PWM TECHNIQUES FOR CONTROL OF DUAL-INVERTER SUPPLIED SIX-PHASE DRIVES

FAZLLI PATKAR

A thesis submitted in partial fulfilment of the requirements of Liverpool John Moores University for the degree of Doctor of Philosophy

November 2013

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ABSTRACT

Among the different multiphase ac drive solutions, one of the most widely reported in the literature is the six-phase machine. The machines can be realised into two different configurations, symmetrical and asymmetrical. For the symmetrical configuration, the stator winding consists of two sets of three-phase windings that are spatially shifted by 60° where spatial displacement between any two consecutive phases is the same and equal to 60°. For the asymmetrical configuration, the two sets of three-phase windings are spatially shifted by 30°. As a result, the spatial shift between consecutive phases becomes non-equidistant.

In this thesis, modulation techniques for both symmetrical and asymmetrical six-phase machines are investigated. The machines are configured in open-end winding configuration where both ends of the stator winding are connected to separate isolated inverters in a topology known as dual-inverter supply. Compared to conventional single-sided supply topology where one end of the winding is connected to an inverter while the other side is star-connected, some additional benefits are offered by the dual-inverter supply topology. First, fault tolerance of the drive is improved, since the supply is realised with two independent inverters. In case one of the inverters is faulted, the other can continue to provide power to the machine. Second, the same phase voltages can be achieved with half the dc-link voltages on the two inverter inputs compared to the single-sided supply, which can be useful in applications such as electric and hybrid electric vehicles and medium sized ships, where the dc voltage levels are limited. Further, due to the nature of the topology, additional diodes and capacitors like in the Neutral Point Clamped (NPC) and Flying Capacitor (FC) VSIs are not required. The latter results in a further advantage - capacitor voltage balancing techniques are not required.

Two pulse width modulation (PWM) techniques for control of the dual-inverter supplied six-phase drives are proposed in this thesis. The first is a reference sharing algorithm where the inverters are modulated using reference voltage that is shared equally and unequally between the two modulators. For both symmetrical and asymmetrical six-phase drives, a better performance, in term of total harmonic distortion (THD) of phase voltage is obtained when the reference is shared unequally between the two modulators. The second technique is carrier-based modulation where the modulation of the two inverters is determined by the disposition of the carrier signals. Three variations of carrier signals disposition are investigated namely; the phase disposition (PD-PWM), alternate phase opposition disposition (APOD-PWM) and phase-shifted PWM (PS-PWM). For the symmetrical six-phase drive, the best phase voltage and current THDs are obtained using APOD-PWM while for asymmetrical six-phase drive, the APOD-PWM produces the worst current THD despite having the best voltage THD among the three methods.

All the developed modulation techniques are analysed using simulations and experiments undertaken using a laboratory prototypes. The waveforms and spectra of phase voltage and load current obtained from the simulation and experimental works are presented in this thesis together with the THD of both the voltage and current over entire linear modulation range.

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ACKNOWLEDGEMENT

In the name of Allah, the Most Gracious and the Most Merciful

Alhamdulillah, all praises to Allah for the strengths and His blessing in completing this thesis.

First of all, I would like to acknowledge the Malaysian Government and Universiti Teknikal Malaysia Melaka for giving me the opportunity and financial support to pursue my PhD at Liverpool John Moores University, United Kingdom.

My deepest gratitude goes to my supervisors, Prof. Emil Levi and Dr. Martin Jones, for their invaluable guidance, advices and support throughout the duration of this study. Without their guidance and persistence help, this thesis would not have been possible.

My sincerest appreciation goes to my colleagues, in particular Dr. Wahyu Satiawan, Dr. Nando Bodo, Dr. Obrad Dordevic, Lim Chee Shen, and Chee Han Seng for their help, idea and support. Thanks for the friendship and memories and I consider it an honour to work with all of you.

My special appreciation goes to my beloved parents, Haji Patkar bin Haji Tamsir and Hajjah Siti Isyah binti Haji Wagiran, for their endless love, prayers and encouragement. I am also greatly indebted to my beloved wife, Cik Sapiah binti Che Khalib and also my children Nur Izzatun Nadhirah and Muhammad Zharith Fakhri for their love, prayers and support.

Last but not least, I wish to express my sincere thanks to all those who have one way or another helped me in making this study a success.

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LIST OF PRINCIPAL SYMBOLS

a	Number of phases for each machine sub-winding.
$a, b, c, \ldots, n$	Phases of the machine/machine or used in subscript to associate the principal symbol with a certain phase.
$A, B, C, \ldots, N$	Inverter legs in general or used in subscript to associate the principal symbol with a certain leg.
f	Frequency.
f_s	Switching frequency.
i	Current.
k	Number of machine sub-winding.
l	Number of levels of the inverter voltage output.
L	Inductance.
m	Number of cells for multicell inverter.
M	Modulation index; an added subscript identifies association with a particular inverter.
n	Number of phases of the machine (or the inverter).
N	Neutral points of the machine/machine or the negative rail of the dc bus; indices 1 and 2 refer to a particular inverter.
N_{sw}	Number of switching state combinations.
R	Resistance.
t	Time.
T	Times of application (or dwell times) of space vectors, where a subscript identifies association with a particular space vector.
T_s	Switching period.
v	Voltage.
V	Space vector, where a subscript identifies association with a particular space vector of switching state combination.
V_{dc}	dc bus voltage; an added sub-script identifies association with a particular inverter.
$(\alpha\text{-}\beta)$	2-D plane with torque producing quantities.
$(x\text{-}y)$	2-D planes with none-torque producing quantities.
$(0_+\text{-}0_-)$	2-D planes with none-torque producing quantities.

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v^*	Voltage reference; a subscript identifies association with a particular inverter or phase voltage.
$\underline{v}^*$	Reference vector.
$\underline{v}$	Space vector groups in (α-β) and (x-y) planes, where a subscript indicates particular amplitude of the space vector group. An added subscript denotes the numbering of space vectors in each group.
v_z	Space vectors groups in (0_+-0_-) axes or space vectors of 0_--components, where a subscript indicates particular magnitude of space vector group. A superscript defines association with a particular inverter.
α	Phase delay angle.
θ	Instantaneous reference space vector position.
ρ	Control variable.
ω	Angular velocity.

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LIST OF USED ABBREVIATIONS

ac	Alternating current
APOD-PWM	Alternate phase opposition disposition PWM
COTS	Commercial-off-the-shelf
CSI	Current Source Inverter
CHB	Cascaded H-Bridge
dc	Direct current
DSP	Digital Signal Processor
ERS	Equal Reference Sharing
FC	Flying Capacitor
FFT	Fast Fourier Transformation
LS-PWM	Level-shifted PWM
MMF	Magneto-motive Force
MV	Medium voltage
NPC	Neutral Point Clamped
PWM	Pulse Width Modulation
rms	Root mean square
PD-PWM	Phase disposition PWM
POD-PWM	Phase opposition disposition PWM
PI	Proportional Integral
p.u.	Per-unit
PS-PWM	Phase-shifted PWM
SPWM	Sinusoidal Pulse Width Modulation
SVPWM	Space Vector Pulse Width Modulation
THD	Total Harmonic Distortion
URS	Unequal Reference Sharing
VSD	Vector Space Decomposition
VSI	Voltage Source Inverter
2D	Two-dimensional

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Chapter 1

INTRODUCTION

1.1 Preliminary considerations

Higher power demands on converters and drives are continuously being imposed by industrial users. The reasons for this are the requirements to reach higher production rates, cost reduction (large-scale economy), improved efficiency, etc. Available mature drive topologies, which are mainly based on two-level inverters and three-phase machines, are currently unable to meet the high power demands due to the lack of availability of semiconductor devices that possess the required high current carrying and voltage blocking capability. Since the available semiconductor devices (which are currently up to 6 kV and 6 kA [Franquelo et al. (2010)]) can only be used for limited power applications, alternative solutions have to be devised for higher power industrial applications in the region of tens of megawatt.

High power demands are currently met by using two different approaches. The first approach is to continue to use the three-phase machine, but the per-phase power of the machine is distributed among a higher number of semiconductor devices than the number normally used in a two-level inverter. Such an inverter is known as multilevel inverter, and it produces output leg voltage with more than two levels. Multilevel inverters produce a better quality of output voltage waveform, but the implementation requires a higher number of semiconductor devices; hence request for more complex switching strategy. Nevertheless, various multilevel inverter topologies have been reported for various high power industrial applications such as traction, mining, automotive, renewable energy, adjustable speed drives and uninterruptible power supply [Franquelo et al. (2008)].

In the second approach, the high power demand is met by utilising a multiphase machine, which is a machine with stator winding consisting of more than three phases. The idea is to divide the total power across more phases, so that a reduced per-phase power rating can be achieved, hence allowing the usage of the currently available power semiconductor devices. As the number of phases increases, higher power demands can be

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meet. For example, a six-phase winding has been used for a 25 MW synchronous motor drive [Zdenek (1986)] while a nine-phase winding has been utilised for a 36.5MW ship propulsion drive [Gritter et al. (2005)]. Another example is utilisation of a fifteen-phase 19MW induction motor drive for military ship application [Benamatmane and McCoy (1998)].

Certain aspects however, regarding the utilisation of multiphase drives for high power application, such as the required converter topology, converter control strategy, and the machine construction, ask for significant modifications of the methods and techniques that are conventionally applied to the three-phase drives. In terms of the construction of the multiphase machine, the phase number of a stator winding can be selected either as an odd number or as an even number. Different winding arrangements can be made, and in general the winding can be realised as a symmetrical or asymmetrical configuration [Levi et al. (2007)]. Machine with a prime number of phases (5, 7, 11, 13 and etc) can only be realised using a symmetrical configuration, and the stator windings are connected to a single neutral point. For this configuration, a spatial displacement between any two consecutive phases is always equal to $\alpha = 2\pi/n$, where n is the number of phases. Examples of such a machine are mainly reported for five-phase machines [Shuai and Corzine (2005), Ward and Härer (1969)] and seven-phase machines [Casadei et al. (2010), Grandi et al. (2006), Khan et al. (2009)].

As for a machine with an even phase number (4, 6, 8, 10 and etc) or with an odd composite phase number (9, 15, 21 and etc), the arrangement of the stator windings can be realised in at least four different ways. Consider a machine that has an $n = ak$ number of phases with $a = 3, 5, 7 \ldots$ and $k = 2, 3, 4 \ldots$ For symmetrical configuration, with $\alpha = 2\pi/n$, the complete winding can be configured to have k sub-winding with a phases each. Alternatively, the windings can also be constructed as asymmetrical configuration, where the first phases of the k sub-winding are spatially displaced by $\alpha = \pi/n$. For both symmetrical and asymmetrical configurations, the windings could either be connected to a single neutral point or to k isolated neutral points. Multiphase machine, having phase number equal to a multiple of three, are regularly considered for such configurations. For example, a symmetrical configuration with winding connected into a single neutral point is reported for six-phase machines [Dujic et al. (2007a), Kianinezhad et al. (2005)] and nine-phase machines [Dujic et al. (2007b), Grandi et al. (2007b)], while windings connected to multiple neutral points are reported for six-phase machine (with two neutral points) [Correa et al. (2003b)], nine-phase machine (with three neutral points) [Grandi et al.

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(2007a)] and fifteen-phase machine (with five neutral points) [Youlong et al. (2007)]. For the asymmetrical configuration, multiphase machines with two isolated neutral points are the most common for six-phase machines [Bakhshai et al. (1998), Gopakumar et al. (1993), Hadiouche et al. (2006), Marouani et al. (2008), Prieto et al. (2010), Zhao and Lipo (1995)]. Also, an example of a machine with windings connected to multiple neutral points has been reported for nine-phase machine (with three neutral points) [Steiner et al. (2000)]. Next, multiphase machine can also be realised by using multiple sets of five-phase windings. Such a configuration, for example, is reported for fifteen-phase machine [Benamatmane and McCoy (1998)].

One particular even phase number, very frequently considered in the literature, is six. In this project, the scope of research is focused towards the development of PWM techniques for six-phase machines, where both asymmetrical and symmetrical winding configurations will be considered. The windings of the machine are excited by using inverter topologies that are able to produce multilevel voltage waveforms. The supply of the machines is obtained from two two-level inverters in so-called open-end winding configuration.

In what follows a brief review of various multiphase variable speed drive aspects is provided. The emphasis of the review is placed mainly on the current state-of-the-art in the area of six-phase drives and also multiphase drives that have a composite number of phases.

1.2 An overview of PWM control of multiphase drives

Multiphase drives, although known for many decades, have started to attract greater attention of researchers and industry worldwide only relatively recently. Multiphase drives are at present considered as serious contenders for specialised applications, where high reliability and high power ratings are required, such as electric ship propulsion [Gritter et al. (2005), Parsa and Toliyat (2005)], locomotive traction [Abolhassani (2005), Steiner et al. (2000)], industrial high power applications [McSharry et al. (1998)], electric and hybrid-electric vehicles [Bojoi et al. (2005), Parsa et al. (2005)] and more-electric aircraft [Atkinson et al. (2005)].

An upsurge in interest in multiphase drives has been driven by several benefits of multiphase machines, which include higher torque density, lower per-phase power handling requirement, improved reliability, increased fault tolerance, improved noise characteristics and greater efficiency [Levi et al. (2007), Parsa (2005)]. Different types of

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multiphase machines have been developed, designed and studied. These include induction and synchronous machines having stator windings with different number of phases where five, six and seven are the most dominant ones. Thus an opportunity exists to explore different control strategies that are best suited for a given application [Levi (2008)]. Detailed mathematical models of multiphase machines have been derived and this, combined with the rapid development of digital signal processors and power electronic components, has enabled investigation and implementation of numerous control methods for multiphase machines [Levi et al. (2007)].

Utilisation of multiphase machines in industrial applications is possible due to the fact that an ac machine, when used in a variable speed drive system, is not connected directly to the utility supply. Instead, there is an interface between the utility supply and the machine, a power electronic converter. The converter can easily provide the required number of phase voltages (with the necessary phase difference) that matches the number of machine's stator winding phases. The converter is most frequently an inverter, and inverter that produces more than three-phase output is normally referred to as a multiphase inverter.

In the pre-PWM era and early days of multiphase machines, multiphase inverter was switched at a fundamental frequency. Six-step mode of operation of three-phase inverter inevitably produces low frequency torque ripple and at the time the utilisation of multiphase machines was considered as one approach to solve the problem. A six-phase induction machine, constructed based on asymmetrical stator winding configuration with two isolated neutrals, was extensively investigated in order to push the harmonics to higher frequencies. The six-phase supply of the machine was normally obtained by means of two three-phase voltage source inverters (VSI) [Abbas et al. (1984), Nelson and Krause (1974)] or by two three-phase current source inverters (CSI) [Gopakumar et al. (1984)].

When the era of PWM started, this advantage became less important since the harmonics can now be effectively controlled by using a PWM technique. However, for very high power applications, in order to maintain low switching losses, this advantage is still relevant due to the limitation of the switching frequency of currently available semiconductors. Research on PWM techniques for multiphase inverters has also gradually increased, particularly for low and medium power applications.

In the following sub-sections, PWM techniques, applicable to two-level and multilevel multiphase drives, are discussed.

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1.2.1 Two-level inverter supplied multiphase drives

At present, multiphase variable speed drives are invariably supplied from two-level multiphase inverters, which are controlled using appropriate PWM techniques. Two main groups of PWM techniques are usually considered which are carrier-based PWM and space vector PWM (SVPWM).

For multiphase inverters, the simplest way to implement the carrier-based PWM technique is by comparing a set of sinusoidal reference voltages (with appropriate phase difference) with a triangular carrier waveform. The technique is normally known as sinusoidal PWM (SPWM) and the output from the comparison is used to generate switching signals for the semiconductor switches in each inverter leg. Further, the carrier-based PWM is usually implemented with an injection of appropriate harmonics into the reference signals. Similar to three-phase inverter with the third harmonic injection, it is also possible to improve the utilisation of the dc bus voltage of multiphase inverters (without moving into over-modulation range) by injecting the appropriate zero-sequence harmonics into the reference voltages. This technique can be easily extended to multiphase inverters with an odd number of phases and single neutral point. However, the effect of improvement that can be achieved regarding dc bus voltage utilisation is weakened as the number of phases increases [Iqbal et al. (2006)].

The principle of carrier-based PWM with zero-sequence harmonic injection can also be utilised for asymmetrical multiphase machines that have a number of phases that is a multiple of three. The machines are configured to have a number of three-phase sub-windings and each sub-winding needs to be connected to an isolated neutral point and supplied by a three-phase inverter. Such an implementation has been realised for an asymmetrical six-phase induction machine with two isolated neutral points, constructed by using two sets of three-phase windings. Zero-sequence harmonics are injected into the reference voltage of each set [Bojoi et al. (2002)], resulting in the same improvement of the dc bus voltage utilisation as in the three-phase inverter.

For SVPWM techniques, the set of sinusoidal reference voltages is represented as a reference voltage vector that needs to be generated by the inverter. Each switching state combination of inverter legs produces a different voltage vector. By using SVPWM, a certain number of space vectors will be used over one switching period, each with an appropriately calculated dwell time, in order to produce output voltage vector that has an average value equal to the reference.

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Basically, compared to SVPWM, carrier-based PWM technique is simpler and more straightforward to implement, since the modulator just has to compare the carrier and the reference signals. This advantage becomes more and more pronounced as the number of phases increases [Dong et al. (2008a)]. Implementation of carrier-based PWM has been considered for a nine-phase inverter [Dong et al. (2008a)] and a fifteen-phase inverter (with three isolated neutral points) [Benamatmane and McCoy (1998)]. For SVPWM implementation, the number of switching state combinations for two-level multiphase inverter can be calculated as $N_{sw} = 2^n$. Therefore, compared to a three-phase inverter where the number of switching states is $2^3 = 8$, the process of selecting the appropriate space vectors and devising SVPWM from, for example, $2^{15} = 32768$ switching state combinations for fifteen-phase machine is obviously not an easy task.

For a machine with a single neutral point, the other advantage of the SVPWM technique, which relates to dc bus voltage utilisation, also becomes less significant for machines with high number of phases. While SVPWM can improve the dc bus voltage utilisation of a three-phase inverter by 15.47%, the improvement that can be achieved in a nine-phase inverter is 1.54% and in a fifteen-phase inverter is merely 0.55% [Dong et al. (2008a)]. The same improvements in the dc bus voltage utilisation can be obtained by means of carrier-based PWM methods if zero-sequence injection is used. However, it is important to notice that the dc bus utilisation in multiphase VSI supplied drives with a composite stator phase number varies depending on the winding configurations (symmetrical or asymmetrical) and also the number of neutral points [Dujic et al. (2010)]. For example, asymmetrical six-phase drive with stator winding of the machine connected to a single neural point has a maximum dc bus voltage utilisation of 103.53% while with stator winding connected to two isolated neutral points, the maximum dc bus voltage utilisation is 115.47%. For symmetrical six-phase drive with machine's stator winding connected to a single neutral point, no increase of dc bus voltage utilisation is obtained, i.e. the utilisation is 100%.

By and large, the existing research in connection with SVPWM control of two-level inverters is mainly related to multiphase machines with a lower number of phases such as five, six, seven, and nine. For these machines, the SVPWM approach is in general analysed more frequently than the carrier-based PWM because it offers a better insight into the properties of multiphase drives. SVPWM techniques for two-level multiphase inverters have been widely applied for six-phase VSIs, in both symmetrical configuration [Correa et al. (2003a), Dujic et al. (2007a), Kianinezhad et al. (2005)] and asymmetrical configuration

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[Bakhshai et al. (1998), Gopakumar et al. (1993), Hadiouche et al. (2006), Marouani et al. (2008), Prieto et al. (2010), Zhao and Lipo (1995)], as well as for nine-phase VSIs [Dujic et al. (2007b), Grandi et al. (2007a), Grandi et al. (2007b), Kelly et al. (2003)]. SVPWM approach for fifteen-phase inverter is rarely investigated, and one example of such a study is reported in [Youlong et al. (2007)]. A comprehensive analysis of the relationship between carrier-based PWM and SVPWM techniques for multiphase inverters has been reported for a five-phase inverter [Iqbal and Moinuddin (2009)].

1.2.2 Multilevel inverter supplied multiphase drives

Multilevel inverters operate by synthesising a near-sinusoidal output voltage from several dc voltage levels, usually obtained from capacitors as voltage sources. As the number of levels increases, the synthesised output waveform has more and more steps. Hence a staircase waveform is produced that approaches the desired sinusoidal waveform. Multilevel inverters have some distinct advantages compared to two-level inverters. They lead to higher power capability, without requiring high voltage rating of semiconductor devices. Besides that, multilevel inverters also produce low harmonic distortion, reduced switching frequency, increased efficiency and good electromagnetic compatibility. However, as the number of levels increases, the complexity of the control circuit also increases.

Since the birth of the first multilevel three-phase inverter about 30 years ago [Nabae et al. (1981)], extensive research on multilevel inverters has been carried out worldwide. Today, multilevel inverters are considered as one of the most viable solutions for high-power and high-power quality demanding applications [Rodriguez et al. (2009)]. Over the years, a number of different types of multilevel inverter topologies have been developed. The most frequently considered and well established topologies are diode-clamped inverter (which is usually also called neutral point clamped inverter (NPC)), flying capacitor inverter (FC) and cascaded H-bridge inverter (CHB) [Wu (2006)].

Today, multilevel inverters have been commercialised by many manufactures, with variety of control methods in use, in order to cater for different markets [Franquelo et al. (2008)]. NPC VSIs have become a mature solution for high power ac motor drive applications such as conveyors, pumps, fans and mills, which offer solutions for various industries such as oil and gas, power generation and distribution, mining, water, metal and marine [Klug and Klaassen (2005)]. On the other hand, FC VSIs have found specific applications for high-power-bandwidth high-switching-frequency applications such as

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medium-voltage traction drives [Meynard et al. (2002)]. As for CHB VSIs, they have been successfully commercialized for very high power and power quality demanding applications, due to their series expansion capability. Some examples of areas of application for CHB VSIs are reactive power compensation [Dixon et al. (2005)], electric vehicles [Zhong et al. (2006)] and photovoltaic power supplies [Naik and Udaya (2005)].

As has been explained at the beginning of this chapter, the demand for high power industrial applications is currently met either by using multilevel inverters or by using multiphase drives. Since both methods are able to produce a high output power (by using only medium power semiconductor devices), combination of multilevel inverters and multiphase drives is expected to be able to produce higher output power than any of the two can individually, while at the same time retaining the advantages offered by each of them. For this reason, an initial attempt to integrate the multilevel inverter and multiphase machine has been carried out and the advantages of combining both topologies have been described in [Lu and Corzine (2005)].

The benefits of combining multilevel inverters and multiphase drives have lead to interest in investigation of multilevel multiphase drives. Currently, there are two different arrangements for multilevel multiphase drives. The first arrangement is so-called a single-sided supply. One end of the machine's multiphase winding is connected to a multilevel inverter, while the other end is star-connected. The second arrangement is a dual-inverter supply. Here, both ends of the machine windings are connected to either two-level or multilevel inverters. This arrangement is also known as an open-end winding topology. The two inverters that are connected at both ends of the open-end windings can have an equal or different number of levels.

The number of switching state combinations for multilevel multiphase inverter supply depends on the number of inverter's phase legs n (i.e. machine's phases) and the number of inverter's output voltage levels l. For a single-sided topology, the number of switching states can be calculated as $N_{sw} = l^n$. For example, if the number of output voltage levels is three, a three-phase inverter has $3^3 = 27$ switching state combinations, while a five-phase inverter has $3^5 = 243$ switching state combinations and a six-phase inverter has $3^6 = 729$ switching state combinations. Therefore, with an increase in the number of voltage levels, the difference between the number of switching state combinations for three-phase and multiphase inverters becomes bigger and bigger.

For an open-end winding topology, both ends of the machine's winding are connected to two different inverters. Therefore, the total number of switching states is

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multiplication of the number of switching states produced by each inverter, i.e. $N_{sw} = l_1^n \ l_2^n$, where indices 1 and 2 refer to the first and the second inverter. If the open-end winding is supplied by two three-level inverters, the number of switching states for an open-end winding three-phase drive is 3^3 x 3^3 = 729, for a five-phase drive 3^5 x 3^5 = 59,049, while for an open-end winding six-phase drives it is 3^6 x 3^6 = 531,441. This is much higher than the number of switching states for the single-sided supply topology. The abundance of switching states provides some advantages for drives with the open-end winding configuration. One of them is that a higher number of output voltage levels can be achieved, where for example utilisation of two two-level inverters produces the same output voltage as a three-level inverter in a single-sided topology [Shivakumar et al. (2001a), Stemmler and Guggenbach (1993)]. The selection of which switching states are to be used will also have an effect on the performance of the multilevel multiphase drive in terms of harmonic content, common mode voltage, dc bus voltage utilisation, etc.

Multilevel multiphase drives, in a single inverter or dual-inverter supply topology, always possess a higher number of switching states than the traditional two-level multiphase drives. However, some of the switching states lead to the same voltage vectors. Therefore, for both topologies, the total number of voltage vectors is always less than the number of switching states, meaning that there are redundant switching states (the difference between the total number of switching states and the number of different space vectors). These redundant switching states are very beneficial, especially for determining switching sequence that could minimise the switching losses of the inverters.

PWM techniques for multilevel multiphase drives, implemented by using single-sided and dual-inverter supply, are reviewed next.

1.2.2.1 Multilevel multiphase drives with single-sided supply

For a single-sided configuration, an initial attempt to integrate a multilevel inverter with a multiphase machine was carried out for a five-phase NPC VSI [Lu and Corzine (2005)]. The inverter is modulated by using a SVPWM strategy and it has been found that, compared to a two-level VSI supplied five-phase drive, torque ripple in three-level five-phase system can be reduced significantly, due to the abundance of space vectors. However, the basic rule which says that the number of applied vectors must equal the number of phases, was not respected. Instead, the nearest three vector concept was used, as

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in three-phase drives, leading to uncontrollable harmonics in the stator current that belong to the second plane.

More research has followed, mainly based on the SVPWM approach. Investigations and new developments of SVPWM for three-level five-phase NPC VSI have been supported by simulation [Song et al. (2006)] and by experimental [Gao and Fletcher (2010)] results. Development of a general SVPWM scheme for multiphase multilevel VSIs, including implementation of SVPWM for five-level five-phase CHB VSI, has been reported in [Lopez et al. (2008)] and [Lopez et al. (2009)].

An attempt to develop a SVPWM scheme for asymmetrical six-phase induction machine, by means of two five-level three-phase NPC VSIs, is described in [Oudjebour et al. (2004)]. Further, a SVPWM scheme has also been developed for six-phase synchronous motor, supplied by two three-level three-phase NPC VSIs having the same dc bus capacitor [Yao et al. (2006)].

Research on multilevel multiphase drives that utilise carrier-based PWM has been carried out to a lesser extent. One example, related to asymmetrical six-phase induction machine, is carried out by using two five-level three-phase VSIs [Oudjebour and Berkouk (2005)]. The switches of each inverter's leg are controlled based on the signal generated by comparing the sinusoidal reference voltages with four triangular carrier signals.

Multilevel multiphase drives, based on single-sided supply, are at present already considered for a few industrial applications. One example is the supply of 36.5MW ship propulsion drive from four- or five-level nine-phase NPC VSI [Gritter et al. (2005)]. A nine-phase transformerless ac traction drive supplied by three three-level three-phase VSI bridges has been discussed in [Steiner et al. (2000)]. A rather unusual application of multilevel multiphase drives has also been reported, where the drive has been considered for micro-electromechanical systems (MEMS) [Neugebauer et al. (2004)].

1.2.2.2 Multilevel multiphase drives with dual-inverter supply

Multilevel multiphase drives with dual-inverter supply topology have several advantages, compared to the single-sided topology. One advantage is that the effect of a multilevel supply can be achieved by using two-level inverters. Besides that, if one of the inverters is inoperable, the system can be reconfigured to be driven by a single inverter [Grandi et al. (2011)].

Dual-inverter supply topology for machines with open-end windings was initially introduced for three-phase drives [Stemmler and Guggenbach (1993)]. Two two-level VSIs

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have been used, with supply coming from isolated dc bus voltage sources. This arrangement effectively operates as a three-level VSI equivalent in single-sided supply topologies. A number of alternative solutions have been also investigated. These include use of three-level inverter in conjunction with a two-level inverter at two winding sides, with a suggestion that one of the sources can be a capacitor that supplies only reactive power [Kawabata et al. (1996)]. The dc supplies have a 2:1 ratio and the resulting feeding scheme can emulate four-level equivalent of single-sided supply inverter. By using asymmetrical dc voltage sources (i.e. voltage ratio different from unity), two two-level inverters can produce voltages which are identical to those generated by three-level and four-level inverters in single-sided supply mode [Corzine et al. (1999)].

Although numerous versions of dual-inverter supply for three-phase drive systems have been reported, implementation of this topology in the multiphase drives has started to gain momentum only recently. Such an attempt was initially carried out for asymmetrical six-phase machine fed by four two-level three-phase VSIs [Mohapatra et al. (2002)], [Mohapatra and Gopakumar (2006)]. However, the goal of the research was harmonic elimination, rather than multilevel operation. Hence the created output voltages are not those that would result with a multilevel supply.

In the last few years, several modulation strategies that are able to create multilevel output voltage, produced in an open-end winding multiphase configuration, have been reported. Two main types of drive topology have been considered. The first is to use two two-level inverters to supply the open-end winding machine with five [Bodo et al. (2011b), Bodo et al. (2012b), Jones et al. (2012), Levi et al. (2012), Satiawan (2012)], six [Jones et al. (2013), Patkar et al. (2012)], seven [Bodo et al. (2011a)] and nine [Bodo et al. (2013a)] phases. The second topology is to utilise four two-level inverters where asymmetrical machine with six phases is the main focus of the study [Grandi et al. (2010a), Grandi et al. (2010b)]. The current state-of -the-art regarding the control of multiphase open-end drive is summarised in [Levi et al. (2013)].

The control strategies and drive topologies for the multiphase drives which are discussed throughout Section 1.2 are developed based on strategies and topologies that have been explored before for the three-phase drives. The correlation between the developed drive topologies for the multiphase and three-phase drives and the advantages and disadvantages of each topology are depicted in Fig.1.1.

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Two-level three-phase drives

Advantages:

- Standard drive found in industry.
- Readily available off the shelf product.
- Long established and well understood.

Disadvantages:

- Not suitable for medium and high power application.
- Not fault tolerant without additional hardware.

Two-level multiphase drives

Advantages:

- Suitable for medium and high power application
- High torque density.
- Lower per phase power.
- Better fault tolerance.

Disadvantages:

- Bespoke, not readily available off the shelf inverter/machine.
- More complicated control algorithm.
- Increased number of sensors and cables.

Multilevel three-phase single-sided supplied drives

Advantages:

- Becoming standard solution for medium power applications.
- Readily available off-the-shelf product.
- Lower THD, reduced switching frequency leading to higher efficiency.

Disadvantages:

- Increased hardware complexity, leading to reduced reliability.
- More complex control required.

Multilevel multiphase single-sided supplied drives

Advantages:

- A good solution for medium/high power applications.
- Lower THD, reduced switching frequency leading to higher efficiency.
- High torque density, lower per phase power and better fault tolerance.

Disadvantages:

- Increased hardware complexity, leading to reduced reliability.
- More complex control required.
- Bespoke, not readily available off the shelf inverter/machine.
- Increased number of sensors and cables.

Multilevel three-phase dual-inverter supplied drives

Advantages:

- Application for medium power applications.
- Simpler and cheaper topology than standard single-sided topology.
- Lower THD, reduced switching frequency leading to higher efficiency.
- Increased fault tolerant capabilities
- Simpler control, no capacitor voltage balancing issues.

Disadvantages:

- Requirement of isolated dc supplies.
- More complex control.
- Both sides of terminals of the machine must be accessible.
- Increased cable requirement.

Multilevel multiphase dual-inverter supplied drives

Advantages:

- Application for medium/high power applications
- Simpler and cheaper topology than standard single-sided multiphase topology.
- Lower THD, reduced switching frequency leading to higher efficiency.
- Increased fault tolerant capabilities.
- Simpler control, no capacitor voltage balancing issues.
- High torque density, lower per phase power and better fault tolerance.

Disadvantages:

- Requirement of isolated dc supplies.
- More complex control.
- Both sides of terminals of the machine must be accessible.
- Bespoke, not readily available off the shelf inverter/machine.
- Increased number on sensors and cables.

Fig. 1.1: Research development in the area of multiphase VSI supplied drives.

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1.3 Research aim and objectives

The aim of the research is to develop PWM techniques for control of dual-inverter supplied six-phase machines with both symmetrical and asymmetrical winding configurations.

The goal of the research has been met by achieving a number of research objectives, which are the following:

1) Development of reference sharing algorithms for control of two six-phase two-level inverters based on open-end topology, using PWM techniques that initially developed for single-sided six-phase inverters.
2) Development of carrier-based PWM techniques for the control of six-phase machines, supplied by two two-level six-phase inverters.
3) Creation of computer simulation for the developed PWM techniques using MATLAB/Simulink software.
4) Implementation of the developed PWM techniques in the available laboratory rigs and experimental verification of theoretical findings.

1.4 Research contributions

This research constitutes a part of a wider research project, related to multilevel multiphase drive systems, which comprise four PhD theses. The work commenced with the first PhD [Satiawan (2012)] and continued with the subsequent two projects, [Bodo (2013)] and [Dordevic (2013)].

In principle, multilevel supply waveform can be realised using either a single-sided supply mode, with the multiphase machine having an isolated neutral point, or using dual-inverter supply in conjunction with an open-end winding topology. Further, a multiphase stator winding can be designed to have an odd prime number, an odd composite number or an even number of phases. The four projects are designed to cater for the two different supply options (single-sided mode and dual-inverter supply) and for different phase numbers.

In particular, [Satiawan (2012)] deals with an open-end winding topology of a five-phase machine and relies on utilisation of two two-level five-phase inverters. [Bodo (2013)] extends the work of [Satiawan (2012)] by looking at seven- and nine-phase drives in dual-inverter supply mode, using at each side two-level inverters, as well as the five-phase drives in various conditions not covered by [Satiawan (2012)]. Finally, [Dordevic

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(2013)] is intended to cover again odd phase numbers (the emphasis is on five and seven, with a possible extension to nine), but this time using a single-sided supply mode with a three-level NPC multiphase inverter.

It follows from the description above that the three current PhD projects all deal with odd phase numbers in either single-sided or dual-inverter supply mode. This project is therefore designed to cover dual-inverter supply modes, but for machines with even phase numbers. The emphasis in the research is placed on six-phase machines, where multilevel supply for both symmetrical and asymmetrical winding topologies of six-phase machines is investigated.

The contribution of the research is backed by the publications listed in Appendix 2.

1.5 Organisation of the thesis

This thesis is organised in eight chapters and two appendices.

Chapter 1 gives a brief review of various aspects of multiphase variable speed drives. Different arrangements of stator winding for the multiphase drives are explained and various inverter topologies and PWM control strategies for the drives are described. The emphasis of the review is placed mainly on the current state-of-the-art in the area of six-phase drive. Finally, the aim, objectives and originality of the research have also been stated.

Chapter 2 presents a literature review in the area of PWM control for the six-phase drive. PWM techniques for two-level six-phase drive are discussed first, followed by the PWM techniques for multilevel multiphase drives, covering both single-sided and dual-inverter supply topologies. Reviews of PWM techniques for the dual-inverter supplying open-end windings of three-phase drives are included for the sake of completeness of the literature studies.

Chapter 3 discusses space vector model of a two-level six-phase VSI fed asymmetrical machine with both two isolated neutral and single neutral points configuration. Then, several PWM techniques for two-level asymmetrical six-phase VSI with machine windings connected to two isolated neutral points are described. Simulation study has been conducted to analyse the performance. The investigated PWM techniques are as follows:

i. Carrier-based SPWM,
ii. Carrier-based PWM with double zero-sequence injection [Bojoi et al. (2002)],
iii. Conventional SVPWM [Gopakumar et al. (1993)],

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