

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

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Invited Paper

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.

Keywords—AC–AC power conversion, ac motor drives, induction motors, industrial motor drives, permanent magnet motors, rail transportation propulsion, road vehicle electric propulsion, traction motor drives.

I. INTRODUCTION

A. 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].

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.

While the focus of this paper is on power electronics, important advances have simultaneously been taking place in several of the other constituent technologies that fall beyond

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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].

B. 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 electric

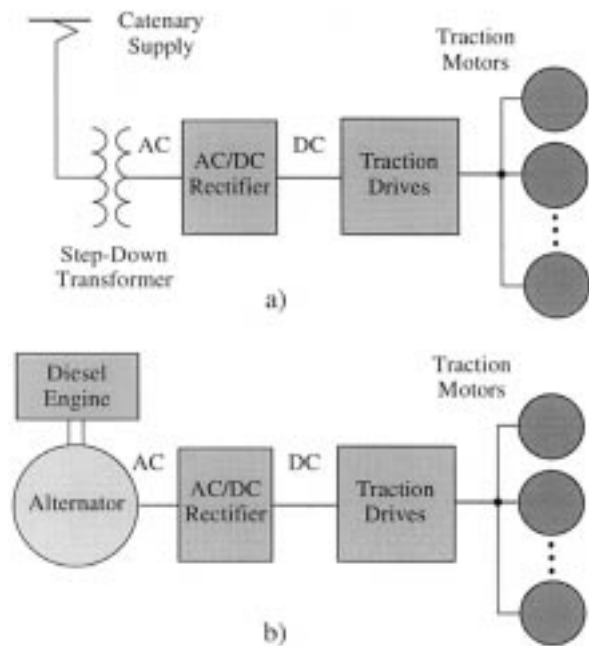


Fig. 1. Rail electric traction system configurations: (a) catenary supply and (b) diesel–electric.

rail 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.

The continuing unavailability of electrochemical batteries with the required combination of energy storage capacity,

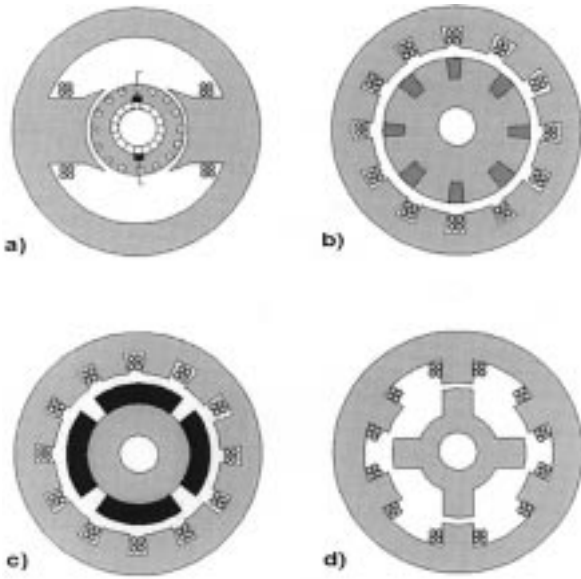


Fig. 2. Industrial and traction machines: (a) dc commutator, (b) squirrel-cage induction, (c) PM synchronous, and (d) switched reluctance.

cost, and lifetime has prevented electric vehicles from seriously challenging ICE-based vehicles for supremacy in road vehicle propulsion systems. However, recent advances in fuel cell technology [8] and hybrid propulsion systems that combine internal combustion engines and electric drives in the same power plant have generated major renewed interest in electric propulsion technology. Against this backdrop, world petroleum prices and environmental emissions standards are playing major roles in shaping the prospects for broad adoption of this technology during coming years.

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

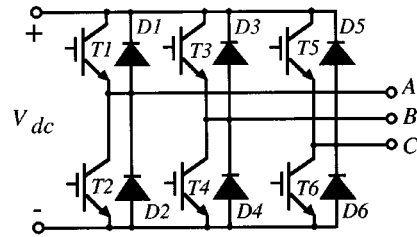


Fig. 3. Basic three-phase voltage-source inverter bridge.

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 pulswidth 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.

II. INDUSTRIAL DRIVES

A. Overview

Squirrel-cage induction machines dominate ac industrial drive applications around the world for both new and retrofit applications [11]. Permanent magnet (PM) synchronous machines are increasingly popular choices for high-performance servo applications because of their high power density. However, these represent only a small fraction of the total number of industrial drive applications, the majority of which (i.e., pumps, fans) can be satisfied with general-purpose induction motor drives using constant volts-per-hertz control [12]. Other types of brushless machines including switched reluctance account for only a small fraction of new industrial drive applications.

Three-phase voltage source inverters using the basic six-switch bridge topology shown in Fig. 3 have become the overwhelming favorite for industrial drive applications less than 2 MW. During the past decade, IGBTs packaged in compact plastic power modules have rapidly expanded their voltage and current ratings so that they now dominate nearly all of the new industrial drive inverter designs. Power modules are now available from several manufacturers

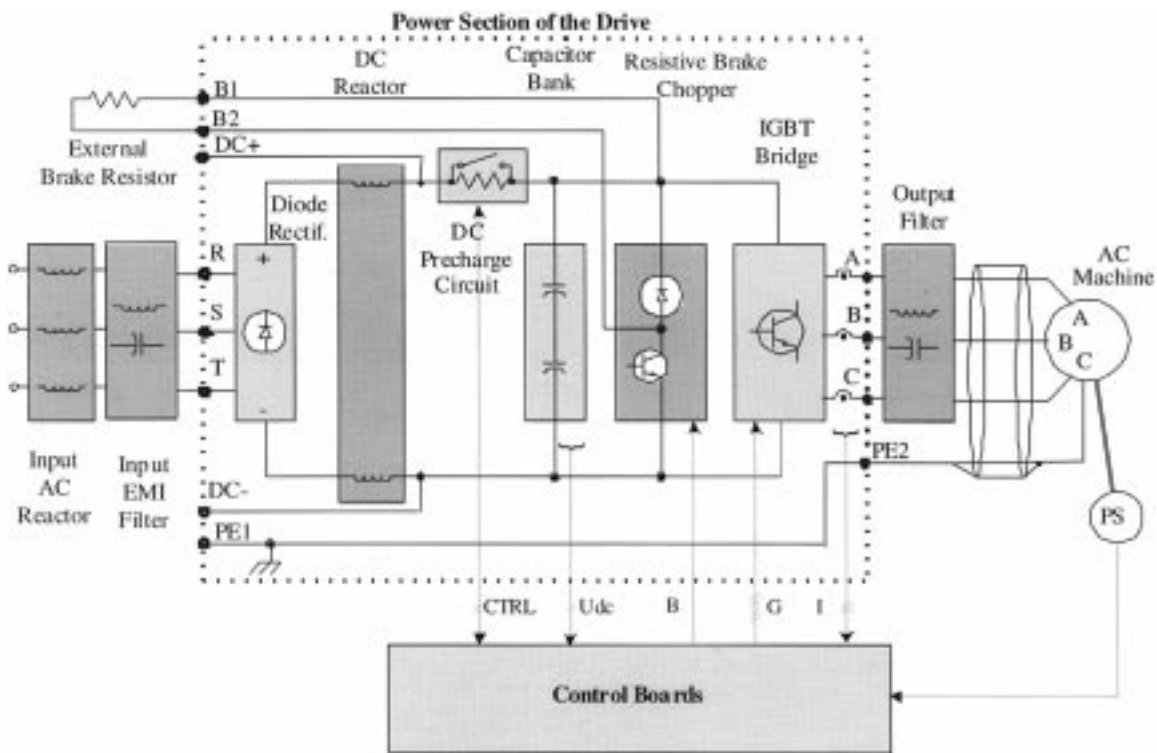


Fig. 4. Typical industrial drive configuration.

with 1200-V IGBTs (appropriate for 460-V machines) that are packaged either as single-switches ($<\sim 2400$ A), dual-switch phase legs ($<\sim 800$ A), or complete six-switch bridges ($<\sim 400$ A), depending on the required current ratings. Continuing improvements in IGBT switching characteristics allow these devices to be used with PWM switching frequencies that range from 1 to 2 kHz in high-power drives (>1 MW) to more than 20 kHz in lower power ratings (<30 kW).

IGBT power modules are being offered with gate drives and protective functions built into the same package. Another mark of progress is the growing availability of integrated power modules (IPMs) that provide all of the power semiconductors for a complete industrial drive in a single package, including IGBTs and diodes for the rectifier, inverter, and brake stages described in the following section. These integrated modules are already being produced with ratings of 1200 V and 50 A, with higher current ratings now in development.

B. Industrial Drive Design Issues

The architecture for a typical panel-mounted chassis drive in the 50-kW power range is illustrated in Fig. 4. The core of the power circuitry for this drive consists of an input three-phase diode rectifier, a precharge circuit, dc link capacitor bank, and IGBT inverter stage. Other power components shown in this figure including the input line ac reactor, input electromagnetic interference (EMI) filter, dc link reactor, dynamic brake, and output filter are all optional depending on the application requirements.

1) *Inverter Stage:* Modern IGBTs have matured to a high state of electrical ruggedness that make it possible to design the inverter stages with a minimum of additional snubber circuitry [14] to limit either the rate of current change (di/dt) or the rate of voltage change (dv/dt) at the IGBT terminals. In fact, many new IGBT inverters are designed without any snubbers at all. This approach has the advantage of saving cost, space, and losses in the inverter—all positive effects.

However, the resulting switching rates at the IGBT output terminals in snubberless inverter designs can sometimes exceed 1000 A/ μ s and 10000 V/ μ s, with undesired and, in some cases, harmful consequences. For example, it has been confirmed that the high dv/dt switching rates can interact with the inverter output cables and the machine windings to cause large transient voltages to appear across the outermost turns of the stator windings [15]–[19]. Field experience has demonstrated that this situation sometimes leads to catastrophic failure of the stator winding insulation. Such conditions are most likely to occur in installations with unusually long cables between the drive inverter and machine. Some machine manufacturers have responded by strengthening the stator winding insulation, at least for the outermost turns.

It was also found that the high dv/dt switching rates can induce unbalanced charge build-ups on the machine rotor by means of parasitic capacitances coupling the machine stator, the rotor, inverter switches, and ground. This accumulated rotor charge eventually discharges through the bearings if no other galvanic current path is provided. Over time, these discharges can cause serious pitting of the bearing balls and races that eventually leads to bearing failures under some circumstances that have been experienced in field installa-

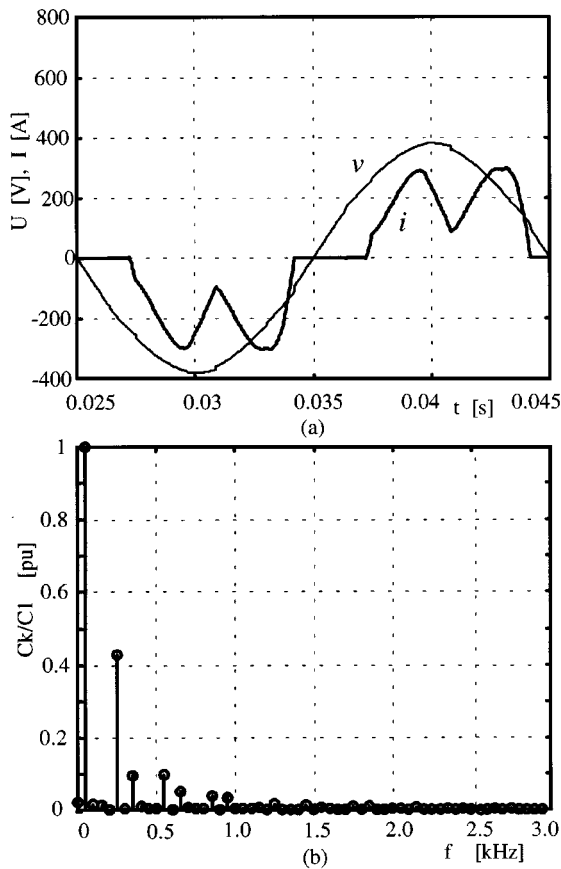


Fig. 5. Three-phase diode rectifier characteristics. (a) Input voltage and current waveforms. (b) Input current frequency spectrum.

tions [20]–[25]. The introduction of insulated bearings or grounded rotor shaft brushes are among the solutions adopted by machine manufacturers to prevent these bearing failures.

A third problem caused by the high dv/dt and di/dt switching rates is elevated levels of conducted EMI in the drive input lines and ground that can easily exceed acceptable levels [26]–[30]. Common-mode EMI can be significantly reduced by adding common-mode inductors in both the input and output lines, together with small capacitors between each dc link bus and earth ground to prevent these high-frequency currents from reaching the utility grid or machine. Modifications of the PWM switching algorithm can also be introduced to minimize the generation of common-mode EMI. Differential-mode EMI can be reduced by adding passive or active filters on the inverter output lines. Another effective, albeit somewhat ironic solution to these EMI problems is to use the IGBT gate drives to artificially slow their switching speeds, trading reduced EMI for elevated switching losses.

2) *Input Rectifier Stage:* By showing a diode rectifier stage in Fig. 4, the illustrated architecture is typical of the large majority of today’s industrial drives (>90%) that do not permit braking power to be returned to the utility lines. Although the diode rectifier has the advantage of low cost, it also imposes several constraints and disadvantages on the drive system that are attracting more attention every year.

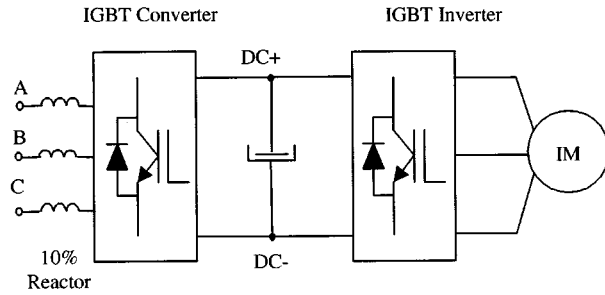


Fig. 6. Regenerative drive configuration with common dc bus.

Perhaps most importantly, the basic diode rectifier draws current from each input line that is significantly distorted from its desired sinusoidal shape [Fig. 5(a)].

One of the purposes of including in either a dc link reactor or three-phase input line reactors in the drive power circuitry is to reduce the amplitude of the input current harmonics in addition to limiting the peak dc link capacitor current and reducing the conducted EMI. However, Fig. 5(b) shows that, even when the ac line reactors are introduced with typical ratings (3% of the drive base impedance, in this case), the input line current harmonics are still very substantial, containing a fifth harmonic component greater than 40% of the fundamental component.

Another constraint imposed by diode rectifiers is the need for precharging of the dc link capacitors to avoid dangerous surge current when the drive is initially connected to the ac line. A variety of precharge circuits are used depending on the drive power rating, including the parallel combination of resistor and bypass contactor illustrated in Fig. 4.

For industrial drives with ratings greater than 30 kW, the diodes in the input rectifier stage are often partially or completely replaced by phase-controlled thyristors. Although more expensive than the diodes, the thyristors serve multiple purposes by providing the precharge function and serving as a fast electronic circuit breaker to remove power from the dc link in case of ground-fault or inverter failures.

Many industrial drive applications that demand only limited and infrequent machine braking capability (e.g., conveyors) can be satisfied by means of a dynamic brake assembly that dissipates the excess electrical energy appearing on the dc link in external resistors (see Fig. 4). However, applications that involve frequent and extended periods of braking (e.g., cranes) can justify the introduction of a regenerative input converter bridge as shown in Fig. 6 to provide the drive with bidirectional power conversion capabilities. The topology of the input converter bridge is identical to that of the inverter using six controlled switches (i.e., IGBTs) and six diodes, as shown previously in Fig. 3. Three-phase input line reactors are essential with the active input bridge configuration to provide the necessary input impedance characteristics to the bridge terminals.

The addition of the regenerative active input bridge clearly represents an expensive solution that can only be justified today in applications that truly need bidirectional power flow. However, appropriate PWM control of the active input bridge results in significant system advantages by eliminating all of

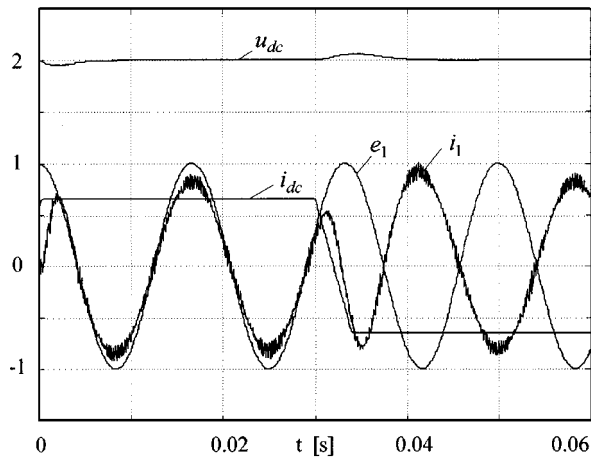


Fig. 7. Waveforms showing operation of regenerative input converter during sudden change from motoring to regenerating; u_{dc} : dc bus voltage; i_1 : line current; e_1 : phase voltage; i_{dc} : dc bus current (Vertical: 1 pu = 375 V, 250 A).

the undesirable low-order current harmonics that are associated with either diode or thyristor bridges, as well as providing independent control of the input power factor.

Fig. 7 shows typical input line and dc link voltage/current waveforms for a regenerative drive system, illustrating the major improvement in line current harmonics compared to the diode rectifier waveform shown earlier in Fig. 5. This figure also illustrates the fast response that regenerative input stages can provide using vector control principles [31]–[38], handling a step change in drive operation from full-load motoring to full-load braking with minimal perturbations of the dc link voltage.

3) *Bus Capacitors:* Electrolytic capacitors are the preferred choice for the dc link capacitors in almost all industrial drives. Minimum dc link capacitance requirements are usually determined by the rms current-carrying capacity of the electrolytic capacitors and the need for sufficient dc link energy storage to allow the drive to “ride through” transient utility voltage sags [39]–[42]. Typical electrolytic capacitor bank values for general-purpose drives fall between 25 and 50 μF per amp of inverter rms output current. Since the voltage ratings of electrolytic capacitors are usually limited to 500 Vdc or less, series and parallel combinations are required in many drive applications to support dc link voltages that exceed these ratings.

Newer film capacitors are available with higher rms current ratings per μF of capacitance and better reliability characteristics than their electrolytic counterparts. However, film capacitors are seldom used in place of electrolytics today because they are more expensive, and smaller bus capacitance provides less drive ride-through protection during utility voltage sag events.

C. Drive Implementation and Packaging

Industrial drives generally fall into one of three categories based on their power ratings. Although standard terminology is lacking, these three drive classes will be referred to in this paper as low-power package drives (<20 kW), medium-

power chassis drives (20 kW to 500 kW) and high-power cabinet drives (>500 kW). The power rating boundaries between these drive classes are only approximate and vary from manufacturer to manufacturer with considerable overlap.

1) *Low-Power Package Drives:* Package drives are manufactured in the largest numbers and have achieved the highest levels of design integration and automated manufacturing. Power and current levels are low enough for these drives to be designed onto a single printed-circuit board (PCB) using widened and thickened board traces as the power stage bus interconnections. All of the power components are packaged into one or, at most, two power modules that can be mounted directly on the PCB together with all of the necessary control circuitry.

Manufacturing of this type of drive is highly automated using extensions of techniques developed for signal-level PCB construction. As such, these drives are typically catalog items with a defined set of options, unless they are being built to order for an original equipment manufacturer (OEM) application. Most of these package drives use simple volts-per-hertz control appropriate for general-purpose speed control of fans and pumps, but the available operating modes and user interface can be quite sophisticated.

2) *Medium-Power Chassis Drives:* A major distinguishing factor of these drives is that the power levels are high enough that dedicated buswork is generally required to interconnect the power stage components. The IGBT switch modules, typically in dual-switch phase-leg configurations for this power range, are mounted on an aluminum heatsink and connected into bridge configurations using laminated busbar structures [43] designed to minimize parasitic inductances. However, power modules with all six switches in the same package are becoming increasingly available for this power range, simplifying the external interconnection requirements. Cooling is usually accomplished by forced air over finned heatsinks, sometimes assisted by heatsink-mounted heat pipes to efficiently extract the heat from the compact power stage section where the losses are concentrated.

The control functions in chassis drives are typically partitioned into two or more cards and the drive components are then assembled manually into a steel chassis enclosure. Much of the customization for these drives is typically accomplished during the final assembly stages by mounting the completed chassis drive onto a flat panel that subsequently receives the desired auxiliary components including circuit breakers, contactors, and reactors.

3) *High-Power Cabinet Drives:* The basic drive partitioning and construction techniques used in these large units are very similar to those used for the chassis drives, although the power stage is physically larger and the power switches are typically packaged as single-switch modules. As power ratings climb above 1 MW, competition between IGBTs, GTOs, and thyristors intensifies. Thyristors are used in large current-source inverters with induction machines, and also in load-commutated inverters with overexcited synchronous machines [44]. Forced air is the standard cooling technique for these drives, often in combination with heat pipes to

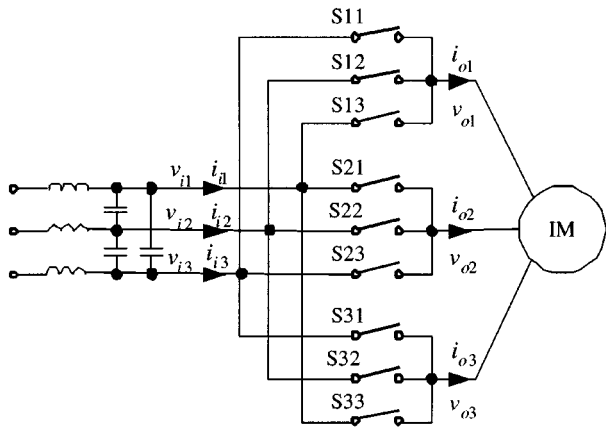


Fig. 8. Basic matrix converter circuit topology.

efficiently extract the heat from the compact power stage. Water-cooled heatsinks are also available when required by the application.

A major distinguishing feature of these large drives is that they are individually built to order in large steel cabinets that are often big enough for maintenance workers to step inside. All of the necessary drive components, including auxiliary transformers, circuit breakers, etc., are mounted inside the cabinet. It is not unusual for these auxiliary components to take up the majority of the available space in such drive installations, and the physical layout typically emphasizes ease of maintenance rather than power density.

D. Matrix Converters

The matrix converter is a power circuit topology that has the capability of directly converting ac power at one frequency and voltage into ac power at a second frequency and voltage [45]–[53]. The basic matrix converter topology only uses nine switches as shown in Fig. 8, although each switch must provide bidirectional current control (i.e., each switch must be capable of conducting and turning off current in both directions). Since all commercially available power switches provide unidirectional control, each switch in Fig. 8 is typically implemented using two power switches (and two diodes) in an antiparallel connection, for a total of 18 controlled switches. At least one major power semiconductor manufacturer is already offering an IGBT power module that contains all of the necessary switch elements to construct a low-power matrix converter.

Although no industrial drives are presently manufactured using the matrix converter power circuit, associated development activities are sufficiently intense that the topology merits discussion here. Matrix converters using high-frequency PWM control [52], [53] offer some important potential advantages in drive applications including inherent regenerative power capability and the ability to control both the power factor and current harmonics at the converter input as well as its output. Sample waveforms for a prototype matrix converter are shown in Fig. 9 that demonstrate these characteristics.

The absence of an intermediate dc link with its storage capacitors can be seen as either a strength or a weakness,

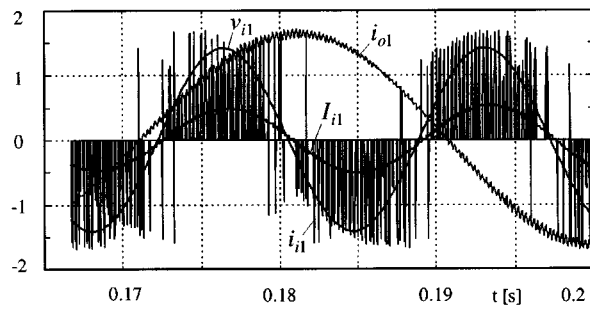


Fig. 9. Matrix converter waveforms showing output current i_{o1} , instantaneous input current i_{i1} , locally averaged input current I_{i1} , and input voltage v_{i1} with vector-controlled induction motor load (Vertical: 1 pu = 265 V, 14 A).

depending on the application. While there are no bulky electrolytic capacitors, there is also no stored energy to assist the drive during utility voltage sag events. Insuring adequate input power quality under all operating conditions presents additional challenges for the matrix converter that are presently being addressed by academic and industrial researchers around the world.

The future of the matrix converter is uncertain as of this writing. There is little expectation that the dominance of the basic rectifier-inverter topology will be seriously challenged in the foreseeable future. Nevertheless, long-term demands for improved input power quality in all industrial drives may cause the playing field to eventually shift in a direction that will create important market opportunities for the matrix converter. Applications that demand regenerative power capability will be the first to test this approach.

III. TRACTION DRIVES

A. Rail Vehicles

Squirrel-cage induction machines have established an increasingly dominant position in new generations of rail vehicle traction systems developed since the early 1990s. Although synchronous machines were selected to power the French TGV high-speed train in at least two generations of locomotives placed in operation as recently as 1993, new state-of-the-art locomotive equipment introduced since that time has been predominantly designed with induction machines as the prime movers.

GTO power switches became the preferred power switches for traction drives during the early 1990s using devices with ratings of 4.5 kV and 4 kA turnoff current. However, GTO traction inverters are typically limited to PWM switching frequencies of 500 Hz or less and require relatively complicated gating circuits that can impose reliability penalties. The development of high-voltage IGBTs during the past decade has encouraged traction drive manufacturers to choose IGBTs for their newest drive equipment in order to take advantage of their higher switching frequencies and simpler gate drives. Such IGBTs are conveniently available with ratings of 3.3 kV and 1.5 kA, and new devices with higher voltage ratings up to 6.5 kV at 0.6 kA are being commercially produced by at least one manufacturer. These IGBTs make it possible to increase the

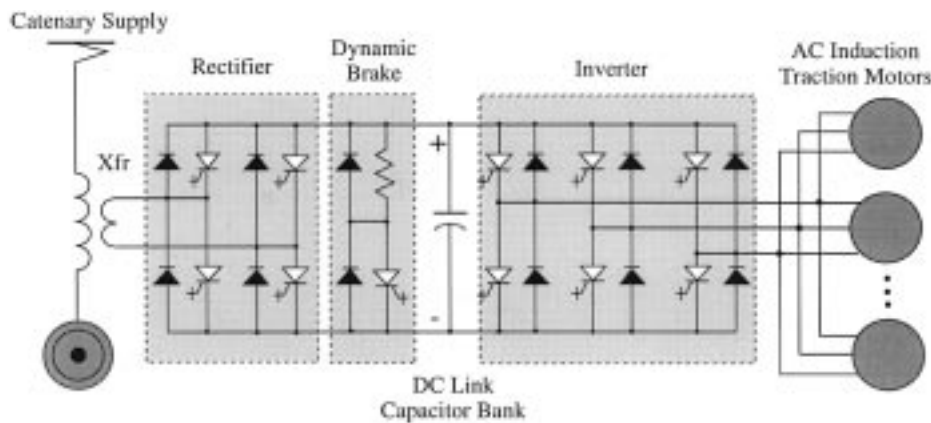


Fig. 10. Basic power circuit for ac catenary-supply rail traction system.

PWM switching frequency from 500 to 1500 Hz or more in order to minimize harmonic currents at both the input and output while simultaneously achieving inverter efficiencies of 98% or higher.

The availability of high-performance ac machine control algorithms including field-oriented control [54] and direct torque control [55] has made it possible to significantly enhance the dynamic performance of rail vehicle traction drives, in spite of the low PWM switching frequencies that are typical in such systems. Since tractive effort per axle is a major competitive discriminator for rail propulsion systems (particularly for heavy-rail freight locomotives), major efforts have been focused on the development of improved wheel slip-slide control algorithms [56]. These algorithms have demonstrated their ability to optimize wheel adhesion characteristics using closed-loop speed control techniques, demanding fast dynamic control of the traction motor torque (rise time <10 ms) as a requirement for their effectiveness.

1) *Heavy-Rail Catenary Supply Systems:* Despite the wide range of single-phase ac supply systems and train configurations found around the world, the electric traction drive architecture selected by traction equipment manufacturers for heavy-rail catenary systems during recent years has generally converged on the basic voltage-source rectifier/inverter structure shown in Fig. 10 (with GTO power switches). However, there are many significant variations in the details of the rectifier/inverter configuration selected for specific applications. These variations include the number of paralleled induction machines excited by each three-phase inverter, as well as the number of single-phase dc/ac rectifier units paralleled to supply the dc link.

The inverter power circuit topology has been developed by traction drive manufacturers to generally take one of two forms—either the classic two-level phase leg topology shown previously in Fig. 3 or the three-level neutral-point clamped (NPC) topology shown in Fig. 11 (with IGBT power switches). The principal attractiveness of the three-level NPC configuration is the ability to approximately double the dc link voltage for a given power switch voltage rating [57]. This feature has made it possible to apply 3.3-kV IGBTs in NPC inverters with a 3-kV dc link voltage, permitting a direct replacement of two-level GTO inverters built with

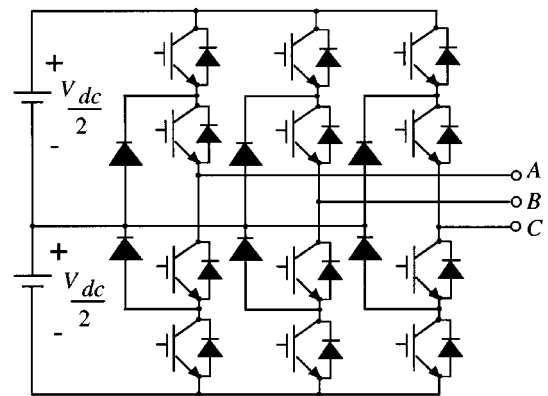


Fig. 11. Three-phase neutral point clamped inverter.

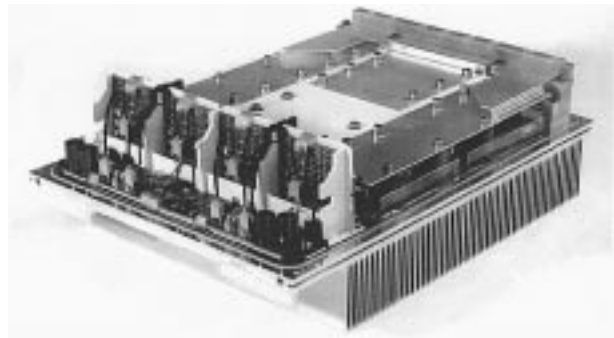


Fig. 12. IGBT phase module of Siemens SIBAC traction inverter. (Courtesy of Siemens AG.)

4.5-kV devices. The same NPC concept can also be applied to the single-phase rectifier stage in Fig. 10, using only two of the three phase legs shown in Fig. 11.

The net result of these technology trends has been the development of compact IGBT-based traction inverter units by several manufacturers with power ratings in the range of 1000–1500 kVA. The dc bus voltage for these inverter units is typically between 1.5 and 3.0 kV depending on whether a two-level or three-level bridge topology is selected. A photo of one of these state-of-the-art traction inverters is provided in Fig. 12.

Although traction inverters have traditionally preferred rugged press-pak (“hockey-puck”) power semiconductor

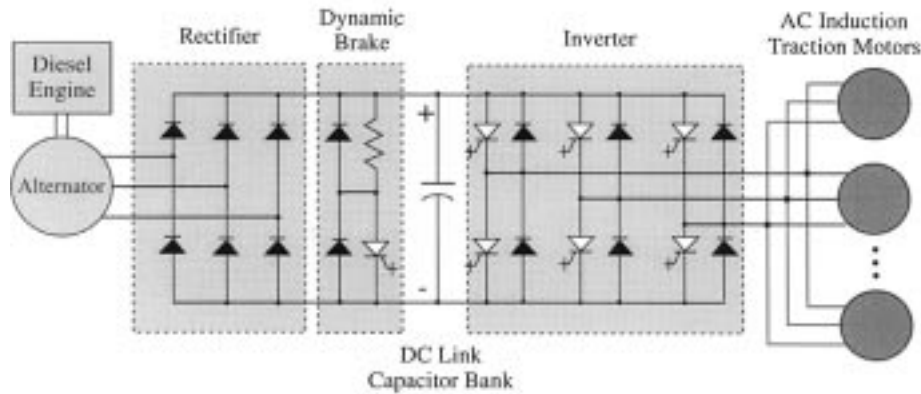


Fig. 13. Basic power circuit for diesel–electric rail traction system.

packages because of their proven ruggedness, several of the newest traction inverters have adopted the popular plastic power module package using wire-bonded power devices. This notable transition has been made on the basis of important improvements in wire-bond ruggedness confirmed by extensive reliability testing of the resulting IGBT modules [58].

The weight and volume of the traction inverters depends heavily on the selected cooling configuration. A significant amount of research effort has been invested during recent years in the development of improved cooling technology based on various combinations of heat pipes, evaporative cooling [59], circulating coolant, forced-air, and natural-air convection cooling. The choice of a particular cooling approach is typically decided on the basis of system issues that depend on the specific rail vehicle requirements.

2) *Heavy-Rail Diesel–Electric Systems:* In contrast to the catenary supply systems, the electrical propulsion system in a diesel–electric locomotive consists of a self-contained electrical system that includes the electrical power generation in addition to the traction motor drives. While synchronous machines have long been used for the alternators in such systems, dc machines dominated as the preferred traction machines until the early 1990s. A major technology shift was made at that time to ac induction machines, leading to propulsion system architectures of the type illustrated in Fig. 13. New ac diesel–electric locomotives are now being manufactured with traction power ratings in excess of 4200 kW.

Key variations of this basic architecture are defined by the decision whether to drive several traction motors in parallel with each inverter or to dedicate a separate inverter to each machine. While there are economic advantages associated with building a larger inverter to excite paralleled machines, the use of individual dedicated inverters provides opportunities for enhanced traction characteristics via customized slip control of each traction motor. The superiority of either approach continues to be a topic of spirited debate and competing commercial claims in the industry.

Field control of the synchronous alternator in the diesel–electric locomotives makes it possible to adjust

the dc link voltage supplied to the traction inverters more conveniently than in the catenary supply units. This important degree of freedom can be used to control the flux levels in the traction machines as a function of speed and load in combination with PWM inverter control, providing opportunities for enhanced inverter operating characteristics and efficiency.

The inverter designs adopted in these new diesel–electric locomotives draw on much of the same power electronics technology developed for the catenary supply units that made the conversion to ac traction machines several years earlier. In particular, modular inverters rated at 1000 kW or higher using IGBTs instead of GTOs are appearing in the latest generation of diesel–electric traction drives. Significant differences in the choice of inverter cooling technology still exist among competing product offerings, paralleling the range of cooling schemes found in the catenary supply system traction drives.

3) *Light-Rail Rapid Transit Systems:* Major distinguishing characteristics of light-rail rapid transit systems include their use of dc electric power distribution (often via a third rail) with voltages in the range of 600–3000 Vdc, and their need for robust braking capabilities to handle frequent deceleration/stop cycles. Since rapid transit systems typically take the form of multiple-unit powered passenger cars, the traction drives must be compactly packaged for under-floor mounting.

Traction drives for rapid-transit applications use the same basic combinations of voltage-source inverters and induction machines found in heavy-rail applications. High-voltage IGBTs are rapidly displacing GTOs in new inverter designs for rapid transit applications as they are in the heavy-rail systems. Cooling of the under-floor inverters in rapid transit systems is typically accomplished using ram air generated by the vehicle movement, providing a robust cooling configuration.

B. Road Vehicles

Electric traction drives for road vehicles generally fall in the power range between 10 and 100 kW, depending on the vehicle size and the propulsion drive configuration. Unlike

the situation for rail traction drives described above, there is no international consensus on the preferred machine type for electric traction drives in road vehicles. Interestingly, machine type preferences seem to break down along regional lines, with permanent magnet (PM) synchronous machines typically selected by Japanese developers, while induction machines are generally preferred in both North America and Europe. Switched reluctance machines are also attracting attention in several laboratories around the world.

Regardless of the electrical energy source, the dc supply voltage for road vehicle traction drives typically is between 200 and 400 Vdc (nominal). Three-phase voltage-source inverters using the classic six-switch bridge topology (see Fig. 3) are widely used for both the induction and synchronous machine drives, while the converters for switched reluctance machines modify the phase-leg topology by placing each phase winding in series between the two switches [60]. Both of these power converter configurations are inherently bidirectional permitting power flow from the machine back to the electrical energy source (e.g., batteries) during regenerative braking.

IGBTs have emerged as the preferred power switches in new road vehicle electric traction drives, just as they have in rail traction drives. They are most often used in the form of plastic power modules comprising either a single phase leg including two power switches or a complete six-switch inverter bridge. Switch ratings of 600 V and 400–600 A are typical for these applications. Special development efforts have been taken to insure that these switch modules can withstand the severe environmental stresses associated with automotive operation. For example, Ford requires that such IGBT modules survive >500 000 thermal cycles with a ΔT of 40 °C and 1000 extreme thermal cycles from –40 °C to +125 °C [61].

Most road vehicle traction drive inverters are packaged as separate units from the motor, although there is a clear desire to explore opportunities for tighter physical integration if the higher thermal and vibration stresses associated with the traction machine environment can be tolerated [62]. Cooling of the power electronics is typically accomplished using either air or water cooling. While air cooling has the advantage of simplicity and low cost, water cooling (often with a dedicated cooling loop to limit the maximum coolant temperature) makes it possible to achieve much higher power densities in the vicinity of 10 kW/kg [63].

Major strides have been made during recent years toward improving the performance and power density of these traction drives, but cost continues to be one of the most significant barriers that is still being addressed. Although targets differ among automotive manufacturers, there is general agreement that the production cost of the power electronics needs to be substantially reduced by at least 2 : 1 for electric traction drives to be able to compete economically with conventional ICE powerplants in the absence of special subsidies [64].

1) *Hybrid Electric Vehicles:* As a result of the performance limitations imposed by electrochemical batteries, international research and development efforts during the

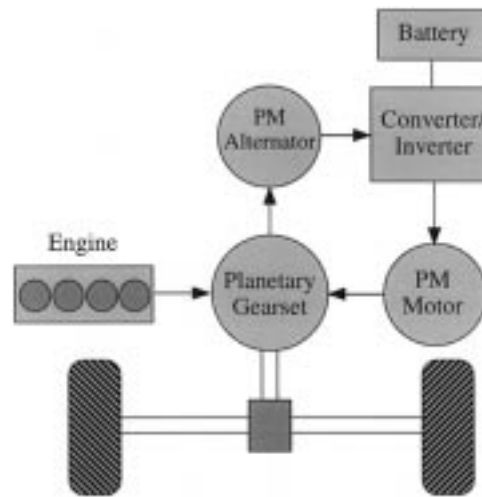


Fig. 14. Powertrain block diagram for Toyota Prius.

past decade have been increasingly focused on various types of hybrid-electric vehicles (HEVs) combining electric traction drives with internal combustion engines (ICEs). Although HEVs cannot meet the stringent emission requirements for zero-emission vehicles (ZEVs), they represent important compromise system solutions that deliver significant improvements in fuel economy and emissions levels while matching the travel range of conventional ICE vehicles.

A wide variety of HEV powertrain configurations have been actively developed [65], [66], and only a couple of the most interesting architectures can be discussed here. Particularly notable has been the market introduction of at least two HEVs, the Toyota Prius and the Honda Insight, first in Japan and, more recently, in North America.

The Prius uses a sophisticated propulsion drive configuration (see Fig. 14) employing a high-efficiency gasoline engine and two electric machines (both PM synchronous), one operating as a generator (rated at 15 kW) and the other as a motor (30 kW). By connecting these three energy-conversion units to the three rotational elements of a planetary gearset, the system operates as a continuously variable transmission (CVT) with the gear ratio determined by the power transfer between the generator and motor [67]. A nickel metal hydride battery allows the system to operate with adjustable proportions of ICE and electric propulsion power, achieving significant improvements in overall vehicle fuel economy and reduced emissions. However, the electric traction drive components are not inexpensive, requiring a separate converter for each of the two machines. A photo of the Prius power electronics that includes both of the converters is shown in Fig. 15.

The powertrain configuration of the Honda Insight HEV is somewhat simpler, combining a three-cylinder gasoline engine with a 10-kW PM synchronous machine mounted in place of the conventional flywheel between the engine and transmission. Very similar HEV powertrain configurations have been receiving serious attention by automotive manufacturers in other parts of the world, including Ford in North America [61]. The size of the electric traction drive is pur-



Fig. 15. Cutaway view of Prius power electronics module. (From “Products of Hirose Plant” brochure, courtesy of Toyota Motor Corp.)

posedly minimized in such “mild” hybrid configurations so that the electric machine only contributes significant torque and power during transient loading events including periods of major acceleration or deceleration. In addition, the electric machine is sized to be able to rapidly accelerate the engine from standstill to idle speed in less than 0.3 s. This capability permits both fuel consumption and emissions to be reduced by stopping the engine whenever the vehicle is at standstill for more than a few seconds, and then instantly restarting it as soon as the driver presses on the accelerator pedal.

2) *Pure Electric Vehicles:* Recent advances in fuel-cell technology have significantly revived interest in automotive propulsion systems that are entirely electric. This represents a major reversal of the trends away from such systems caused by the growing pessimism about the prospects for electrochemical batteries to provide the necessary vehicle range between recharging at an acceptable cost.

The propulsion system architectures adopted in these pure electric vehicles (EVs) are not as varied as those for HEVs, with many of the differences associated with the number of electric machines and the packaging concepts. While use of a single electric machine is most popular as a means of minimizing total system cost, prototype vehicles have been developed with as many as four propulsion motors, one built into each wheel [63].

There is generally a more concentrated focus on drive train efficiency in these EV drivetrains since the available stored electrical energy is such a valuable and limited resource. Although PM synchronous machines demonstrate an acknowledged efficiency advantage at low speeds, this advantage is eroded at high speeds due to their need for extra stator current to accomplish flux weakening [68] in this operating regime. As a result, induction and PM synchronous machines continue to battle for supremacy in such systems, with SR machines vying for attention as the least mature of the three competing technologies.

IV. CONCLUSION

A. Future Trends

This past decade has witnessed major advances in power electronics technology for both industrial and traction drives.

These advances have made it possible to significantly improve the electrical performance of these systems while simultaneously reducing their size and weight and, perhaps most importantly, reducing their cost. Improvements in all of these key metrics are expected to continue during coming years, with a few trends meriting special attention:

1) *Modularization and Automated Manufacturing:* Improved packaging of the power electronics components and subsystems is expected to be one of the most active development areas because of the significant cost reductions that are achievable by modularizing the power electronics and automating its manufacturing. Major progress toward these objectives can already be observed in many of the new industrial drive products with ratings of 10 kW or less. Wider acceptance of power electronics in automotive applications during coming years—both for traction and accessory applications—will likely provide a substantial boost for this trend by focusing the energies of the automotive industry on achieving these manufacturing economies.

2) *Increasing Silicon Content:* As the cost of power switches and their driver circuitry continues to diminish, trends toward increasing the proportion of active silicon-based power electronics in future drive products at the expense of passive components (i.e., capacitors, inductors, transformers) is certain to continue. Particularly in industrial drives, international trends toward tighter regulation of the input power quality of new products is expected to motivate the wider introduction of active rectifier stages using additional power switches with less dependence on special transformers and passive L-C filters. Direct ac/ac power converter topologies such as the matrix converter are expected to appear in some new applications, although their ability to broadly displace the dominant rectifier-inverter topology is very uncertain. Serious efforts are under way to use new high-voltage power switches in innovative configurations [69] to eliminate the need for heavy and expensive transformers in future heavy-rail traction drives operating directly from 25-kV ac catenary supplies.

3) *Power Converter/Machine Integration:* The third notable technology trend, and perhaps the most controversial, is wider adoption of integrated packaging of the power electronics and the electrical machine in the same mechanical package. Several industrial drive manufacturers have introduced product offerings (<10 kW) based on this approach during recent years with limited initial market appeal, but anecdotal evidence indicates that acceptance among skeptical customers is gradually improving. Automotive manufacturers are exploring this approach as a long-term approach for modularizing the EV and HEV electric propulsion units while simultaneously reducing EMI emissions by eliminating long interconnecting cables between the inverter and machine. Significant technical hurdles associated with the ability of the power electronics to survive the heat and vibration of the harsh machine environment are gradually being overcome, making the “electronic motor” concept increasingly attractive for many drive applications from both a technical and economic standpoint.

B. 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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