2.1 INTRODUCTION

Since the beginning of last century electrical power has been generated, transmitted and distributed using three phases. As a consequence the induction machines and all other AC machines were developed as three-phase devices. Initially fixed speed drives were used in major applications such as pumps. Later on it was realized that the variable speed motor drives offer higher efficiency when compared to the fixed speed drives. Several methods were developed to vary the motor speed. The basic principle of variable speed drives lies in generating the variable voltage and variable frequency supply to feed the motors. Hence most variable speed induction motor drives are constructed by combining a three-phase motor with a three-phase inverter. While the number of phases feeding the input converter is governed by the utility supply (three phase), the inverter can be constructed to have as many output phases as desired. In theory, AC motors may be constructed with any number of phases. Motors with phase numbers greater than the traditional three possess certain advantages over their three-phase counterpart [Levi (2008)]. This thesis explores the modulation techniques of multi-phase (more than three phases) voltage source inverter feeding multi-phase AC machines. Thus the literature review is focused on the work related to the multi-phase motor drive system. The first section discusses the advantages of the multi-phase motor drives compared to their three-phase counterpart. This is followed by modelling and control issues of multi-phase motor drives.

2.2 ADVANTAGES OF MULTI-PHASE MACHINES

Early interest in multi-phase machines was caused by the need to reduce torque pulsations developed by inverter-fed three-phase drives. The first investigation into the use of a multi-phase machine within a variable speed electric drive was carried out by Ward and Härer (1969), when a five-phase induction motor, supplied from a five-phase ten-step voltage source inverter VSI was considered. It was found that the amplitude of the torque pulsation was reduced by a third and the frequency of pulsation was shifted to the higher values. This significantly reduces the filter requirement in a five-phase drive system and offer smoother torque. However, the improvement was at the cost of severe distortion of the supply currents, this was due to the square wave mode of operation of the five-phase inverter supplying the five-phase induction machine. Pavithran et al (1988) solved this
problem by employing a pulse-width-modulated PWM VSI instead of operating the inverter in square wave mode.

A six-phase induction machine (composed of two three-phase windings with isolated neutral points and shifted by 30 degrees in space and often called dual three phase) was originally introduced because of the smoother torque. The supply may be coming from a six-phase VSI [Abbas et al (1984), Hadiouche et al (2000), Grochowalski (2000), Monti et al (1995), Xu and Ye (1995), Nelson and Krause (1974), Abbas and Christen (1984)] or from a six-phase current source inverter (CSI) [Gopakumar et al (1984), Andresen and Bieniek (1980), Andresen and Bieniek (1981)]. With the advent of the PWM era the need to reduce the torque ripple by using multi-phase machines has become less important in the low to medium power range. However, this advantage is still applicable in the high power range where the current limitations of semiconductor devices restrict the use of PWM [Xu and Ye (1995)].

Multi-phase drives possess some other important advantages compared to a three-phase motor drive. First of all, multi-phase machines offer significant advantages in high power applications. For the given motor power an increase in the number of phases enables reduction of the power per phase, which translates into a reduction of the power per inverter leg (that is, a semiconductor rating). Multi-phase machines are therefore often considered and applied in very high power applications. A six-phase (double star) 850 kW 6-pole field oriented controlled drive was developed by Camillis et al (2001) for use in an extruder pump in a polyethylene plant. In order to reduce the losses obtained when a 1400 kW permanent magnet synchronous generator is wound with a three-phase stator, a quasi nine-phase configuration is employed in Veen et al (1997). The nine-phase configuration is formed using three three-phase windings, supplied from three three-phase inverters. Zdenek (1986) describes a six-phase 25 MW synchronous motor drive for use in a turbo-compressor set. Steiner et al (2000) developed a special configuration of a nine-phase (triple star) induction motor drive for application in high power traction vehicles. A high power six-phase (double star) induction motor drive used in Adtranz locomotives is analysed by Mantero et al (1999). Other high power applications of multi-phase machines include a traction application of a two-level GTO inverter feeding a six-phase (double star) induction motor [Monti et al (1995)]. For use in automotive applications, Miller et al (2001) investigate the use of pole phase modulation (PPM) to allow extension of the constant power range of a nine-phase toroidal induction machine for an integrated starter-generator application. A five-phase permanent magnet 5 kW motor with square wave current excitation (BDCM) was developed
for propulsion purposes in an electric vehicle by Chan et al (1994) because it possesses high power density, high efficiency and superior dynamic performance.

The ability of multi-phase drives to operate under fault conditions is the main reason for their use in safety critical applications such as locomotive traction [Steiner et al (2000), Mantero et al (1999)] and 'more electric aircraft' [Mitcham and Cullen (2002)]. A general multi-phase machine allows application of the parallel redundancy concept [Jahns (1980)] since it has $n$ separate input terminals and continues to operate when only $(n-1)$ terminals or less are supplied. If one phase is open circuited, three-phase drives require a neutral line connected between the motor and the DC midpoint in order to allow the current in the remaining phases to be controlled to provide a rotating mmf. In multi-phase machines there exist additional degrees of freedom as a result of there being more phases. Thus the current combination required to produce a rotating mmf during fault conditions is no longer unique [Fu and Lipo (1994)]. Typical fault studies in motor drives suggest that short circuit and open circuit are the most significant fault conditions and they are classified as most commonly occurring faults. Jahns (1980) studied VSI and Current Source Inverter fed machines for both types of fault conditions. It was found for the open circuit case that in VSI fed drives the drive compensates for the loss of current in one phase by increasing the current amplitudes in the remaining exited phases. However, in the CSI fed case the current excitation does not permit the current in the remaining excited phases to change from the balanced excited values and so the performance of the machine was more seriously degraded. For the case where a six-phase machine was fed by a VSI the developed torque decreased by 10% and a 20% decrease was recorded for the case when the machine was fed via a CSI. It was shown by Jahns (1980) that the performance of the machine under fault conditions improved as the number of phases was increased. By controlling the remaining currents in multi-phase drives using a current regulated PWM inverter, it is possible to start and run the drive with loss of a phase (open circuited) without any reduction in torque [Fu and Lipo (1994), Toliyat (1998)]. The current required in the remaining phases was found by Fu and Lipo (1994) to decrease as the number of phases originally supplying the machine was increased. High power drives are particularly vulnerable to failures due to their high component count, which reduces the drive's mean-time-between failures [Jahns (1980)]. An increase in the number of phases supplying the machine results in a reduction in the power per phase compared to an equivalent three-phase machine. This means that the need for parallel or series stack switches in high power drives may not exist anymore [Williamson
and Smith (2001)], resulting in a lower component count and a less complex inverter structure. Thus improved reliability is anticipated for high power applications.

A potential benefit of multi-phase machines is that with an increase in the number of phases an increased torque per ampere for the same volume machine may be achieved [Toliyat et al (1998), Weh and Schroder (1985), Toliyat and Lipo (1994)]. Increased torque production can be achieved in multi-phase machines by virtue of higher harmonics other than the fundamental contributing towards torque production [Lyra and Lipo (2001), Xu et al (2001), Toliyat et al (1991), Kestelyn et al (2002), Hodge et al (2002)]. This is so since a three-phase machine can utilise only the fundamental component to develop torque, while a five-phase machine can utilise both the fundamental and the third harmonic components. By extension a seven-phase machine can be controlled to utilise the first, third and fifth harmonics for torque production [Xu et al (2001), Toliyat et al (1991)], while in a nine-phase machine it is possible to use injection of the third, the fifth and the seventh current harmonics [Coates et al (2001)]. This advantage stems from the fact that vector control of the machines' flux and torque, produced by the interaction of the fundamental field component and the fundamental stator current component, requires only two stator currents (d-q current components). In a multi-phase machine, with at least five phases or more, there are therefore additional degrees of freedom, which can be utilised to enhance the torque production through injection of higher order current harmonics. This is so since injection of any specific current harmonic requires again two current components, similar to the torque/flux production due to fundamental harmonic. In general, the possibility for an increase in torque density increases with the number of phases by injecting higher order harmonics in addition to the fundamental in concentrated type of multi-phase machines. However, it appears that once when the number of phases reaches 15, further increase does not provide any further important advantage [Hodge et al (2002)]. It was reported by Xu et al (2001) that a 10% increase in torque is possible for a five-phase induction machine with concentrated windings. A synchronous reluctance machine with concentrated windings was investigated by Toliyat et al (1998), Toliyat et al (1992), Xu and Fu (2002), Shi et al (2001a) and a 10% increase in torque was reported. The research carried out thus far has not been confined to only five-phase machines. Lyra and Lipo (2001) considered a six-phase (double star) machine. The machine was reported to increase torque production by up to 40% compared to the equivalent three-phase machine. It was reported that the improvement in torque is due to two factors. First, by injecting the third harmonic current there is a reduction in the peak flux density of the air gap flux and so additional torque can be gained.
by increasing the fundamental flux component without saturating the machine. Secondly, the rotating field created by the third harmonic currents generates a small increase in torque. Torque enhancement is recently reported for a seven-phase induction machine by injecting third and fifth harmonic components of current in addition to the fundamental [Kestelyn et al (2010)].

Further advantages of multi-phase machines over the three-phase counterpart include reduction in stator and rotor losses [Williamson and Smith (2001)] and a reduction in vibration and noise generated by the machine [Golubev and Ignatenko (2000)]. Recent surveys [Singh (2002), Jones and Levi (2002), Levi (2006) and Levi (2008)] indicate an increasing interest in multi-phase machines within the scientific community. It has to be noted that some of the advantages of the multi-phase machines, which exist in the case of a single multi-phase motor drive, will not be applicable in the investigated multi-motor multi-phase drive system. For example, torque density cannot be enhanced in the manner previously discussed, since the existing degrees of freedom are to be used to control other machines in the group. Similarly, fault tolerance will be substantially reduced since all the available degrees of freedom are to be utilised for control of the machines in the system. Nevertheless, the thesis developed the control strategies of multi-phase voltage source inverter supplying multi-phase multi-motor drive system.

2.3 MODELLING OF MULTI-PHASE MACHINES

Modelling of multi-phase machine is an interesting topic which has attracted the attention of researchers for long. The general $n$-phase machine model is presented way back in first half of the 20th century by White and Woodson (1959). A general $n$-phase decoupling transformation matrix is presented which is applicable to any odd or even phase number machines. With standard assumptions for a sinusoidal field distribution machine, a set of $n$ equations are produced by applying decoupling (Clarke’s) transformation matrix. The first $\alpha - \beta$ pair is identical to the corresponding pair of equations for a three-phase machine. The last equation (odd phase number) and last two equations (even phase number) represent zero sequence components, same as three-phase machine. The remaining $(n-3)$ sets (odd phase number) and $(n-4)$ sets (even phase number) are extra components which are termed as $x$-$y$ or non-torque producing components. These components are limited by leakage impedance only similar to the zero sequence components, thus will generate significant current distortion unless restricted by proper PWM control. The stator $\alpha - \beta$ component interacts with rotor $\alpha - \beta$ component to produce the working torque. The stator and rotor $x$-
y components are localised and they do not interact with each other or with stator to rotor or rotor to stator. Thus these pairs of components do not take part in production of torque in a machine. They produce distortion in currents. Since coupling between stator and rotor appears after decoupling transformation only in $\alpha - \beta$ equations of the multi-phase machine, it is only this set of equation that have to be transformed further, using rotational transformation. The form of this transformation is the same as for the corresponding three-phase machine. The resulting final $d-q$ model in the common reference frame contains $d-q$ and torque equations identical to that of a three-phase machine. Thus same vector control principle is thus applied to a multi-phase machine as that of a three-phase machine.

In case of a quasi six-phase machine the transformation matrix depends on the neutral connection. If there is only one neutral point then the transformation matrix is identical to that of the symmetrical machine. In case of a multi-phase machine of even numbers with $p$ isolated neutral points the total number of equations reduces to $(n-p)$ after decoupling transformation since zero sequence components cannot flow in any of the star connected $p$ windings.


The phase variable and $d-q$ model of a concentrated winding machine is different compared to distributed winding machine. The inductance terms with fundamental and higher harmonics have to be included in contrast to the distributed winding machine where only fundamental component of inductance is considered. Application of decoupling transformation matrix results in $(n-1)$ equations for odd and $(n-2)$ equations for even phase number machine. An appropriate rotational transformation matrix is now applied to all the equations and the final $d-q$ model contains $(n-1)$ equations of the form valid for $d-q$ equations of a three-phase machine. Torque equation has now, in addition to the components due to fundamental stator current, $(n-3)$ new equations, each of which is due to the interaction of a certain stator current harmonic and the corresponding spatial harmonic of the field.
2.4 CONTROL OF ADJUSTABLE SPEED MULTI-PHASE DRIVE

Variable speed control of ac drive is achieved by scalar or vector based control schemes. V/f is the most popular scalar control scheme which is of now little interest due to availability of cheap high performance drive. The vector control principle of sinusoidally distributed stator winding multi-phase machine is identical to that of a three-phase machine as demonstrated by [Iqbal et al (2003), Iqbal et al (2006), Bojoi et al (2002), Bojoi et al (2003), Bojoi et al (2005), Bojoi et al (2006), Hou et al (2003), Sudhoff et al (1997), Vukosavic et al (2005), Hua et al (2006)]. The only difference is that the coordinate transformation has to produce \( n \)-phase current references for current control in stationary reference frame and \( n \)-phase voltage references for current control in rotational reference frame. For current control is stationary reference frame \((n-1)\) stationary current controllers are required. Either phase currents or phase current components are controlled using ramp-comparison closed-loop current control scheme. For current control in rotational reference frame in principle only two current controllers are required since only two current components are required for torque production. However, since \( n \)-phase machine has \( n-1 \) independent currents, using only two current controllers is not sufficient in practice as asymmetries in the windings or supply may lead to detuned operation of the vector controller. Thus four current controllers are normally employed to control a quasi six-phase machine.

The vector control principle of a concentrated winding machine is different from a distributed winding machine. This difference is attributed to the low order harmonic current which are injected for torque enhancement. The injected low order harmonic currents are firmly tied to the fundamental in terms of magnitude, phase and frequency. The modification is done for the calculation of references of low order harmonics and the calculation of rotational transformation. In such vector control schemes \( n-1 \) current controllers have to be used.

2.5 MODELLING AND CONTROL OF MULTI-PHASE VSI

The general theory of rotating machines, applied in analyses of three-phase machines, is also adequate for analysing multi-phase machines [White and Woodson (1959)]. The machines are modelled as a set of magnetically coupled coils. The flux linkage terms differ depending on the type of machine and the construction of the stator windings. For example, a six-phase stator can be constructed either with windings 60 degrees apart (true six-phase) or as in double star machines with two three-phase windings displaced by 30 degrees.
Mathematical models have been developed for many different types of multi-phase machines both for the steady-state and the dynamic case. Transformation of machine equations from phase variable to d-q form is performed using either real or complex variable transformations. For example, d-q axis models for five-phase induction machines and synchronous reluctance machines are available in Ward and Härer (1969) and Toliyat et al (1992), respectively. Abbas et al (1984) modelled a double star induction machine, while the generalised case of a six-phase induction machine with an arbitrary displacement between the two sets of three-phase windings is given in Hadiouche et al (2000), Grochowalski (2000), Nelson and Krause (1974). Transformation of the phase variable model of multi-phase machines results in two components (d-q) contributing to torque and flux production, and n-2 components which do not contribute to torque production under the condition of sinusoidal mmf distribution [Klingshirn (1983), Zhao and Lipo (1995)]. Multi-phase machines can be modelled by considering an n-dimensional approach to the space vector theory [Gataric (2000), Lipo (1984), Zhao and Lipo (1995), Kestelyn et al (2002)]. This method allows an n-phase machine to be modelled in n-dimensional space. Kestelyn et al (2002) demonstrated that a multi-phase machine is equivalent to a group of machines having smaller phase numbers and shows that a five-phase concentrated winding permanent magnet synchronous machine can be represented as a group of two two-phase and a single one-phase machine. Each phase of the machine is supplied by its own inverter (requiring 20 switches in total). It is on the basis of these transformed models that the methods of vector control for multi-phase machines are developed.

The well-known field oriented control (FOC) method, used to achieve high performance control of three-phase machines, can be extended to multi-phase machines. It has been shown by Nelson and Krause (1974) and Toliyat (1998) that multi-phase machine models can be transformed into a system of decoupled equations in orthogonal reference frames. The d-q axis reference frame currents contribute towards torque and flux production due to the fundamental of the mmf, whereas the remaining x-y components plus the zero sequence component(s) do not. This allows a simple extension of the rotor flux FOC principle in which the rotor flux linkage is maintained entirely in the d-axis, resulting in the q-axis component of rotor flux being maintained at zero. The electromagnetic torque equation is therefore reduced to the same form as that of a DC machine or a rotor flux oriented three-phase machine. Thus the electromagnetic torque and the rotor flux can be controlled independently by controlling the d and q components of stator current independently. Toliyat et al (2000) carried out the development of a vector control scheme.
for a five-phase synchronous reluctance machine. The strategy investigated was an indirect rotor flux oriented control technique using a space vector PWM strategy. Coates et al (2001) constructed a nine-phase four pole 5 kW synchronous reluctance drive under rotor flux oriented vector control. Rotor flux oriented control has been investigated for a five-phase induction and synchronous reluctance machine including third harmonic current injection by Xu et al (2001) and Shi et al (2001a), respectively, thus controlling both the fundamental and the third harmonic and resulting in a high performance drive with an increased torque. The other control method recently developed for high performance three-phase drives, direct torque control (DTC), is starting to be looked at in conjunction with multi-phase drives as well [Shi et al (2001b), Toliyat and Xu (2000)]. Shi et al (2001b) proposed DTC of a five-phase synchronous reluctance machine, while Toliyat and Xu (2000) analysed DTC of a five-phase induction machine.


It is recognised that the PWM of multi-phase inverters generate undesirable low order harmonics due to the presence of x-y components. This can be easily avoided by extending the carrier-based PWM scheme of three-phase VSIs to multi-phase VSIs. However, the dc bus utilisation is poor in carrier-based PWM and third harmonic injection and zero sequence signal injection is employed to improve the dc bus utilisation in three-phase VSIs [Holmes and Lipo (2003)]. The techniques of harmonic injection and offset addition is extended for multi-phase VSIs by Kelly et al (2001), Ojo and Dong (2005), Iqbal et al (2006) and Moinuddin and Iqbal (2007). It is shown that the gain in dc bus utilisation reduces with increasing phase number. The maximum fundamental obtainable with 3rd harmonic injection is 15.47% in a three-phase VSI, with 5th harmonic injection it is 5.15% in a five-phase VSI and with 7th harmonic injection it is merely 2.57% for a seven-phase VSI and so on.
In quasi six-phase machines with isolated neutral points supplied by two three-phase VSIs, the same approach of harmonic injection is employed by Bojoi et al (2002) and Siala et al (2003). In this approach two sets of 3rd harmonics are injected in the leg references of the two inverters and are termed here as double zero sequence injection scheme. Two three-phase inverters are controlled independently by two three-phase identical modulators employing the injection of two three-phase zero sequence waveforms. The linear modulation is extended to 15.47% as in case of a three-phase machine. The main attraction of carrier-based PWM method is ease of their implementation especially in high phase numbers such as 15-phase inverters, as the number of space vector in this case would be 32768. Thus implementation of space vector PWM would be highly complex. Carrier-based PWM is also used by Takami and Matsumoto (1993) to control a nine-phase machine with three isolated neutral point. An optimum pulse pattern is generated which yield better harmonic performance compared to conventional carrier-based PWM.

Carrier-based PWM scheme is also implemented successfully by Iqbal et al (2006) for controlling two series-connected five-phase machines supplied by a single voltage source inverter. The single VSI supplying series-connected multi-phase machines require to generate multi frequency output with different phase, magnitude and frequency. It is possible to utilise the advantage of harmonic injection in such applications as well as demonstrated by Iqbal et al (2006).

into the first α-β plane, while all the other harmonics map into the other \( \frac{(n-3)}{2} \) planes. For instance, for a five-phase VSI, harmonics of the order \( 10k \pm 1, (k = 0, 1, 2, \ldots) \) map into the α-β plane and \( 10k \pm 3, (k = 0, 1, 2, \ldots) \) map into the \( x-y \) plane. In case of a seven-phase VSI, \( 14k \pm 1, (k = 0, 1, 2, \ldots) \) map into α-β plane and \( 14k \pm 5, k = 0, 1, 2, \ldots \) map into first \( x-y \) plane and \( 14k \pm 3, k = 0, 1, 2, \ldots \) map into the second \( x-y \) plane. These extra components are limited by machine leakage impedance hence they should be removed using PWM techniques.

The use of only largest length space vectors to implement SVPWM is derived from the concept of space vector PWM of three-phase VSI. The same approach is used by Toliyat et al (2000), Xu et al (2002) and Shi and Toliyat (2002) for a five-phase VSI where they have used only ten large length vectors. This method is seen to generate low order harmonic components. A method was devised by Silva et al (2004) to generate sinusoidal output voltages. They have used four active vectors and one zero vector to implement SVPWM for a five-phase VSI. An alternative approach was proposed by Iqbal and Levi (2006) to generate sinusoidal output. The basic requirement for producing sinusoidal output is to use \( (n-1) \) active vectors along with one zero vector in one switching period to generate sinusoidal output as demonstrated by Kelly et al (2003). A number of SVPWM methods are available in the literature for six-phase VSI for both symmetrical and asymmetrical configurations. The first proposal for a quasi six-phase VSI is proposed by Zhao and Lipo (1995) where vector space decomposition technique is used. The complete set of space vectors are decomposed into three sets of orthogonal planes. The four neighbouring active and one zero vector is selected and dwell time of each switch is formulated in such a way to suppress the low order harmonics. A comprehensive relationship between the space vector PWM and carrier-based PWM as applied to five-phase VSI is presented in Iqbal and Moinuddin (2009). It is shown that there exist explicit relationship between these two popular and commonly employed PWM schemes.

Another control technique called ‘Model predictive control (MPC)’ is gaining attention for application to multi-phase drive system. Although, MPC is generally applied for process control, their application to power electronics and drives is being recently explored [Rodriguez (2009)]. It is assumed that MPC will play a key role in effective control of power electronic converters and electric drives. However, their application to multi-phase drive system is also being considered recently [Iqbal et al (2009)].

Fedrico et al (2009) proposes one step modulation predictive current control method for the asymmetrical dual three-phase induction machine. The proposed current control
algorithm uses a predictive horizon of one sampling period. Based on the use of predictive model the control algorithm determines the switching state which minimizes the errors between predictive and reference state variables.

The space vector PWM of a symmetrical six-phase is reported by Correa et al (2003) and Dujic et al (2006). One specific feature of SVPWM for inverter with an even number of phases is that it possible to eliminate the instantaneous common mode voltage. One important difference between three-phase and multi-phase VSI is that the dc bus utilisation is poor in case of multi-phase inverters due to application of large and medium space vectors.

Space vector PWM for multi-phase inverters is inherently a multi dimensional problem as recognised by Duran and Levi (2006). A SVPWM for a five-phase VSI is developed for feeding two series-connected five-phase machines. However, the practical realisation of such problem is a tedious job. Vector space decomposition technique is a simple way of realising the SVPWM using equivalent two dimensional sub spaces.

The alternative to multi-phase VSI is the multi-level inverters, although the output is only three phases but the output voltage level is more than two and such inverters are suitable for driving high power loads. The control techniques of such inverters are once again carrier-based PWM and space vector PWM. However, the number of available space vectors is more compared to corresponding two level inverters, thus offering more control flexibility. A comprehensive comparison between carrier based and SVPWM for three-level inverter is presented by Wang (2002). The three-level SVPWM equivalent can be realised by carrier-based PWM using harmonic injection, while three-level sine triangle PWM can be realised by electing proper dwell time.

The machine type is irrelevant in the context of the concept of the multi-machine system developed here and the research described in this thesis applies equally to multi-phase induction, synchronous reluctance, permanent magnet and wound rotor synchronous machines. The only requirements are that the supply is current controlled, since vector control will be ultimately applied and that the machine can be regarded as having sinusoidal distributed windings.

Anees Mohd. et al (2009) proposed a new space vector PWM for \textit{n level} multi phase voltage source inverter by which two level inverters are translated to the switching vectors of the multilevel inverter by adding the centre of the subhexagon to the two level inverter.
Lopez et al (2009) proposes a SVPWM scheme for multilevel multi-phase inverter using switching state redundancy which permits to achieve different goals like extending the modulation index and reduce the number of switching.

Kaushik et al (2009) proposes PWM scheme for minimising the rms torque ripple in inverter fed induction motor drive subject to a given average switching frequency of the inverter. This is a combination of optimal continuous and discontinuous modulation. The proposed method reduces the torque ripple by about 30% of the rated speed compared to conventional SVPWM.

Tsung (2009) proposes dual modulator compensation PWM technique for parallel connected three-phase inverter using space vector modulation. The magnitude and phase angle of three-phase inverter can be adjusted to control power sharing. This paper provides detailed analysis of the zero sequence circulating current and proposes novel dual modulator compensation technique for eliminating the zero sequence circulating current caused by the power sharing control system.

Jones et al (2009) analysed the parallel connected multi-phase multi-drive system with single inverter supply. This shows that it eliminate the shortcoming of the series arrangement, with the subsequent development concentrating on the two motor five-phase drive system. It is shown that parallel connected multi-motor multi drive represents advanced example of well known analogy between series and parallel connection. However, parallel connection suffers from a number of serious shortcomings that will prevent its application in industry.

A literature review, provided in this chapter, has surveyed the state of the art in all the areas relevant for the research undertaken in the thesis. The advantages of multi-phase machines over their three-phase counterpart were highlighted and the methods for a multi-phase drive control were surveyed.

This research aims to develop a multi-phase multi-machine drive that allows for independent high performance control of each machine in the set, while using a single multi-phase inverter as the supply. In order to explain the concept of this system, mathematical modelling of an $n$-phase machine is elaborated next.