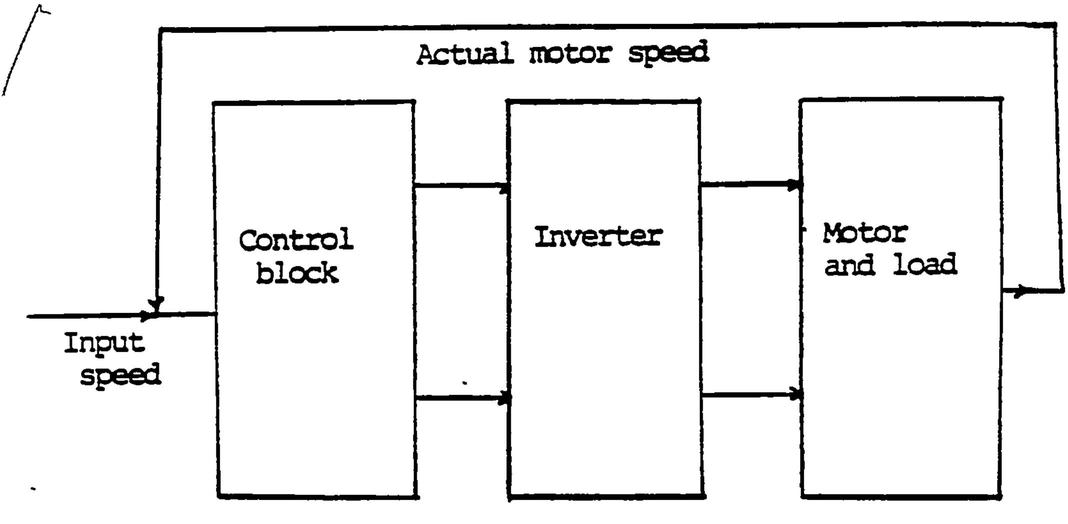

Figure 2.1: Block diagram of inverter-induction motor drive system

The inverter-induction motor drive system can be represented in three stages as shown in Figure 2.1. The first stage is the controller for the system which generates the trigger signals for the SCRs. The trigger signals control the switching of the SCRs, which in turn modulate the input dc supply to generate the necessary pulse train. This pulse train feeds the induction motor which drives the load. The actual system would have motor speed and current fed back to the input of controller, to calculate the accurate triggering sequence. This thesis emphasizes the development of the control algorithm and analysis of the inverter circuit with the generated clock signals, to determine its steady state and dynamic behavior which is covered in the fifth chapter.

2.2 IMPULSE COMMUTATED INVERTERS

An essential part of an inverter operation is to commutate(turn off) a conducting SCR effectively. This is not a difficult task when the load is resistive or capacitive, but for an inductive load like an induction motor, the current in the conducting SCR does not reduce to zero instantaneously when the voltage goes to zero. In such cases, an impulse is used briefly to reverse the current through a conducting SCR thereby turning it off.

The magnitude of the commutating pulse must be sufficient to extinguish the current in the conducting SCR and the time period of the pulse must be longer than the turn off time of the SCR. The power circuit shown in Figure 1.12 uses an oscillatory inductance-capacitance circuit to generate the commutating pulse. The required time period of this LC network is based on the turnoff time of the SCRs. The time period of the commutating circuit is calculated for the maximum value of load current and DC supply voltage. This is held constant irrespective of frequency of operation and load current, so that the total commutating time remains the same for all frequencies of operation and thus occupies a greater portion of the the half cycle as the frequency increases.

The impulse commutated inverters are classified in terms of the way the impulse is initiated. When the impulse is generated by auxiliary means, separate from the power circuit, it is termed an auxiliary impulse commutated inverter as shown in Figure 1.12. This is explained in detail in the next section.

Alternatively, the impulse may be initiated by turning on the SCR which is complementary to the conducting SCR. The schematic for such an inverter is shown in Figure 2.2.

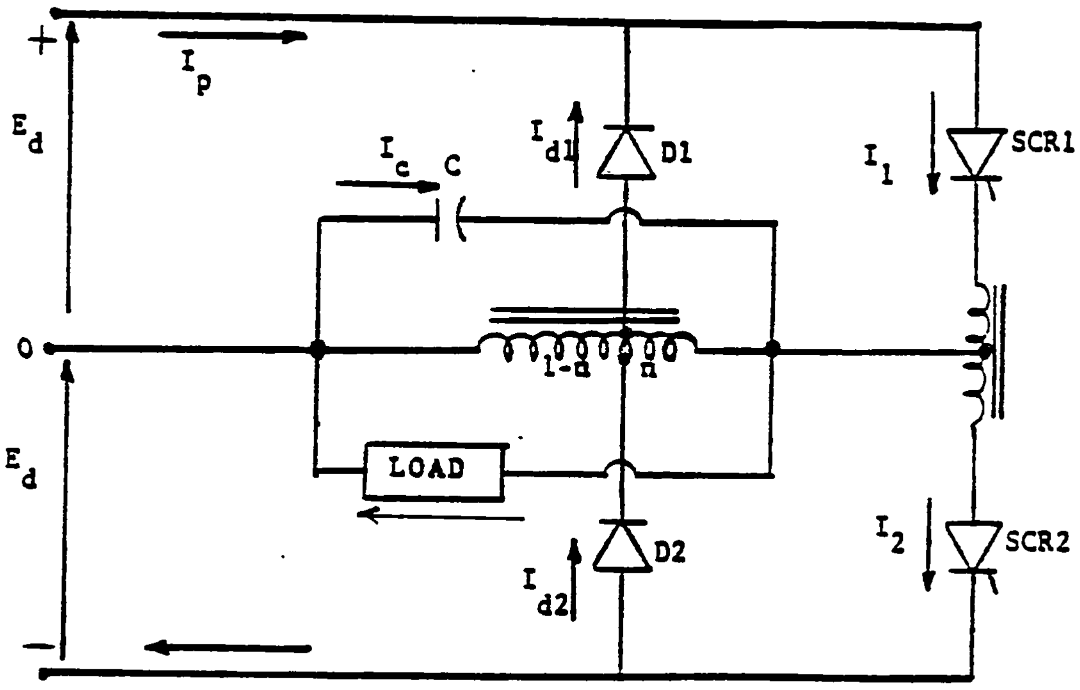

Figure 2.2: Complementary commutated inverter

In another method of impulse commutation, the impulse is generated as the SCR is turned on. In this case, the SCR is turned off automatically after a fixed time period and does not need any action by the control circuit. This is known as a self commutated inverter and is shown in Figure 2.3.

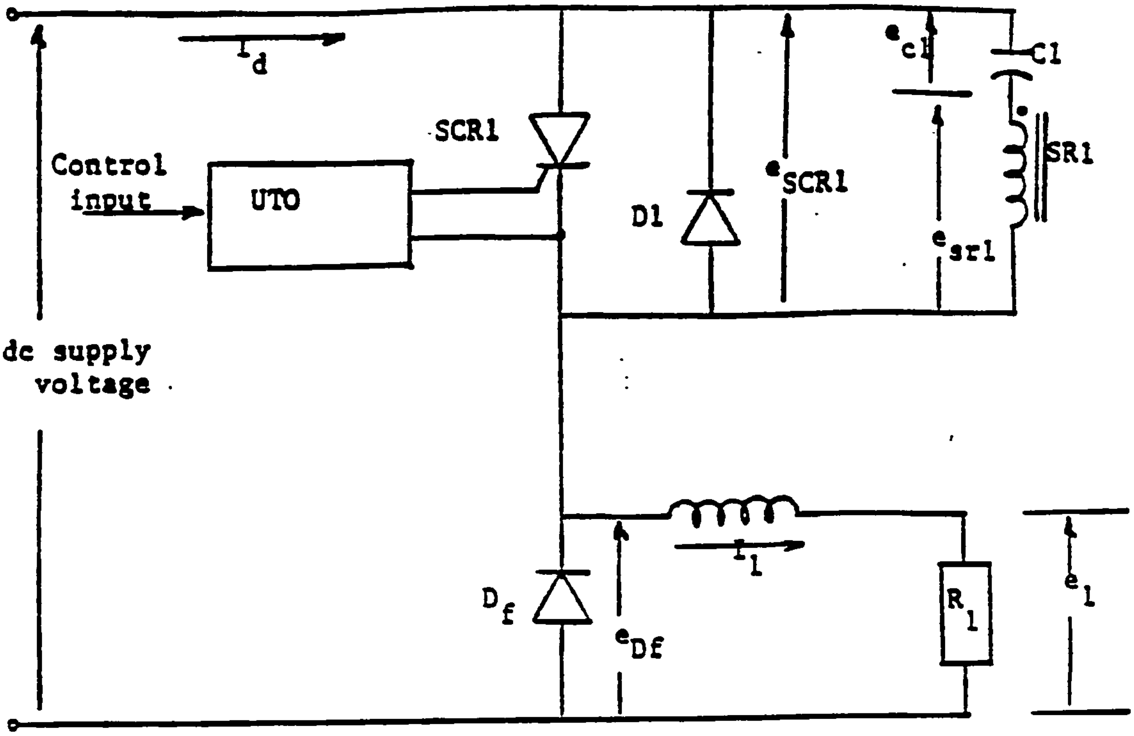

Figure 2.3: Self commutated inverter

2.3 AUXILIARY IMPULSE COMMUTATED INVERTER (A.I.C.I)

In an auxiliary impulse commutated inverter, the turn-off pulse is initiated by triggering an auxiliary SCR. As shown in Figure 1.12 and 2.4 for a single phase inverter, there are four main SCRs(1,2,3,4) and four