Historical Evolution of Motor Technology

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OVERVIEW: Driven by a strong desire to produce electric motors using domestic rather than foreign technology, Hitachi's founder, Namihei Odaira, produced three 5-HP electric motors in 1910. Now, a century later, electric motors incorporate a variety of different technologies and have undergone significant changes in their size, performance, and other features. They have become a key device that underpins society in a wide range of fields including power generation, industry, transport, and home appliances.

INTRODUCTION

2010 marked the 100th anniversary of Hitachi's formation and it is widely known that the company's first product was a 5-HP (horse power) induction motor (see Fig. 1). Although most electric motors in Japan at the time were imported from overseas, Hitachi's founder, Namihei Odaira, embarked on development driven by a strong desire to produce electric motors using his team's own technology developed locally in place of foreign technology. After overcoming numerous technical challenges, the result was three 5-HP motors produced in 1910. This was the beginning of Hitachi's activities in the field of electric motors as well as its starting point in motor technology development.

Now, a century later, the electric motor has become a key device that underpins society in a wide range of fields including power generation, industry, transport, and home appliances (see Fig. 2). In particular, in conjunction with advances in microelectronics technology and power semiconductor devices since the 1980s, rapid progress has been made in the field of inverters (a form of electrical conversion system) and the drive control systems that combine inverters with motors. Along with control functions that have made it possible to supply motors with operating characteristics tailored to specific system applications, it also seems likely that this progress was helped along by the desire for greater energy efficiency. Almost all power generation involves the use of generators and electric motors are widely used as power sources in factories, railways, and home appliances, and even in vehicles and data processing equipment. It is also widely known that motors account for approximately

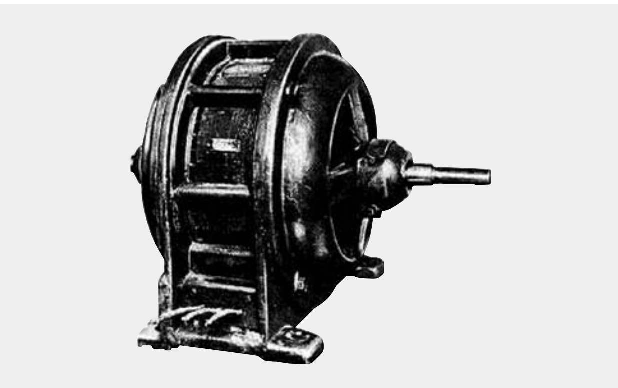


Fig. 1—5-HP (horse power) Induction Motor.
After building up experience and skills through the repair of electrical machinery, Hitachi produced three induction motors with an external diameter of approximately 400 mm and a weight of approximately 150 kg. The motors were designed by Naosaburo Takao (who later became Vice-President) and manufactured from parts made using a sheet steel processing machine imported from the UK and a coil winding machine they built themselves.

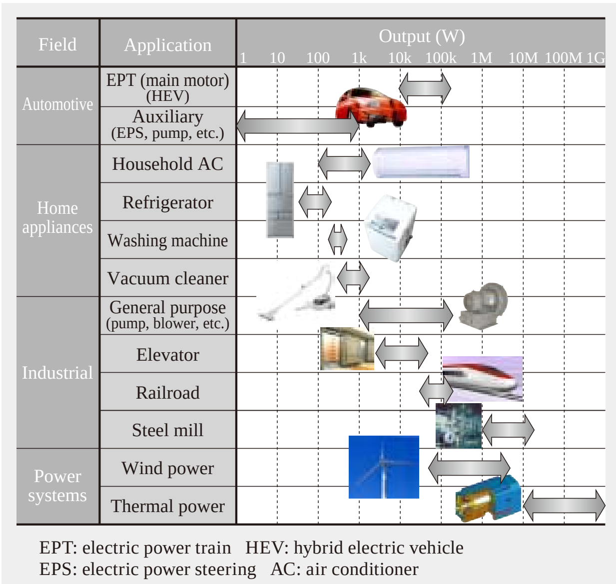


Fig. 2—Examples of Hitachi Electric Motor Products.
Motors and generators have advanced to become key devices that help underpin society.

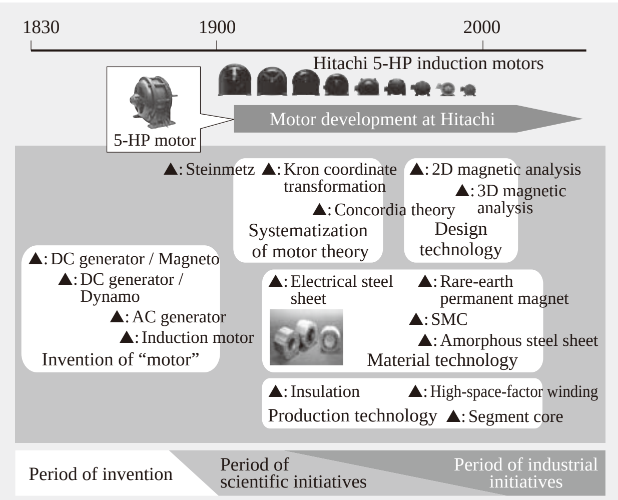
40% of all electricity consumption[1]. As well as playing a major role in industrial progress, it is no exaggeration to say that rotating machinery in the form of motors and generators form part of the foundations of modern society.

This article reviews the historical evolution of the technology used in electric motors together with generators, inverter control, and other associated components, describes examples of work being done on the ongoing development of motors, and looks at the outlook for the future.

CHANGES IN MOTOR TECHNOLOGY

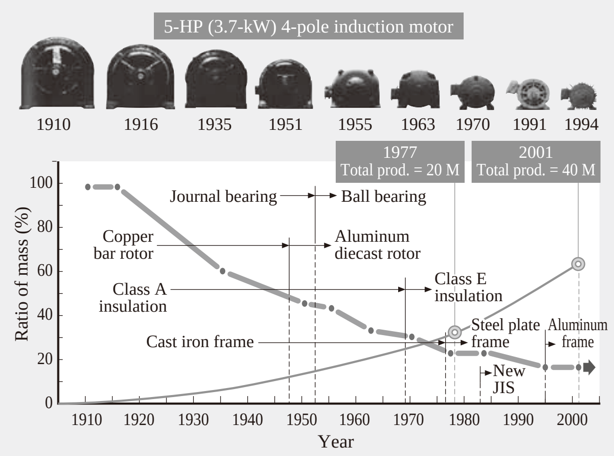
Fig. 3 shows the history of motors and associated technology. This history goes back nearly two centuries to a series of inventions inspired by Faraday's laws of electromagnetic induction in the first half of the 19th century. Because early motors were powered by batteries, most progress focused on DC (direct current) motors. This was followed subsequently by the invention of practical induction, synchronous, and other AC (alternating current) motors as AC power technology became more advanced. The principles behind the motors used today were largely worked out during the 19th century and they have undergone steady progress since then by drawing on advances in the three key enabling technologies of design, materials, and production techniques.

The 5-HP electric motor described above was also part of this history of progress. Fig. 4 shows a graph indicating how the weights of 5-HP motors made by Hitachi have changed over time. The adoption of a wide range of technologies has reduced motor size to about one-fifth that of the first motor made back in 1910 and advances in production techniques have seen cumulative production pass 45 million motors in January 2010.



2D: two-dimensional 3D: three-dimensional DC: direct current
AC: alternating current SMC: soft magnetic composite

Fig. 3—History of Motors and Associated Technologies.
The electric motor was invented in the 1830s and underwent scientific and industrial advances during the 20th century.



JIS: Japanese Industrial Standards

Fig. 4—Changing Mass of Hitachi 5-HP Motor.
Numerous technical developments have made motors smaller and lighter.

The following sections describe the changes that have taken place in the key technologies of design (analysis), materials, and production techniques that have underpinned the evolution of the electric motor.

Design and Analysis Technologies

This section takes as an example the use of electromagnetic field analysis in electrical and magnetic design which is considered the most important design and analysis technology for motors and generators.

Fig. 5 plots the progress in electromagnetic field analysis alongside the changes in the capacity of turbine generators which are the largest of all rotating machines. Because conducting studies on full-scale prototypes is impractical when developing large generators, electromagnetic field analysis has played a role in design investigations since the technique was first invented. Quasi two- and three-dimensional analyses were first used in the 1960s and three-dimensional analysis using the edge-element-based finite element method is now widely used[2]. Computing speeds have also been improved, not only because of the obvious improvement in the capabilities of the computers themselves, but also through the adoption of a number of computational techniques. A relationship is evident between this trend and the

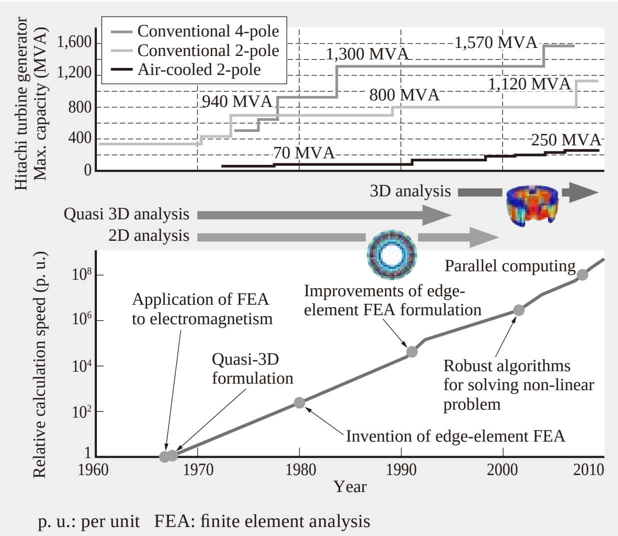


Fig. 5—Advances in Analysis and Design Techniques Relating to Electromagnetic Field Analysis.
Large and complex analyses have facilitated the development of motors, generators, and other machines thanks to advances in the computing environment.

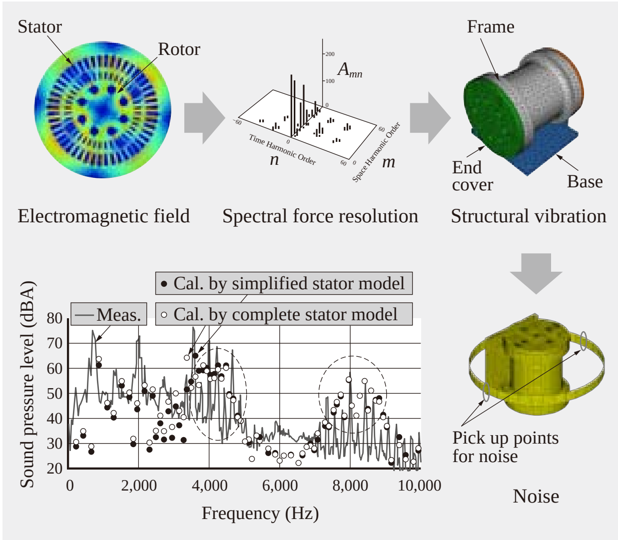


Fig. 6—Motor Electromagnetism and Noise Analysis.
Motor noise can be estimated quantitatively based on a coupled electromagnetic force, structure, and fluid analysis.

increase in the capacity of the turbine generators made by Hitachi, which has utilized electromagnetic field analysis from its very beginnings, and this corroborates the role that analysis techniques have played in increasing capacity.

The ability to use two-dimensional electromagnetic field analysis to analyze the mechanical movement of the rotating part of the motor (rotor) dates back to the latter half of the 1980s. This analysis took a considerable length of time in those days meaning that it could not necessarily simulate all the different motor operating conditions and accordingly it was only used in a limited way. To eliminate restrictions like this, Hitachi developed techniques for shortening the calculation time by taking advantage of the various cyclic aspects of internal motor operation based on motor theory(3). These expanded the range of cases that could be analyzed and allowed a complete cycle of the waveform to be calculated from analysis information for a particular region only, including analysis of situations that combined both long-wavelength components and very short-wavelength components as occur in induction motor rotor currents. Based on analysis techniques like these, it became possible to calculate losses caused by short-wavelength/high-frequency components that occur due to the motor structure and to separate fully the electromagnetic force components associated with each mode and frequency(4). Progress has also been made on coupled analysis techniques such as electromagnetic field analysis, structural analysis, and vibration and noise analysis and it has become possible in recent years to analyze motor noise through coupled electromagnetic force, structure, and fluid analysis(5) (see Fig. 6).

Materials and Production Techniques

Materials and production techniques have made a major contribution to improvements in motor performance over recent years. In terms of materials, mass production of electrical steel commenced in the 1960s and this material was quickly adopted for use in motors. Similarly, rare-earth magnets invented in

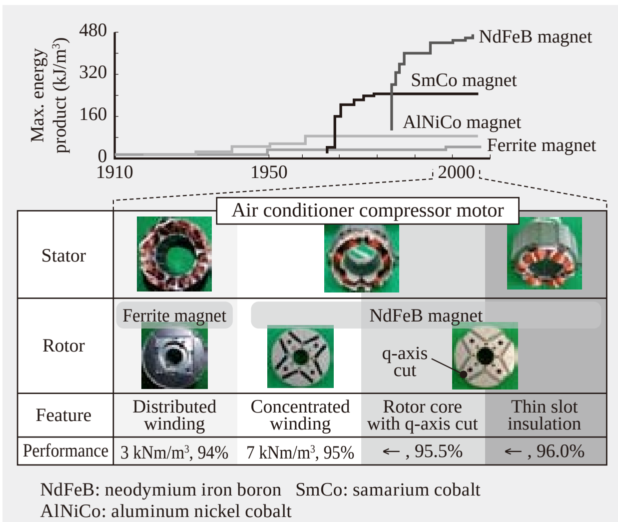


Fig. 7—Advances in Motors Due to Rare-earth Magnets.
The invention of the neodymium magnet led to a major step forward in motor performance.

1983 have played a major role in reducing motor size and improving performance.

Fig. 7 shows the history of permanent magnet development and advances in permanent magnet motors. Magnet energy product improves progressively from ferrite through alnico and samarium-cobalt magnets. While the most commonly used magnet in earlier times was the low-cost ferrite magnet, use of neodymium magnets (the strongest type of magnet) grew rapidly after their invention. Looking at the influence these magnets have had on Hitachi's air conditioner compressor motors, initially these motors used ferrite magnet rotors combined with distributed-winding stators. The arrival of the neodymium magnet saw the adoption of concentrated windings for the stator and, as shown in the figure, smaller coil end size. Although coil ends with concentrated windings are smaller, because they produce large harmonic components in the magnetic flux distribution, the stator and rotor shape become important design considerations. Consequently, advances in the electromagnetic field analysis techniques described above have been complementary with those in magnet materials and have allowed both axial length to be roughly halved and efficiency to be improved.

One example of production technology is a technique for achieving a high space factor (winding density) through use of a split core. Fig. 8 shows an example of a technique for increasing the density of wires in the winding slots by using a press-forming machine to pressure-mold an aligned pre-wound core. This achieves a high space factor by molding the wire into the shape of the slot that is to hold the winding without compromising the insulation performance

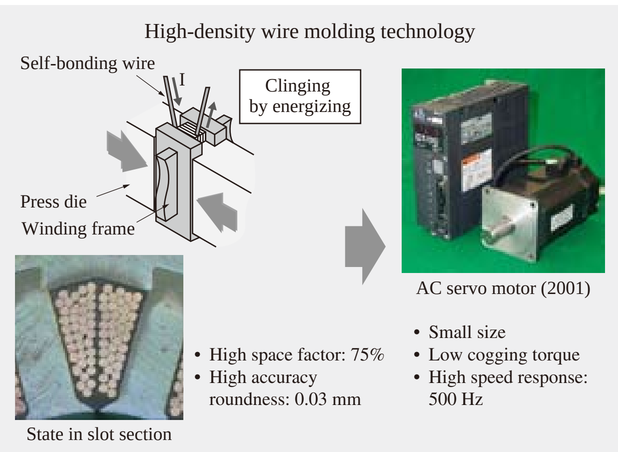


Fig. 8—Split Core and Winding with High Space Factor.
Better motor performance was achieved by improving the coil space factor and the precision of split core assembly.

of the coil wound around the mold. Technology was also developed to ensure that the stator core is put together with a high degree of roundness when it is separated and reassembled, resulting in small size and low cogging torque. This technology has been used in industrial servo motors since 2000(6).

INVERTER AND DRIVE CONTROL TECHNOLOGIES

Changes in Variable-speed Systems

Whereas DC motors had previously been the mainstay for variable-speed motor control, a major shift to AC motors took place in the 1980s. Fig. 9 shows the history of advances in motor drive control. The major factors behind these advances are the performance improvements in microcomputers and the main circuit elements used in inverters. The main control method changed progressively to AC motor vector control and, in terms of precision, response, and speed range, the performance of AC motors came to surpass that of DC motors.

Sensorless Control

Fig. 10 shows how vector control of induction motors has evolved. The general-purpose inverter has provided the driving force behind induction motor control technology. Sensorless vector control was incorporated in general-purpose inverters in 1989.

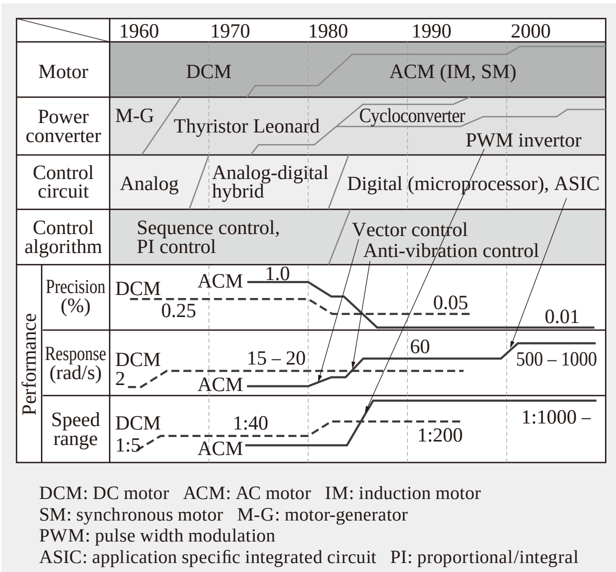


Fig. 9—History of Advances in Motor Drive Control.
The performance of variable-speed AC motor systems has improved with advances in control and power conversion equipment (Reference: 2001 Annual Conference of Industry Applications Society, The Institute of Electrical Engineers of Japan, S11-1).

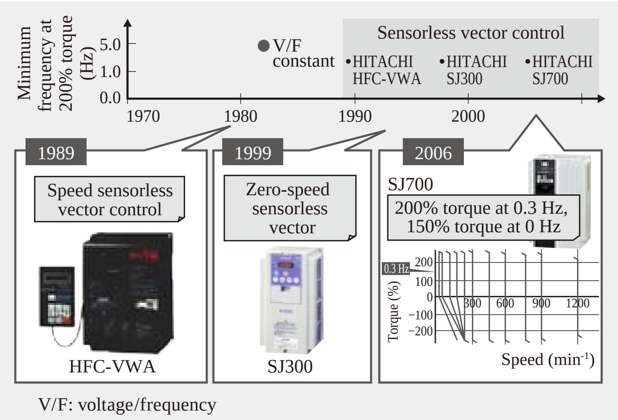


Fig. 10—Advances in Vector Control for Induction Motors.
Advances in vector control provided improvements in motor functionality.

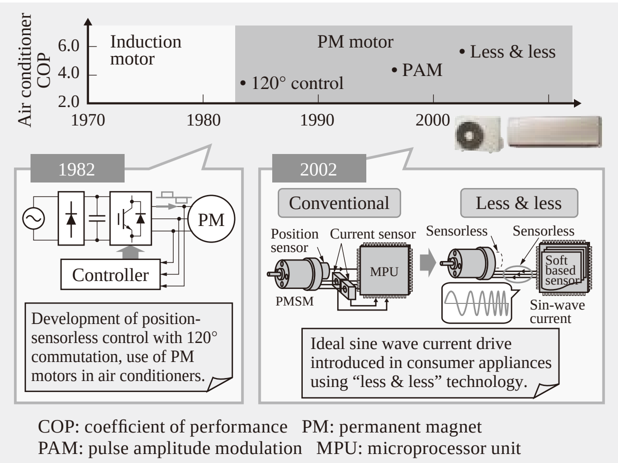


Fig. 11—Advances in Sensorless Control of Permanent Magnet Motors.
Advances in control techniques for permanent magnet motors that do not use position and current sensors and which were developed for use in air conditioners.

Compared to V/F (voltage/frequency) control used previously which kept the flux swing constant, vector control achieves a significant improvement in low-speed torque by controlling the torque components. Zero-hertz sensorless technology was first commercialized in 1999 and succeeded in performing vector control at 0 Hz, something that was not previously possible.

Fig. 11 shows the history of sensorless control techniques for permanent magnet motors. Development of permanent magnet motor control was undertaken primarily for air conditioning appliances. The size and efficiency of permanent magnet motors underwent a sudden improvement with the invention of rare-earth magnets, but because they cannot be started without an inverter, the applications for these motors have grown with the help of control technology.

Permanent magnet motors were introduced in Hitachi air conditioners in 1982 and mass-market models have used sensorless control since that time. Since then, permanent magnet motors and sensorless control have become the industry standard for air conditioners. PAM (pulse amplitude modulation) control which varies the amplitude of voltage pulses was developed subsequently and technology for driving motors with an ideal sine wave current was developed in 2002. A form of sensorless control that used neither the position sensor nor current sensor originally required when using vector control to drive a motor was developed at the same time, resulting in the ultimate circuit configuration for an ideal drive(7).

Sensorless control without position or current sensors is now being widely adopted in home appliances such as refrigerators, cordless cleaners, and washing machines as well as in other fields such as in industry or for auxiliary automotive motors.

EXAMPLE INITIATIVES FOR FUTURE

Concerns in recent years about how to prevent global warming are driving demands to reduce motor energy consumption by making motors even smaller and more efficient. To achieve both smaller size and higher efficiency, it is necessary to minimize as far as possible the various types of energy loss that occur inside motors while simultaneously dealing with the reduction in heat dissipation performance that results when motors are made smaller.

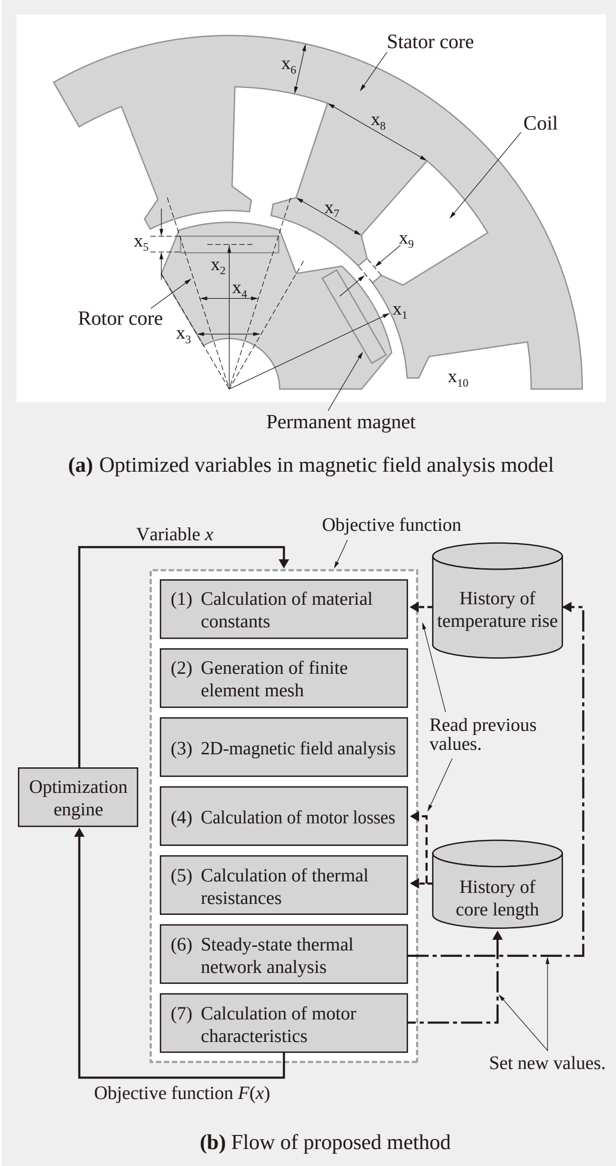
Against this background and on the occasion of the 100th anniversary of the company's founding, Hitachi, Ltd. in collaboration with Hitachi Industrial Equipment Systems Co., Ltd. produced a prototype concept motor in 2010 with the intention of achieving even smaller motor sizes in future. The prototype involved the development of technology to improve heat dissipation, a coupled magnetic field and thermal analysis technique that simultaneously analyzes the magnetic flux and heat flow in the motor, and design optimization techniques that are based on this analysis technology. It is this analysis technology that makes the greatest contribution to the design of motors for small size and the following sections describe the technology itself together with the prototype motor that was investigated with its aid(8).

Coupled Magnetic Field and Thermal Analysis and Shape Optimization Techniques

Because the objective was to make a smaller motor, a permanent magnet configuration was chosen for the prototype. The technologies required for permanent magnet motor design can be broadly divided into electrical design, cooling design, and demagnetization analysis (demagnetization: the loss by a magnet of its magnetism). Conventionally, the most common design approach has been to treat electrical design, cooling design, and demagnetization analysis separately and base the design on individual analyses that dealt with losses, temperature, or other parameters. Also, design conditions such as the variation in material characteristics or dimensional tolerances often have specific ranges. Accordingly, it was essential to run analyses based on severe conditions to ensure performance could be achieved even under worst-case conditions. This design methodology meant that excess margins were built into the motor's structural design and performance, in which case a series of prototypes would be produced after the design stage to adjust the extent of these structural design and performance margins.

Typically, the structural design of a motor is determined by the required torque performance and permitted temperature rise. Problems that arise when a motor is made smaller while keeping the same output and efficiency include that losses remain the same despite the smaller chassis and the excessive rise in temperature due to the reduction in surface area for dissipating heat. The problems associated with higher temperature include loss of magnetism in permanent magnets and an increase in winding resistance, resulting in a deterioration in motor torque characteristics. In other words, there is a trade-off between motor size and temperature. Accordingly, striking a good balance between temperature rise and torque performance is a key point when designing motors for small size and it is considered essential that the temperature in the actual environment where the motor is to be used be considered in the analysis if a design that achieves this balance is to be obtained.

In response, Hitachi has developed analysis technologies that can be used to design smaller permanent magnet motors by linking magnetic field analysis using the two-dimensional finite element method with thermal analysis using the equivalent thermal network method and combining these with shape optimization using mathematical programming methods. Fig. 12 shows a flow chart of this analysis technique. The analysis starts by setting assorted motor variables which are used as the basis of a two-dimensional magnetic field analysis which is followed by a thermal analysis. The results of the analysis are



(a) Optimized variables in magnetic field analysis model

(b) Flow of proposed method

Fig. 12—Newly Developed Coupled Magnetic Field and Thermal Analysis and Shape Optimization Techniques.
Linked analysis of heat and magnetic fields together with shape optimization achieved both a shorter design time and a smaller motor.

set in the objective function and the calculation is repeated until the objective function criterion (which in this case is the minimum motor size) is satisfied, with the optimization engine used each time to set the variables for the next iteration subject to the specified restrictions.

Prototype Results

A prototype 5-HP permanent magnet motor produced using the above techniques achieved a volume only one-fifteenth that of Hitachi's original 5-HP induction motor from 1910 (and only one-third

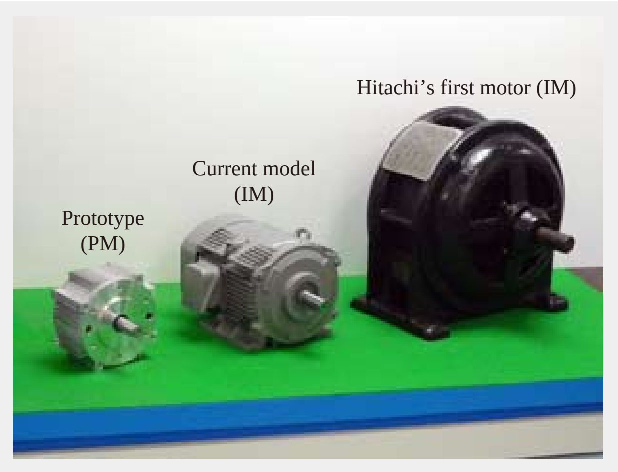


Fig. 13—Comparison of Original 5-HP Motor, Current Production Model, and New Prototype.
The body of the prototype motor is only one-fifteenth the size of Hitachi's original motor.

Fig. 14—Prototype Motor on Show at Hitachi uVALUE Convention 2010 held in Japan.
The prototype motor was included in the 100th Anniversary Exhibit and was made using a design prepared by Hitachi's Design Division.

the volume of current 5-HP induction motors) (see Fig. 13). The motor development also drew on the leading-edge materials of the Hitachi Group including the use of neodymium magnets from Hitachi Metals, Ltd. in the rotor, enameled wire from Hitachi Cable, Ltd., and organic chemical materials from Hitachi Chemical Co., Ltd.

An example of the prototype motor produced using a design from Hitachi's Design Division was unveiled to the public at the "Hitachi uVALUE Convention 2010" held in July 2010 in Japan where it was included in an exhibit celebrating the company's 100th anniversary (see Fig. 14).

Despite having such a high degree of miniaturization, the motor achieved a very high efficiency of approximately 94% in continuous operation tests.

FUTURE OUTLOOK

The evolution of the electric motor has been underpinned by design, production, and material technologies. In recent years in particular, motor performance has received a major boost from a variety of simulation techniques and other advances such as in materials technology, particularly in the field of permanent magnet motors. Prompted by concerns about reducing the burden on the environment, it is anticipated that, in addition to the expected further improvements in efficiency, the future will also see further research into motor structure aimed at reducing material usage through smaller motor sizes and making available materials that do not include scarce resources[9]. With use of electric motors and inverters becoming standard practice, it is also anticipated that motors, inverters, and motor control will become integrated in both a structural and design sense. In terms of control, vector control has entered widespread use starting with 120° commutation control, and it seems likely that control techniques that take account of motor non-linearity caused by magnetic saturation will enter practical use in order to combine controllability with small size and light weight[10]. In the field of design technology, meanwhile, it is anticipated that integrated design methods will be adopted using techniques based on overall optimization instead of designing the inverter, motor, and control separately as in the past and then having to tune their combined operation.

CONCLUSIONS

Motors and generators are examples of products that utilize magnetism in their operation. This article has reviewed the historical evolution and future outlook for these machines along with the inverter-based control systems used to drive them.

As with the relationship between motors and control and motors and inverters, it is anticipated that electric drive will continue to make rapid advances in the future through the ability to produce designs that are even better at balancing reliability, structural design, and value by designing motors and inverters as a single unit.

REFERENCES

(1) "Energy Efficiency in Motor Driven Systems 2007 Conference Reports," The Japan Electrical Manufacturers' Association, Electrical Manufacture **14** (Oct. 2007).

(2) S. Wakui, "3D Magnetic Field Analysis of a Turbine Generator Stator Core-end Region," The Transactions of the Institute of Electrical Engineers of Japan **124-D**, No. 1, pp. 77–84 (2004).

(3) H. Mikami, "Analysis of Higher Harmonic Components in Magnetic Fields on Three Phase Squirrel-Cage Induction Motors Considering Higher Harmonics in the Secondary Current," The Transactions of the Institute of Electrical Engineers of Japan **116-D**, 158–116 (Jan. 1996).

(4) K. Ide, "Analysis of the Harmonics of the Void Magnetic Flux Waves of the Synchronous Machine Considering Positive-phase/negative-phase Separation," The 1992 National Convention Record I.E.E.Japan, No. 708 (1992).

(5) K. Siohata, "A Method for Analyzing Electromagnetic-Force-Induced Vibration and Noise Analysis," The Transactions of the Institute of Electrical Engineers of Japan **118-D**, No. 11, p. 1301 (Nov. 1998).

(6) Y. Enomoto, "Factor Analysis on Cogging Torques in Segment Core Motors," The Transactions of the Institute of Electrical Engineers of Japan **124-D**, No. 1, p. 85 (Jan. 2004).

(7) Y. Kawabata, "Study of Control for Position Sensorless and Motor Current Sensorless Permanent Magnet Synchronous Motors Drives," Proceedings of the 2002 Japan Industry Applications Society Conference **1**, No. 171 (2002).

(8) N. Iwasaki, "Miniaturization Design and Performance Evaluation of Prototype Permanent Magnet Synchronous Motor Optimally Designed with Thermo-Magnetic Field Coupling Analysis," The Papers of Technical Meeting on Rotating Machinery, IEE Japan, RM-10-66 (May 2010).

(9) H. Amano, "Examination of Applying Amorphous Rolled Core to Permanent Magnet Synchronous Motors," The Papers of Technical Meeting on Rotating Machinery, IEE Japan, RM-08-122 (Nov. 2008).

(10) H. Nagura, "New Vector Controller for PM Motors Which Modeled the Cross-Coupling Magnetic Flux Saturation," Proceedings of the 2009 Japan Industry Applications Society Conference, No. 1-151 (2009).

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