Recent Advances in Power Electronics Technology for Industrial and Traction Machine Drives

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Abstract

The purpose of this paper is to review the state of the art of power electronics technology appearing in the latest generation of industrial and traction drives, including a discussion of technology trends that are likely to be reflected in future systems. An effort has been made to highlight both the areas of commonality and the important differences among the wide ranges of specific applications and power ratings that fall within the broad boundaries of industrial and traction drives. Attention is concentrated on recent developments affecting ac adjustable-frequency drives that have been growing in market importance while acknowledging that dc drives continue to evolve and thrive in some sectors of the industrial and traction drive markets

INTRODUCTION

Overview and Paper Purpose

Markets for adjustable-speed drives continue to expand steadily in response to the well-recognized opportunities for major efficiency and cost improvements made possible by upgrading fixed-speed industrial process equipment to adjustable-speed. The last quarter of the 20th century has been a period of remarkable progress in the development of power electronics technology that lies at the heart of these industrial drives and electric traction drives as well. A major hallmark of this unfolding drive development history has been an accelerating trend away from dc commutator machines toward various types of ac brushless machines as a direct result of the continually improving cost-effectiveness of "electronic commutation" made possible by modern power electronics

This progress in power electronics technology has been largely driven by the appearance of successive generations of gate-controlled power switches [1] beginning with bipolar junction transistors (BJTs), followed by MOSFETs and insulated gate bipolar transistors (IGBTs). These power switches have gradually taken over more and more of the applications and power ratings previously dominated by silicon controlled rectifiers (SCRs) and gate turnoff thyristors (GTOs). The availability of these new switches has made it possible to shrink the size of industrial ac adjustable-speed drives (excluding the machine) by an order of magnitude during the past 20 years while halving their cost per kilowatt [2]

This paper presents a review of the state of the art of power electronics technology in both industrial and traction drive application. Key development trends include the dominance of ac adjustable-speed drives in new applications, with the squirrel-cage induction machine as the preferred machine in most cases. Particularly striking has been the rapid ascendance of the insulated-gate bipolar transistor (IGBT) as the predominant power switch in both industrial and traction applications ranging from fractional kilowatts to multimegawatts. Key current issues such as industrial drive input power quality and the effects of fast IGBT switching transients on the machines and electromagnetic interference (EMI) production are reviewed. Recent developments in electric traction for both rail and road vehicles are discussed, including the increasing modularity of new traction inverters in all sizes and the market introduction of new hybrid vehicles using advanced power electronics. The paper concludes with a discussion of expected future trends in power electronics technology that will likely expand the markets for industrial and traction drives during coming years

the scope of this paper. In particular, advances in the development of high-performance ac machine control algorithms [3] and the high-speed digital processors to implement them [4] have been major factors in the improved controllability of modern industrial and traction drives. Similarly, continuing improvements in the material properties and cost of neodymium–iron (Nd–Fe) permanent magnets is having a significant impact on development trends in several classes of industrial and road vehicle traction drives [5].

Background

1) Applications:

a) Industrial drives:

Prior to the availability of electronics, clever electromechanical solutions involving combinations of dc and ac machines (e.g., Krämer and Scherbius systems) were developed early in the 20th century to control the speed of electric machines in industrial processes. The emergence of mature triggered-arc power switch technology (e.g., grid-controlled mercury-arc rectifiers, thyratrons, ignitrons) in the 1920s and 1930s provided a major boost to dc commutator machines as preferred prime movers for industrial drive applications [6].

This situation persisted for several decades until solid-state thyristors finally provided the crucial power switch breakthrough needed to build practical adjustable-frequency ac machine drives in the 1970s. Since that time, new generations of gate-controlled power switches have successively improved the performance and cost-effectiveness of ac drives in comparison to their dc drive counterparts. Although most of today's growth in the worldwide industrial drive market can be ascribed to ac drives, modern generations of dc drives continue to hold a significant share of the total industrial drive market

b) Rail traction:

Rail transport systems have been a major application area for electric drives since the earliest days of electric machines in the 1800s. While some of the earliest applications of electric drives for rail propulsion systems were in trolley vehicles for urban transport, the adoption of electric machines for heavy-rail propulsion soon followed

However, the architecture of the electric rail propulsion systems evolved quite differently in various parts of the world, and these differences persist to this day (Fig. 1). In particular, rail systems in Europe and Japan took the form of catenary supply systems with electric power supplied to the locomotive propulsion drives via overhead transmission lines. In contrast, intercity rail systems in other parts of the world such as North America adopted self-powered locomotives using hybrid combinations of on-board diesel engines and electrical generators that produce electrical power which is subsequently fed to wheel-coupled motors. These differences were further aggravated in those regions adopting catenary systems by the choice of significantly different voltages (e.g., 1.5 kV, 15 kV, 25 kV) and frequencies ranging from dc to 60 Hz for the power distribution system [7].

Commutator machines designed for either dc or low-frequency ac (e.g., 16 2/3 Hz) completely dominated electricrail propulsion systems for many decades and are still in wide use today. However, the development of rugged solid-state power semiconductors during the second half of the 20th century made it increasingly practical to introduce ac induction and synchronous machines that eliminate the need for mechanical commutators. Today, ac adjustable-frequency rail propulsion equipment increasingly dominates new production for both light-rail (urban) and heavy-rail (intercity) traction systems around the world. Nevertheless, large inventories of locomotives using commutator machines still prevail in many parts of the world today, and they are expected to remain in use for many years to come

c) Road traction:

The application of electric drives to road vehicle propulsion systems has an interesting history that began promisingly in the late 19th and early 20th centuries when early electric propulsion systems handily outperformed competing equipment using immature internal combustion engine (ICE) technology of the time. However, key ICE technology advances such as the electric starter in 1915 vaulted internal combustion engines to their complete dominance in road vehicle propulsion systems that they maintain to this day

Worldwide concerns about ICE emissions and the impending depletion of petroleum resources reignited interest in electric propulsion systems for automobiles in the 1970s, and active development has been continuing for the past three decades. DC commutator machines were the preferred prime mover for these electric drive systems until the 1980s when the availability of modern power semiconductors gradually shifted the spotlight to various types of commutatorless machines including induction, permanent magnet synchronous, and switched reluctance machines.

2) Technology: Since other papers in this special issue are devoted individually to each of the key components and subsystems in a modern power converter, the technology background review in this paper will be limited to relevant information not provided elsewhere. First, it is worth noting that the major types of electrical machines adopted or under serious consideration for industrial and traction drive applications include dc commutator, ac induction, ac synchronous, and switched reluctance machines. Cross sections of each of these four machine types are provided in Fig. 2. As their names imply, a major differentiator among the machine types is the form of the required electrical excitation. The switched reluctance machine is a special case, requiring pulsed phase excitation that prevents this machine from being directly connected to either a dc or fixed-frequency ac source without an intervening power converter.

The degree of market acceptance of each machine type for industrial and traction drives is closely associated with the comparative availability and cost of its associated power converter technology. Since ac/dc rectifier technology has historically matured considerably earlier than the counterpart dc/ac inverter technology, dc commutator machines rose to prominence in many industrial and traction applications long before they could be effectively challenged by any ac machine Fig. 3. Basic three-phase voltage-source inverter bridge. drive technology.

Nevertheless, the limitations imposed by the brushes and mechanical commutator made the dc machine vulnerable to eventual displacement by more rugged machines such as the squirrel-cage induction machine that are particularly well suited for the rigors of industrial and traction drive environments. The availability of solid-state thyristors in the 1960s marked the beginning of the induction machine’s gradual rise to dominance in many industrial and traction drive applications. However, a thyristor turns off only when the power circuit forces its current to zero. As a result, self-commutated current-source inverters were widely adopted for many of the early induction machine drive systems developed during the 1970s [9], avoiding the complication and expense associated with auxiliary forced commutation circuits. Eventually, the availability of several types of new power semiconductors that can be turned off by the gate/base terminal (e.g., bipolar transistors, IGBTs, GTOs) caused the tide to swing in favor of voltage-source inverters using pulsewidth modulation (PWM) [10]. As a result, current-source inverters are generally found today only in high-power drive applications (1 MW) where thyristors are still able to successfully compete with the various types of controlled-gate power switches

Concluding Remarks

The recent developments outlined briefly in this paper bear testimony to the major progress that has been accomplished during the past few years in applying new power electronics technology to industrial and traction drives. Although the improvements sometimes seem painfully slow and labored to technical experts working in the field every day, the rate of technical progress is actually very impressive when one takes a step back to see how far the technology has progressed during the past 25 years. Where do we go from here? The future of both industrial and traction drives depends not only on advances in the underlying technologies, but the economic and regulatory climate in which they are developing. Despite the risks of predicting future trends, there are many reasons to expect that increasing global concerns about efficient electrical energy utilization, transportation fuel economy, pollutant emissions levels, and electrical power quality will increase during coming years. In light of these pressing concerns, the desire for further major improvements in industrial and traction drives will almost certainly continue to place a high premium on new advances in power electronics technology

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