125 years running

From the very beginning, ABB has been a pioneer in electrical motors and machines

Sture Eriksson

Rotating electrical machines have played a fundamental role in the development of modern society. They generate practically all electricity and perform most of the mechanical work in industries, public sectors and private households. The electrical motor is, by far, the most versatile type of motor, overshadowing combustion engines, hydraulic and pneumatic motors, as well as different types of turbines. The electrical motor's dominance is mainly due to its simple and clean supply of power, relatively low costs, high efficiency and reliability, good controllability, and adaptability to different applications. These rotating electrical machines cover an unrivaled power range, from microwatts to gigawatts. ABB, along with its predecessors ASEA and BBC, has contributed significantly to electrical machine development, especially for industrial and infrastructure applications.

PERPETUAL PIONEERING

The basic electromagnetic discoveries that were prerequisite to the development of electric motors were made in the 1820s and 1830s, with inventions of some primitive electrical machines being presented by the mid-19th century. The manufacture of useable machines began in the 1870s. Such electrical machines were fundamental for the establishment of both ASEA and BBC.

The Swedish company ASEA was founded in 1883 as a result of the invention of a DC dynamo by a young engineer called Jonas Wenström (1855–1893). These dynamos were intended for the supply of power to lighting installations 1. In 1890, Wenström was also granted a patent for a three-phase system, which consisted of a synchronous generator, a transformer and an asynchronous motor. Wenström is considered one of a few independent inventors of the three-phase motor.

In 1891, Charles E. L. Brown (1863–1924) founded, in partnership with Walter Boveri (1865–1924), the BBC company. Earlier, Brown had been manager for the electrical department in another Swiss company, Oerlikon. There, Brown developed both AC and DC machines, most notably the generator for the world's first three-phase transmission. Charles Brown contributed several other brilliant inventions around the turn of the century, eg, the turbogenerator with cylindrical rotor.

Technical aspects

The function of both generators and motors is based on the interaction between electric currents, magnetic fluxes and mechanical forces. The implementation can be made in several different topologies, but most common has been the traditional radial flux machine with inner rotor and outer stator. A relation for the output of such a machine is given by Equation 1 derived from Maxwell's equations.

Equation 1 $P = k \cdot n \cdot D^2 \cdot L \cdot A_s \cdot B_\delta$

where:
P = power, k = a constant, n = speed, D = air gap diameter, L = active length, A_s = linear current loading, B_δ = airgap flux density

The development of electrical machines has been heavily dependent on other technology fields.

This equation shows that the output is proportional to the speed of rotation, to the physical size of the machine, the airgap diameter and its active length, the linear current loading, and the airgap flux density. Electrical machine designers have always strived to develop smaller and more cost-effective generators and motors. At a given speed, Equation 1 indicates that the machine size can only be reduced by increasing the current loading and/or the flux density. The latter is limited by magnetic saturation of the iron in stator and rotor cores. What remains is the increase of the linear current loading resulting in higher copper losses in the windings. This was the traditional method for developing more and more compact machines by means of materials that could withstand higher temperatures and application of improved cooling methods.

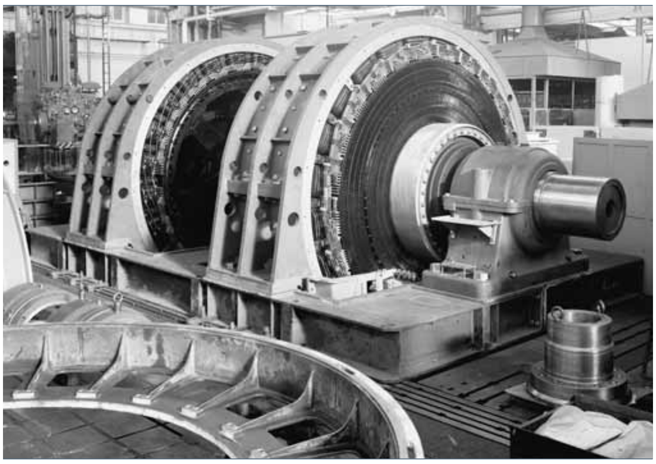
Electrical machines are subject to several types of stresses – electrical, mechanical, thermal and chemical – and often combinations thereof. The insulation must be able to withstand a high electrical field strength, and rotors must be designed with respect to centrifugal forces. Other mechanical stresses include those caused by stationary and transient electro-dynamic forces. In spite of high efficiency, the losses lead to high temperatures in different machine parts. Hazardous atmosphere, humidity and dust also constitute stresses that must be taken into account. It is no surprise then that electrical machine development has become a multi-disciplinary activity, requiring specialists in electrical, mechanical and material sciences, to mention a few.

Development

The 125-year development has focused on customers' need for more reliable and cost-effective machines. Numerous different machine types and variants have been designed to meet the requirements for each individual application. Many industrial drives require wide and accurate

1 Wenström's first dynamo built in 1882

2 Double-armature DC-reversing mill motor; BBC tandem drive from 1956



speed control. Others are located in atmospheres that are so hazardous that the motors must be explosion-proof. Original equipment manufacturer (OEM) customers, such as compressor or pump manufacturers, often specify special motor designs not entirely in accordance with the motor manufacturer's standard. The list of examples is extensive.

The development of electrical machines has been heavily dependent on other technology fields. Material technology has been of utmost importance since the very beginning. Another more recent and equally important area is power and control electronics. Computer-based engineering tools and simulation programs, for example, also had a significant impact.

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DC motors

DC generators and motors formed the basis for the early development of ABB and were also major products for BBC's initial business. A great advantage of this motor type was the ease with which its speed could be controlled, which explains why it has survived until even now. The motor speed is proportional to the voltage and to the inverse of the magnetic flux as indicated by Equation 2.

Equation 2 $n = k \cdot E/\Phi$

where:
n = speed, k = a constant,
E = electromotoric force (induced voltage), Φ = magnetic flux

DC motors are often voltage controlled up to a certain base speed and flux controlled above this speed, resulting in a constant torque region at lower speeds and a constant power region at higher speeds.

The first DC motors were manually controlled by means of resistors – a very inefficient method. A big improvement was the introduction of the Ward Leonard motor control system in which the DC motor was supplied with a variable voltage from a rotary converter consisting of an AC motor and a DC generator. The system not only provided good speed control but it even facilitated regenerative braking. The drawback was, of course, that it required three machines and was therefore expensive and voluminous. The Leonard system was used both by ASEA and BBC from the early to mid-20th century for applications such as paper machines, rolling mills, mine hoists, cranes and machine tools. The growth of motor size was fast – eg, a DC motor for a maximum output of 7,000 kW was delivered in 1915 to a Swedish reversible rolling mill.

DC drives with static converters first came into use during the 1930s when grid-controlled mercury arc rectifiers became available. This improved the system efficiency by 4 to 5 percent compared with the Leonard system, but the rectifiers were expensive and were only used for the supply of relatively large motors. However, these two drive systems were state-of-the-art for demanding applications such as rolling mills and paper machines, until silicon-type semi-conductor converters were introduced around 1960 – first diode rectifiers and soon thereafter thyristor rectifiers. The first thyristors were not powerful enough for very large drive systems – only up to 300 kW – but the development was fast and motors for 12,000 kW were being built by the end of the 60s. DC motors also have been widely used for vehicle propulsion; eg, in trams and trolley buses, fork lifts and electric cars, as well as locomotives and other rail vehicles. These traction motors were usually series-excited until separate excitation became the most common system for converter-fed motors.

All DC machines were outer-pole machines with the armature winding placed in the rotor and connected to the commutator. They were often open ventilated or closed with separate cooling from an external fan. The stator ring and the poles were, for a long period, made from solid iron. But the need for fast control and the introduction of thyristor rectifiers, which caused a lot of harmonics, led to the use of laminated steel in the stator. Commutation has always been a critical and limiting factor for DC machines, even after the situation improved with the use of commutation poles and compensation windings in the early 1900s. Reversible drives, eg, rolling mills, required such a fast change of rotation direction that big efforts were made to develop motors with low inertia. In many cases, it was even necessary to split the power between two mechanically series-coupled motors, known as tandem drives 2.

A remarkable DC motor was supplied by ASEA to the USSR in the mid-1970s for driving a large medical centrifuge to train cosmonauts. This motor, which could accelerate the centrifuge with a torque of 1,100 tm, had a vertical shaft and is probably the largest DC motor ever built. Until then, the largest rolling mill motors had maximum torques of approximately 400 tm.

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The end of the DC motor era has been proclaimed again and again over several decades and nevertheless the technology has managed to survive, although with a much-reduced market share. The DC motor is easy to accurately control, and it is still preferred by many customers for applications such as cranes and mine hoists, mixers and extruders, ski lifts and test rigs, to mention a few. Today, ABB offers DC motors with an output range of 1 to 2,000 kW. ABB's latest series of such motors, covering the output range of 25 to 1,400 kW, was introduced only a few years ago.

Asynchronous motors

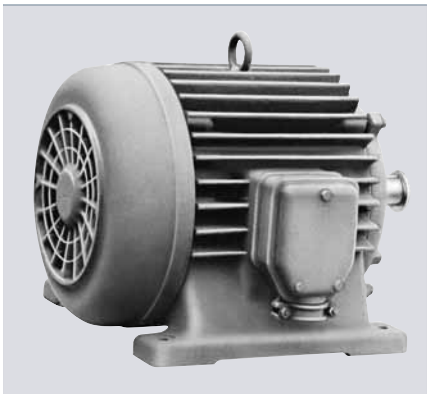
Asynchronous motors, often called induction motors, can be divided into different groups according to the type

of cooling, mounting, voltage, etc. Two common basic categories are:
- Motors with short-circuit rotors provided with so-called squirrel-cage windings
- Motors with wound rotors with the windings connected to slip rings

Both of these types were built by ASEA, BBC and several other manufacturers already before the end of the 19th century. The induction motors were less expensive than other motors and were very robust, and soon became the most common industrial workhorses. Manufacturers developed their own standard series of smaller motors, which were documented in catalogs around the turn of the 20th century.

Most of the old induction motors were open ventilated, and had cast iron stator frames and sleeve bearings. ASEA introduced ball bearings for small motors in 1910, and such bearings became more widely used in the 1920s and 30s. The need for safer motors in industries with dusty or even hazardous atmospheres led to the development of closed motors. These motors had to be derated with respect to the open motors, but the situation was improved by the introduction, in 1930, of forced surface cooling, ie, an external shaft-mounted fan that blew air along the outside of the stator, which was provided with axial cooling fins 3. The slot insulation was first made from particle board (presspan) combined with impregnated cotton fabric, but the latter was replaced by less moisture-sensitive materials in the mid-1920s.

3 Three-phase squirrel-cage motor with ball bearings, completely enclosed with external fan cooling (1934)

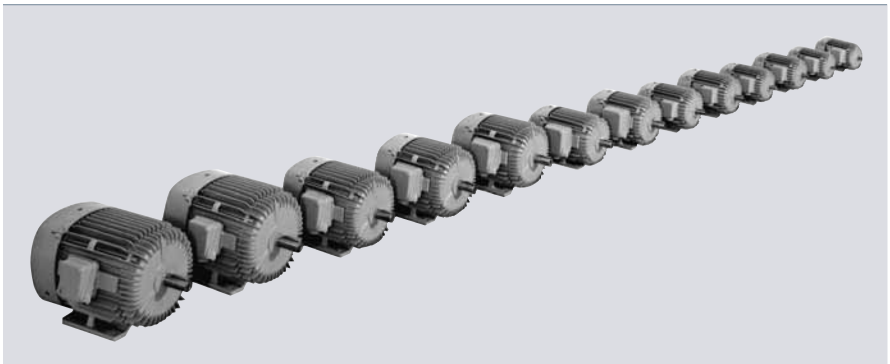


Smaller induction motors became more and more of a commodity, and customers wanted the ability to switch between motors from different suppliers.

Insulation of the individual copper strands was improved at the same time. The squirrel-cage windings in the rotors were made of copper bars placed in circular slots and soldered to short-circuit rings. Rectangular copper bars were introduced in these windings during the 1920s, significantly improving the starting properties. Brazing or welding replaced soldering for connection of the bars to the short-circuit rings.

Slip-ring motors were very common as long as the power grids were too weak to allow for direct-on-line starting. An outer resistor connected to the rotor winding via the slip rings limited the current and increased the torque. The resistance was successively reduced until the slip rings could be short-circuited. In the early 1920s, BBC developed a centrifugal starter consisting of a rotating resistor and a switch that short-circuited the resistor when the rotor had reached a certain speed. This invention improved the starting properties compared with squirrel-cage motors when it facilitated the use of wound rotors and start resistors while eliminating slip rings and external equipment. These motors were quite common for several decades.

4 Small motors with dimensions to IEC recommendations from 0.12 kW to 7.5 kW (1961)



Low-voltage motors and larger high-voltage machines are very different in several respects. The first category is standardized and much of the development has been process oriented. The production volumes have been large, and motor factories have been established in many countries over the years, both by ASEA and BBC. In 1935, an important step in product and process development was introduced by BBC with the squirrel-cage windings of cast aluminum for motors up to 3 kW. ASEA launched its first series of small motors with stator housing and rotor winding from cast aluminum in 1945. Modern synthetic insulation systems based on polyurethane and polyester replaced the old systems a few years later.

Smaller induction motors became more and more of a commodity, and customers wanted the ability to switch between motors from different suppliers. This created pressure for a common standard, which led to the standardization of dimensions, such as shaft height and footprints, as well as standardized ratings (output, voltage and speed). These kinds of standards were introduced by the International Electrotechnical Commission (IEC) in 1959 and in the United States by the National Electrical Manufacturers Association (NEMA) somewhat earlier 4. They have, of course, been subject to a number of revisions throughout the years, but are basically unchanged. Cost reduction has always been a major development goal but much of the recent induction motor development has also focused on improved efficiency and lower noise.

Methods for varying the speed of slip-ring motors through slip control had been long used, but they had significant limitations. The most successful type was the "Scharge" motor, inserted in 1910. Typical applications have been textile machinery, printing presses and others 5. When thyristors became available in the 1960s, allowing forced commutation of inverters, it was suddenly possible to develop variable-speed induction motor drives based on frequency control. In 1964, two BBC engineers presented a method for so-called pulse-width modulation (PWM), which later became the standard for this type of control. It took some years until this technology was ready for commercial introduction – BBC started delivering such drive systems during the 1970s, while ASEA preferred DC motors. However, the Finnish company Oy Strömberg Ab, acquired by ASEA a year before ABB was established, also belonged to the frequency control pioneers: Its knowledge and resources permitted the Finnish unit to establish itself as ABB's center for such drive systems. The inverters created current and voltage harmonics – especially in the first generations – which caused problems for the motors. The current harmonics induced eddy currents, and hence extra losses and overheating, and motors had to be down-rated. Other issues were insulation failures due to steep voltage spikes and capacitive bearing currents that could damage the ball bearings. New types of frequency converters and improved motors have practically eliminated these problems.

Synchronous permanent magnet motors have become an alternative to the induction motor for certain applications, especially low-speed, high-torque drives. This has been feasible due to the development of very powerful rare-earth magnets in the 1980s. ABB has launched a series of such motors, primarily for use in the pulp and paper industry. Even if there are alternative motor types, the induction motor will remain dominant due to its superior properties for fixed frequency drives and its competitiveness in terms of variable-speed drives.

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Synchronous machines

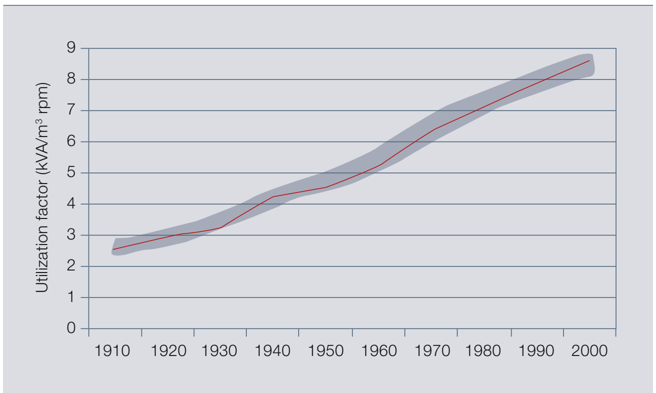
The development of synchronous machines has primarily been focused on large high-voltage machines, such as power plant generators, large motors and synchronous condensers. The generators, covering the range from high-speed turbo-generators to low-speed hydropower generators, were in many respects leading the development. Over the years, ASEA and especially BBC have built many large machines that have been milestones in the international evolution of power plant generators. 30-MVA machines were built in the early 1920s, and 100 MVA was passed in the 30s. Later, both companies would build much larger generators.

The old salient-pole machines had stator frames, rotor hubs and cores, as well as bearing pedestals, all from cast iron. Soon, steel casting replaced cast iron in rotating components, thereby increasing the safety with respect to fractures. Welded designs were introduced in the 1930s. These both increased the mechanical strength and reduced the weight of the structural parts. Stator windings of different types were used: Concentric windings with one coil side per slot dominated for multi-pole machines until the late 30s, when lap windings with two coil sides per slot became more common. For a long while, such windings were used for turbo-generators, offering better possibilities for rational production. The coil sides were, for larger machines, often Roebel bars in which the tiny copper strands were transposed within the coil side. This globally used method was invented and patented in 1912 by BBC engineer Ludwig Roebel (1878–1934). Originally, the companies used shellac-impregnated mica foil for insulating the high-voltage stator windings. Asphalt and mica insulation then came into use around 1930, mainly for machines with higher voltages. A new insulation system based on synthetic resins was developed and introduced by BBC in 1955 under the trade name MICADUR®. ASEA launched corresponding systems during the 1960s: One that used vacuum and pressure impregnation of the mica and glass tape, and one that used semi-cured, pre-impregnated tape.

Cooling is essential for electrical machines: The larger the machines are, the more sophisticated the cooling systems must be. The develop-

5 Three-phase shunt commentator motors with pipe ventilation and built-in spinning regulators (1965)

6 Utilization factor of large air-cooled salient pole synchronous machines



ment has gone from open-ventilated machines to closed machines with forced cooling by either external fans or inner shaft-driven fans, which circulate the air through attached heat exchangers 5. The latter is most common for large synchronous machines. Later, between the 1940s and 1970s, very efficient systems, such as hydrogen-cooling and direct water-cooling systems, were developed for very large machines – namely, turbo generators and synchronous condensers.

The excitation current for the synchronous machines was usually provided to the rotor winding via brushes and slip rings from shaft-driven or separate exciters (DC generators). In the 1960s, the availability of silicon diodes made it possible for ASEA and BBC to build a maintenance-free, brushless excitation system consisting of a three-phase generator with a rotating armature winding and a rotating rectifier that could be directly connected to the rotor winding in the main machine. This required that the diodes withstand high centrifugal forces, in some cases up to 5,000 g. This kind of excitation system has become increasingly common.

Large synchronous machines are used as generators driven by steam and gas turbines, water turbines, diesel engines, and wind turbines. Typical motor applications are compressor drives, large pumps and fans, refiners, rolling mills, mine hoists and ship propulsion. Synchronous machines are more efficient than induction motors; they also enable control of the power factor, but they are more difficult to start. Earlier, ASEA and BBC developed methods for the asynchronous start of synchronous motors. This involved pulling the motors into synchronism by exciting them at near full speed. Such methods are used even nowadays for large salient-pole machines with solid pole plates – a very demanding mode of operation.

The variation in output, speed and other requirements is so wide that standardization of larger machines has been difficult. Many machines were formerly tailor-made, but later development focused on modularization and standardization of components. The machines have become more cost-effective and their specific output has increased, as illustrated in 6. The largest synchronous motors ABB has built thus far are rated at 55 MW. (The company has built turbogenerators rated at up to 1,500 MVA and salient-pole generators rated at 823 MVA.)

In 1998, ABB launched a radically different type of synchronous generator for very high voltages, called Powerformer®, and two years later a corresponding motor, Motorformer™. The stator winding consists of high-voltage cross-linked polyethylene (XLPE) cable, enabling machine voltages in the range of 50 to 200 kV, substantially higher than for conventional machines 7. This allows the machines to be directly connected to a transmission line and step-up (or step-down) transformer, and can eliminate the need for bus bars and some switchgear. The maximum voltage up until this point was 155 kV for a hydropower generator. Earlier machines with unusually high voltages include a 20 kV generator delivered by ASEA in 1906 and a 36 kV machine designed by BBC in 1930.

7 Cable-wound high-voltage motor as used to power the Troll platform in the North Sea

Synchronous machines with super-conducting excitation windings will perhaps be the next major step in electrical machine development.

Attempts have been made from time to time over the last decades to develop synchronous machines with super-conducting excitation windings. High-temperature super-conductors, cooled by liquid nitrogen, have recently renewed the interest in such machines, and it will perhaps be the next major step in electrical machine development. However, such machines are still far away from being commercial, and the development of more cost-effective, traditional-type synchronous machines continues.

Sture Eriksson
formerly with ABB Generation in Västerås, Sweden and the Royal Institute of Technology, Stockholm
sture.ja.eriksson@telia.com

Further reading
Eriksson, S. (2007). *Electrical machine development: A study of four different machine types from a Swedish perspective.* Royal Institute of Technology, Stockholm.