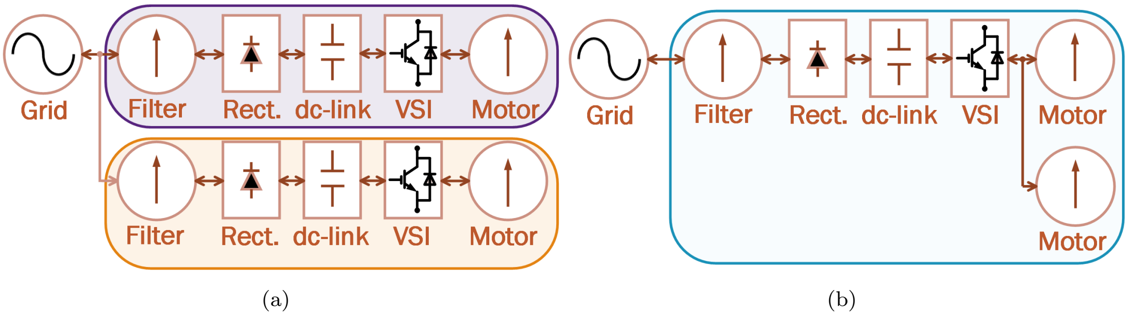
Chapter 1

Introduction

1.1 Background

Multi-drive systems are commonly used in applications that require the simultaneous operation of multiple mechanical loads, each with unique torque or speed demands. These systems typically comprise separate electric machines, each operating under distinct load conditions and controlled independently by dedicated voltage source inverters (VSIs). This traditional configuration enables full independent control of each motor. Dual-motor and multi-motor setups are widely deployed across various industrial sectors, including work machines [1], winders, rolling mills, cranes, escalators [2], textile machinery, paper processing, traction systems, and electric vehicles [3, 4, 5, 6, 7]. Their ability to provide precise and independent control of each motor makes them suitable for a broad range of applications. Conventionally, such systems use multiple VSIs, with each inverter driving a separate machine, as illustrated in Fig. 1.1(a). This architecture ensures control independence and allows each inverter to be optimized for specific power and performance requirements. To enhance cost-effectiveness and simplify system architecture, the parallel machine drive technique has been introduced. It eliminates redundant components such as input filters, rectifiers, controllers, inverters, and communication circuits. As a result, system complexity and cost are significantly reduced. It can also be called the mono-inverter dual-parallel (MIDP) system, shown in Fig. 1.1(b). MIDP systems have been proposed as a cost-effective solution where two motors share a single inverter and a common DC-link. A notable example is found in railway traction systems, where a single inverter is used to drive multiple induction motors connected in parallel [8, 9]. This configuration enhances power transmission efficiency, improves regenerative braking, and increases overall system



(a) (b)

FIGURE 1.1: Dual motor drive system. (a) Individual motor drive system. (b) MIDP motor drive system.

reliability. Moreover, it reduces the number of switching devices, lowers system cost, and leads to a more compact and efficient design. MIDP systems are particularly suitable when multiple motors need to be driven synchronously without requiring fully independent control [10, 11]. Despite these benefits, MIDP systems have seen limited adoption in both research and industry, primarily due to challenges related to synchronized speed operation and performance degradation compared to fully independent systems. Nevertheless, in applications where synchronized operation is acceptable, such as fans, pumps, electric traction, conveyor belts, and railway propulsion, parallel motor drives offer a practical and efficient solution.

To further address the limitations of conventional multi-drive systems, such as high component count and increased complexity, researchers have investigated reduced-switch-count inverter topologies. For example, a two-phase inverter topology using a split DC-link and only four switches was proposed in [12], and later, the B4 inverter was introduced as a low-cost alternative [13]. Another notable development is the five-leg inverter (FLI), in which one phase of each motor shares a common leg [14]. These innovative configurations aim to maintain satisfactory performance while significantly reducing the number of power semiconductor devices required. Among these innovations, the nine-switch inverter (NSI) stands out for its ability to reduce the number of power devices compared to the FLI. The NSI can replace traditional back-to-back converters and parallel inverter configurations in dual-motor drive systems [15], rectifier-inverter systems, uninterruptible power supplies [16], UPQC [17], and microgrids [18]. The NSI retains the essential functions of conventional parallel converters while using fewer switches, gate drivers, and control circuits, contributing to lower cost and system volume [19].

To enhance the performance of the nine-switch inverter (NSI), researchers have extended its architecture into multilevel configurations, leading to the development of several dual-output multilevel converter topologies. One notable topology is the three-level twin-drive inverter (TL-TDI) [20], which integrates a three-level NPC inverter with an NSI structure using 21 switches. While it offers reduced volume and cost, it suffers from limited switching states, poor DC capacitor voltage regulation, and increased conduction losses due to long current paths. To address these issues, a neutral-point piloted (NPP) version of the NSI was proposed in [21], supporting three to nine levels with 21 switches and 12 diodes, fewer than the conventional NPC converter. However, it still faces drawbacks such as reduced DC-link utilization and higher device ratings. In [22], finite control set model predictive control (FCS-MPC) was employed to achieve independent voltage control in dual outputs. Later, a reduced-switch-count dual-output T-type (RSC-DT) inverter was introduced in [23], using one less switch than the NPP based converter. In [24], the DO-T-TLC used sine PWM with DC offset to improve capacitor balancing but lacked redundant switching states. To overcome TL-TDI limitations, a dual-output NPC-based three-level inverter (DO-NPC-TLI) was introduced in [25] with 20 switches and 12 diodes. However, it limited the modulation index to 0.5 and required a higher DC-link voltage, complicating control and increasing input cost. A more flexible NPC-DO converter was proposed in [26], enabling independent control using two diodes and six switches per phase. Though it uses more components than a standard NPC, it extends the operating range, albeit with inaccessible switching states. In [27], a cascaded multi-output multilevel (CMOM) converter was developed by cascading two NSI legs, reducing switch count while maintaining output levels. A modified CMOM in [28] further reduced components, introduced in-phase disposition PWM (IPD-PWM), and a five-level dual-output variant (CDOM) was also presented. All the aforementioned reduced-switch-count topologies suffer from a limited operating region and constrained modulation index, primarily due to the series-connected configuration of their output terminals, which restricts the available switching states and voltage vector combinations.

1.2 Motivation

Constraints of modulation index and operating region arise from the inaccessibility of certain switching states, which negatively impact the modulation strategy, DC-link voltage utilization, and achievable output voltage levels. Specifically, in such topologies, the upper reference signal must always be greater than or equal to the lower reference to avoid generating invalid or conflicting switching states. To manage this, DC offsets are commonly introduced into the reference signals, which in turn limit the range of valid voltage vectors and create unavailable voltage levels for both outputs. This restriction leads to reduced modulation index, asymmetric output performance, and loss of independent control capability, especially under dynamic or unbalanced loading conditions. These drawbacks become even more critical in applications involving heterogeneous machines (e.g., IM + PMSM) or systems requiring variable phase angles and frequency decoupling.

Therefore, there is a clear need for a dual-output converter topology that eliminates this boundary region constraint and enables independent control of both output voltages, regardless of their amplitude, frequency, or phase angle. Such a converter would not only enhance the operational flexibility and control performance of dual-motor systems but also maintain the advantages of a reduced-switch-count design, paving the way for more practical, scalable, and efficient multi-machine drive solutions.

1.3 Major Contribution

This thesis makes three major contributions:

- Most of the existing dual-output converters have been analyzed with respect to their operating boundary region, switch count, and control complexity, and are characterized based on their overall performance and modulation capability.
- Design and development of a three-level dual-output converter for efficient power conversion and control.
- Design of a five-level dual-output converter, offering enhanced voltage control, complete region of operation and reduced harmonic distortion.
- Development of an improved five-level dual-output converter with further reduction in the number of switches.
- Implementation of independent control for two different motors powered by the dual-output three-level converter, ensuring precise and flexible motor operation.

1.4 Organization of the Thesis

The rest of this thesis is organized as follows:

1. Chapter 2 presents a comprehensive background on multilevel multi-output converters, emphasizing their topological features and highlighting the key limitations of existing designs.
2. Chapter 3 discusses the design and development of a three-level dual-output converter, including the proposed modulation technique.
3. Chapter 4 describes the design and implementation of a five-level multi-output converter specifically intended for electric vehicle applications.
4. Chapter 5 introduces a five-level dual-output converter with further reduction in the number of switches, model predictive control (MPC) for output current tracking, and capacitor voltage balancing.
5. Chapter 6 demonstrates the independent control of two different motors supplied by the three-level dual-output converter.
6. Chapter 7 concludes the thesis and proposes potential directions for future research.