Virtual Voltage Vector based Control Schemes for Five-phase Induction Motor Drives

A thesis submitted

in partial fulfillment for the award of the degree of

Doctor of Philosophy

by

Prasoon Chandran Mavila

Department of Avionics

Indian Institute of Space Science and Technology

Thiruvananthapuram, India

March 2024

Abstract

Multiphase motors have gained considerable attention over traditional three-phase motor drives due to benefits such as reduced current and voltage per phase for a given power rating, higher torque density, and increased fault tolerance. These advantages make them well-suited for high-power and safety-critical applications like ship propulsion, electric aircraft, and electric traction. However, there are many features of multiphase drives which have not been explored much for addressing some of the special requirements of such applications. In this context, the objective of the research work was to develop new control schemes for dual inverter fed multiphase induction motor drives with open-end stator windings, especially to address some of the important requirements of the drives used in applications that demand high reliability, fast dynamic response and operations over a wide speed range with limited DC voltage. The research work was mainly focused on five phase induction motor (FPIM) drives; though the control schemes developed can be easily extended to drives with higher number of phases.

A dual inverter-fed IM drive with open-end stator windings offers many advantages like the capability to generate multilevel voltage waveform across the motor windings, increased reliability, operation at reduced DC-link voltage for a given motor voltage thereby facilitating the use of switching devices with reduced voltage ratings, independent control of the two inverters etc. In addition, the dual inverter-fed IM drives with open-end stator windings facilitate elimination of common mode voltages thereby enabling a single DC source to power both inverters, and mitigation of problems due to common mode voltages. The availability of higher number of voltage vectors, higher redundant switching states and the capability to have decoupled control of the two inverters are some of the key features of dual inverter-fed five-phase open-end winding IM drives which are not explored much in the literature. The research work presented in this thesis from chapter-3 to chapter-7 carried out investigations on dual inverter-fed five-phase IM drives with open-end stator windings for developing high-performance control schemes for applications that demand operation of the drive in a wide speed range.

It is well known that the voltage space vector structure of a five-phase voltage source inverter (VSI) consists of two space vector subspaces, namely the fundamental plane and the auxiliary plane. Each switching state of a five-phase VSI maps to both these space

vector planes. Since the auxiliary plane harmonic voltages do not contribute to torque production in a distributed winding machine, they are not opposed by back EMF and can cause circulation of large harmonic currents and the consequent problems like increased losses and reduction in the utilization of the core for useful flux. The schemes proposed in this thesis addressed this issue and ensured that auxiliary plane voltages are nullified in average sense over a switching period. Another distinctive feature of all the control schemes for dual inverter fed FPIM drives proposed in this thesis is the higher DC bus utilisation compared to the conventional two-level inverter-fed FPIM drives.

A five-phase IM drive can have three possible stator winding configurations called star, pentagon and pentacle. The voltage appearing across the stator windings is 17% and 90% higher in pentagon and pentacle configurations respectively, compared to that in star configuration. This is an important feature of a FPIM drive which can be made use of for extending the constant power speed region of the drive since the operation at higher speed demands application of higher voltage across the motor windings to overcome the increased back EMF and voltage drop across the motor inductance at higher speeds. Chapter-3 of this thesis presents a novel voltage space vector based speed range extension scheme for dual inverter-fed FPIM drive with open-end stator windings to achieve virtual reconfiguration of winding connections for extending the speed far above the base speed without physically changing the winding connections and without field weakening. The proposed scheme nullified common mode voltage appearing across the windings thereby enabling a single DC source to power both inverters without causing circulation of common mode current.

At higher speeds voltage drop across the motor inductances will be significant mainly due to the increase in frequency and the consequent increase of motor reactance. Since this voltage drop is reactive in nature it can be compensated by a capacitor-fed inverter, without using a DC source. A dual inverter-fed five-phase open-end winding induction motor drive in which one the inverters is powered by a DC source and the other inverter is connected to a charged capacitor, is explored to develop a virtual voltage space vector based speed range extension scheme with series reactive voltage compensation, in chapter-4.

The concept of virtual line voltage space vectors realised by virtual reconfiguration of winding connections can be used for implementing high performance direct torque control (DTC) schemes suitable for applications demanding fast dynamic response. In chapter-5 of this thesis, the concept of virtual line voltage space vectors is explored further to develop different schemes to implement direct torque control of dual inverter fed five phase open-end winding IM drives powered from a single DC source. Virtual voltage vectors of three different magnitudes are generated to realise a five-level torque comparator based DTC scheme for reducing the torque ripple. Chapter-6 of this thesis proposes a DTC scheme with higher sector resolution to achieve smoother control of torque and flux. All the DTC schemes proposed in this thesis ensured that auxiliary plane harmonic voltages are nullified in a switching period.

One of the important features of the DTC schemes proposed in chapters 5 and 6 is the elimination of resultant common mode voltage (CMV) appearing across the motor windings which facilitated powering of both inverters from a single DC source. However, the individual VSIs were still generating alternating CMV varying identically at both the ends of the windings, even though the resultant CMV across the windings was nullified. It has been established that high frequency CMV generated by the inverters causes common mode leakage currents in the motor due to the existence of parasitic capacitances, leading to bearing currents, and electromagnetic interference. The motor bearing currents cause problems such as deterioration of the bearing lubricant, increased level of noise, vibration, and premature failure of the bearing. To address this issue a DTC scheme for FPIM drives with elimination of alternating common mode voltages and auxiliary plane harmonic voltages is proposed in chapter-7.

All the control schemes proposed in this thesis are validated through extensive simulations and then experimentally verified on a laboratory prototype under both transient and steady-state operating conditions. The proposed schemes were implemented using a digital signal controller with Texas Instruments DSP TMS320F28335 and AMD Xilinx XC3S200 FPGA.