The **Transformer**

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Just a century ago, the transformer made the distribution of electric power a practical endeavor. Many elements of modern life depend on it, yet it remains one of technology's unsung heroes. This article by John Coltman is adapted from his article that was published in the January 1988 issue of Scientific American *magazine (© 1997 by Scientific American, Inc. All rights reserved). Line drawings are by artist Hank Iken. The historical content, and tutorial aspects, should be of interest to IAS members, especially to graduates of recent years, in which computer technology has dominated electrical engineering curricula.*

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The technological revolution that has shaped civilization since the 1880s sprang from fundamental advances in communications, transportation, and electric power. The crowning achievements of inventors in communications and transportation—the telephone, television, automobile, and airplane—are, by now, familiar fixtures of everyday life. In contrast, the invention that ensured the ubiquity of electric power goes largely unrecognized by those whose lives are touched by it. It is a device that does not move, is almost totally silent, and is typically hidden in underground vaults or stowed behind screens.

That device is the transformer, an ingenious instrument developed late in the 19th century. The transformer is an essential component of modern electric power systems. Simply put, it can convert electricity with a low current and a high voltage into electricity with a high current and a low voltage (and vice versa) with almost no loss of energy. The conversion is important because electric power is transmitted most efficiently at high voltages but is best generated and used at low voltages. Were it not for transformers, the distance separating generators from consumers would have to be minimized; many households and industries would require their own power stations, and electricity would be a much less practical form of energy.

In addition to its role in electric power systems, the transformer is an integral component of many things that run on electricity. Desk lamps, battery chargers, toy trains, and television sets all rely on transformers to cut or boost voltage. In its multiplicity of applications, the transformer can range from tiny assemblies the size of a pea to behemoths weighing 500 tons or more. This article will focus on the transformers in power systems, but the principles that govern the function of electrical transformers are the same regardless of size or application.

The English physicist Michael Faraday discovered the basic action of the transformer during his pioneering investigations of electricity in 1831. Some 50 years later, the advent of a practical transformer, containing all the essential elements of the modern instrument, revolutionized the infant electric-lighting industry. By the turn of the century, ac power systems had been universally adopted and the transformer had assumed a key role in electrical transmission and distribution.

Yet, the transformer's tale does not end in 1900. Today's transformers can handle 500 times the power and 15 times the voltage of their turn-of-the-century ancestors; the weight per unit of power has dropped by a factor of 10, and efficiency typically exceeds 99%. These advances reflect the marriage of theoretical inquiry and engineering that first elucidated and then exploited the phenomena governing transformer action.

Foundations

Faraday's investigations were inspired by the Danish physicist Hans Christian Oersted, who had shown in 1820 that an electric current flowing through a conducting material created a magnetic field around the conductor. At the time, Oersted's discovery was considered remarkable since electricity and magnetism were thought to be separate and unrelated forces. If an electric current could generate a magnetic field, it seemed likely that a magnetic field could give rise to an electric current.

In 1831, Faraday demonstrated that, in order for a magnetic field to induce a current in a conductor, the field had to be changing. Faraday caused the strength of the field to fluctuate by making and breaking the electric circuit generating the field. (The same effect can be achieved with a current whose direction alternates in time.) This fascinating interaction of electricity and magnetism came to be known as electromagnetic induction.

Faraday left his ruminations without carrying them much further, certain that other inventors would pick up where he left off. Actually, for several decades there simply were no general applications for transformer-like devices. Initial experiments with "inductors" having a single wire wrapped around an iron core were marked by wonder at their ability to generate sparks when the current supplied to the coil was interrupted. Among the eminent scholars who explored this phenomenon was the American Joseph Henry, first secretary and director of the Smithsonian Institution, after whom the unit of induction is named.

The simple relations in an ideal transformer were by no means clear to the early experimenters. The arrangements they worked with were far from ideal, and the combined phenomena of self and mutual induction, with poorly coupled coils and imperfect iron, gave rise to much complex and mysterious behavior.

During this period of experimentation, it became apparent that currents circulating in solid metal cores were wasting energy. In order to minimize these so-called eddy currents, cores were constructed that were nonconducting in the direction perpendicular to the magnetic lines of force in the transformer. This was accomplished by making the core out of a straight bundle of iron wire (Fig. 1).

All the work of that period was carried out with batteries as power sources, the primary circuit being closed and opened to produce the necessary changing current. In the 1860's, the introduction of the dynamo—an electric generator also based on Faraday's insights—made ac generally available.

The first person to connect a transformer to an ac source was Sir William Grove, who needed high-voltage power for his laboratory work. In the absence of an obvious commercial application, however, the significance of the arrangement was overlooked, and it remained obscure until Thomas Alva Edison began to promote the idea of an electric-lighting system in the 1880s.

Electric Lighting

When Edison launched his scheme, light bulbs equipped with platinum filaments heated by electric current were already available. Arc lamps, using carbon electrodes, were also in use. Both kinds of lamps worked well, but their electrical characteristics placed some constraints on the way they could be wired together. In particular, the lamps had to be connected in series in one continuous circuit, so that all the lights in the system had to be turned on or off simultaneously.

Although such an arrangement was acceptable for applications such as street lighting, the inability to turn individual lamps on and off at will and the very high voltages present in the system when a large number of lamps were joined in series militated against series electric lighting in houses and small installations. On the other hand, parallel systems, in which each lamp operates on its own "subcircuit," required impracticably large copper conductors to supply the low-resistance, high-current lamps of the day. Edison's major accomplishment was the introduction of a carbon-filament lamp that, because of its high resistance, made parallel connection feasible. Edison opened the first commercial lighting plant in 1882 in New York City using carbon-filament lamps and a dc power generator.

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Photo of Faraday's original transformer (courtesy MIT Burndy Library).

The Introduction of Transformers into Lighting Systems

At about the same time transformers were first incorporated in an electric-lighting system in England, Lucien H. Gaulard and John D. Gibbs—a French inventor and an English promoter—used a form of transformer to add incandescent lamps to an ac arc-lighting system. Because the arc lamps were connected in series, with a fixed current running through the circuit, the low-impedance primaries of their transformers were placed in series with the arc lamps. The voltage of the secondary was available to operate lamps that could be turned on or off with little effect on the arc-lighting system. Gaulard and Gibbs were granted a patent for the device, which they called the secondary generator, in 1882, and they demonstrated their system in England in 1883 and in Italy in 1884. The secondary generator was not a very practical piece of equipment; it saw little actual use, but it stimulated thought among other inventors.

Among those who became interested in Gaulard and Gibbs's work were three Hungarian engineers from Ganz and Company in Budapest. They saw the demonstration in Italy and recognized the disadvantages of series connection. When they returned to Budapest, Max Deri, Otto

TRANSFORMER PRINCIPLES REVIEWED

Induction can best be understood in terms of lines of force, a convention Faraday introduced in order to describe the direction and strength of a magnetic field. The lines of force for the magnetic field generated by a current in a loop of wire are shown below. If a second, independent loop of wire is immersed in this field, and if the field changes with time, a voltage will be induced in the loop that is proportional to the time rate of change of the number of force lines enclosed by the loop.

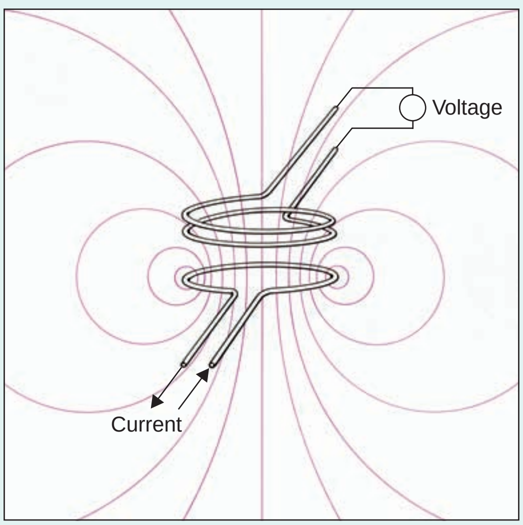
If the loop has two turns, such induction occurs in each turn and twice the voltage results. If a loop has three turns, three times the voltage results, and so on. In a transformer, the loop of wire that is fed the current and generates the magnetic field is called the primary. The loop that intercepts the field is called the secondary. Induction between the primary and the secondary is mutual; that is, a current flowing in the secondary will induce a voltage in the primary in the same way as the primary induces a voltage in the secondary. Furthermore, since the primary loop encloses its own lines of force, it can induce a voltage in itself. This process is known as self-induction, and it takes place in the secondary as well.

The concurrent phenomena of mutual induction between the coils and self-induction in each coil are at the heart of transformer action. In order for a power transformer to do its job effectively, the coils must be almost perfectly coupled and have high self-induction. That is, almost all the lines of force enclosed by the primary must also be enclosed by the secondary, and the number of force lines produced by a given rate of change of current must be high. Both conditions can be met by wrapping the primary and secondary coils around an iron core as Faraday did in his first experiments. Iron increases the number of lines of force generated by a factor of about 10,000, a property known as permeability. It also constrains the lines so that the primary and secondary coils can be spatially separated and still be closely coupled magnetically.

In an ideal transformer, all the lines of force go through all the turns in both coils. Since a changing magnetic field produces the same voltage in each turn of a coil, the total voltage induced in a coil is proportional to the total number of turns in that coil.

If no energy is lost in the transformer, the power available in the secondary must be equal to the power fed into the primary. In other words, the product of the secondary voltage and the secondary current equals the product of the primary voltage and the primary current. Thus, the two currents must be inversely proportional to the two voltages, and, therefore, inversely proportional to the turns ratio between the two coils. (The expressions of power are true only if the currents and voltages are in phase.)

Such an ideal transformer provides the electrical engineer with a tool quite analogous to the lever in mechanics, but instead of converting force and motion, the transformer deals in voltage and current. Instead of lever-arm length ratio, the turns ratio is the operative feature of the instrument. Of course, the ideal transformer has not yet been devised, but it has been closely approached in practice. Iron cores are essential components of all modern power transformers, and copper, because of its low electrical resistance, was and still is the material of choice for the coils.



Lines of force describe the magnetic field emanating from a coil of wire (the primary) carrying a current. A second coil (the secondary) placed in the field intercepts the lines (*color*); if the magnetic field is fluctuating, as it is fed ac, it will induce a voltage in the secondary coil. This phenomenon, which is known as electromagnetic induction, is the foundation of transformer action.

T. Blathy, and Karl Zipernowski built several transformers for parallel connection to a generator. The engineers designed two types of transformers having closed cores of iron wire that were much more efficient than those with straight wire-bundle cores (Fig. 2). One design had conductors wound around a toroidal, or dough-nut-shaped, core. The other had the wires of the iron core wound around a toroidal bundle of conductors.

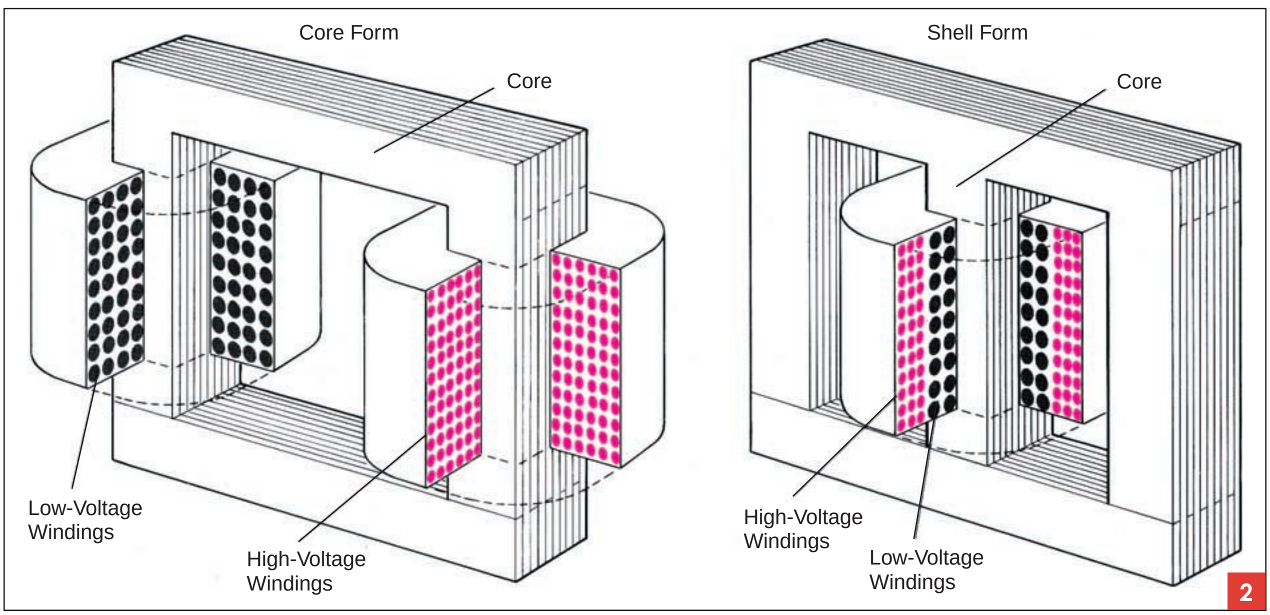
In May 1885, at the Hungarian National Exhibition in Budapest, Deri, Blathy, and Zipernowski demonstrated what is generally considered to be the prototype of today's lighting systems. Their system included 75 transformers in parallel connection, powering 1,067 incandescent Edison lamps from an ac generator supplying 1,350 V. The transformers had toroidal iron cores with the conductors wound laboriously around them. Although they were expensive to build, they were efficient enough to feasibly carry out the function for which they were designed: to operate low-voltage lamps from a high voltage distribution system.

George Westinghouse and William Stanley

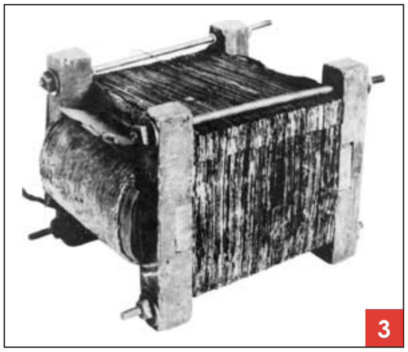
An American named George Westinghouse was also impressed by the Gaulard and Gibbs demonstration in Italy. In the 1880's, Westinghouse, already an established inventor and industrialist, was working on the distribution of natural gas for illumination. At the time of Edison's success he became interested in electric power, but he was wary of its applicability. His skepticism was well founded: in a parallel system, the increased load demands increased current, and a load the size of a city would require huge amounts of current. But transmission of high current demands low resistance conductors; it would be necessary either to send the power over large copper conductors, or build generating plants quite close to their loads, scattering many small plants throughout a large city.

Efficient transmission of high-voltage power, on the other hand, was possible with relatively small conductors, and many people were looking for ways to transmit electric energy at voltages higher than those required at the point of application. In 1884, Westinghouse hired a young engineer, William Stanley, who already had some ideas about solving the problem with transformers. When he heard about Gaulard and Gibbs's work, he encouraged Westinghouse to take an option on the transformer patents. Stanley was convinced of the superiority of parallel connection; by the early summer of 1885, he had designed some closed-core transformers.

Soon afterward health problems made it prudent for Stanley to set up a laboratory away from the smoky Pittsburgh atmosphere. With Westing-



Two transformer designs illustrate different approaches to core structure and wiring. Both cores are made from stacked laminations stamped out of iron sheets. In the design at the left, called core form, the primary encloses one arm of the core and the secondary the other. The shell-form core at the right is made up of E-shaped stampings with the primary and secondary coils nested together on the middle bar. In three-phase transformers the coils are nested on all three bars (see Fig. 4)



This Stanley transformer from the first ac power station in Great Barrington, Massachusetts, dates from 1885. The transformer is about a foot long; copper windings wrapped with cotton protrude between wood endpieces at the left. The middle arm of E-shaped iron laminations was slid into the prewound coil in alternating directions. The ends of the other two arms are visible as dense regions at the top and bottom of the laminations.

house's approval, he moved to Great Barrington, Massachusetts, and continued his work on transformers. In the meantime, Westinghouse, who was not entirely convinced of the wisdom of parallel connection, explored various combinations of the Gaulard and Gibbs secondary generators with another pioneer in electrical engineering, Oliver B. Shallenberger.

By December 1885, Stanley had made enough progress to win Westinghouse over. With the help of Shallenberger and another brilliant engineer, Albert Schmid, Westinghouse set about modifying Stanley's transformer (Fig. 3) so that it (unlike the Hungarian toroidal type) could be manufactured easily and cheaply. The core was made of thin sheets of iron cut in the form of the letter **H.** Coils of insulated copper wire were wound around the crossbar of the **H**, and the ends of the **H** were closed with separate strips of iron. Stanley suggested making the iron stampings in the form of an **E** so that the center prongs could be slid into a prewound coil. The **E**-shaped stampings were inserted in alternating directions, and straight pieces of iron were laid across the ends of the arms to complete the magnetic circuit. This construction is still common today.

The Westinghouse Electric Company was chartered in January, 1886. Over the next few months, Westinghouse and his associates patented the process for inserting stacked iron laminations into prewound coils, the provisions for cooling and insulating the transformer by immersion in oil, and the packaging of the assembly in a hermetically sealed container. Stanley constructed and installed several transformers in Great Barrington and wired the system for 500-V distribution from the laboratory to the town center, a distance of almost 1 mi. To demonstrate the possibility of efficient transmission over longer distances, he also used transformers to step up the electric power to 3,000 V and then cut it down to 500 V before sending it out on the town line. On 16 March 1886, Stanley's plant went into service. It was a great success, and Westinghouse proceeded to establish facilities for the manufacture and sale of equipment for distributing ac electric power.

Rapid Growth of the AC System

Edison and his associates fought the ac system in both the courts and the press, but theirs was a losing battle. The polyphase motor invented by Nikola Tesla provided an efficient way to utilize ac, and Shallenberger's invention of the ac watt-hour meter made it possible to accurately bill customers for energy consumption. These two inventions, together with the low cost of transmitting ac, gave the ac system a flexibility and convenience that soon relegated dc systems to a few specialized applications.

The next decade saw the rapid growth of ac electric power systems, marked by achievements such as the lighting of the 1893 World's Fair in Chicago and the installation of huge 5,000-hp hydroelectric generators at Niagara Falls. The first two of these went into service in 1895. Along with the staggering growth of electric power generating capability came great increases in the size of transformers. In 1895, a furnace at the Carborundum Company in Niagara Falls employed a transformer rated at 750 kVA. Five years later, some transformers were rated at 2,000 kVA and operated at 50,000 V.

It could be argued that the transformer built at the turn of the 20th century was already a mature product; the essential features of the device remain unchanged to this day. In fact, however, the transformer continued to evolve. Although it is still a cooled and insulated assemblage of iron laminations and copper coils, the improvement in transformer performance since 1900 has been quite remarkable. Modern transformers can operate at 765 kV, handle more than a million kVA, and have lifetimes of 25-40 years. These improvements give testimony to the efficacy of the industrial research process, a process whose rapid growth was closely associated with the rise of the electric power industry. The practitioners of industrial research, driven by a competitive system that rewards maximum performance at minimum cost, seek an understanding of natural phenomena in order to develop new products and processes and improve old ones. Competition provides the impetus for eliminating the limitations imposed by materials while, at the same time, giving rise to better designs and fabrication methods that take advantage of improved materials and fresh insight.

The parameters that characterize the ideal transformer depend to a large extent on the properties of the core, and it is in the core that the most significant advances have been made. The properties that are important in core materials are permeability, saturation, resistivity, and hysteresis loss. Permeability, as mentioned earlier, refers to the number of lines of force a material produces in response to a given magnetizing influence. Saturation designates the point at which the material's ability to amplify an external magnetizing force reaches a plateau. These two properties define the power-handling capability of the core. Electrical resistivity is desirable in the core because it minimizes energy losses due to eddy currents.

In contrast, hysteresis, the "memory effect" in magnetic materials, undermines the efficiency of transformer action. Because of the interactions among groups of magnetized atoms, the effects of magnetization tend to "stick" in a material, so that, if the magnetizing force is lowered temporarily, the material does not respond right away. In a transformer, this lag translates into energy wasted during every cycle of ac. Throughout the history of core development, the goal of the engineer has been to increase permeability, saturation, and resistivity while decreasing hysteresis losses.

One of the more important tools in this quest is the B-H curve, which graphically describes the relation in a given magnetized material among permeability, saturation, and hysteresis. It is a plot of the number of lines of force induced in a material (B) as a function of a varying magnetizing force (H). Shaped like an integral sign, tapered at each end, the curve is traced out on each of the cycles of the alternating driving current. Its slope corresponds to the permeability, the point at which it levels out at the top (or bottom) is the saturation value, and the area under the curve corresponds to the hysteresis.

The goal of the scientist has been to find out how these properties are related to the physical constitution of iron. Each property depends on cooperative interactions among the atoms in elementary magnets, which are affected by the crystal structure of iron and the presence of other elements and imperfections. The study of these complicated interactions is called domain theory; the insight it provides guides experimenters in their search for better transformer materials.

The thin wrought-iron sheets of which cores were made in the first Stanley-Westinghouse transformers had substantial hysteresis losses. These were gradually lessened by selecting iron from particular manufacturing sources so that the losses had been cut in half by the year 1900. Aging of the material was a problem; as the transformer grew older, hysteresis losses became progressively worse.

In the early 1900s, an English metallurgist, Robert A. Hadfield, was engaged in a long series of experiments aimed at determining how the properties of iron were affected by the addition of other elements. In a number of papers, Hadfield and his colleagues revealed the potential of silicon iron as a core material. Adding silicon to iron reduced hysteresis losses, increased permeability, virtually eliminated aging, and increased the electrical resistivity of the metal. Silicon iron, however, proved to be intractable to manufacture, and it was seven years before Hadfield's company delivered its first ton of transformer sheet. In the ensuing 17 years, silicon iron saved the electrical industry about $340 million—an enormous amount of money in the 1920s.

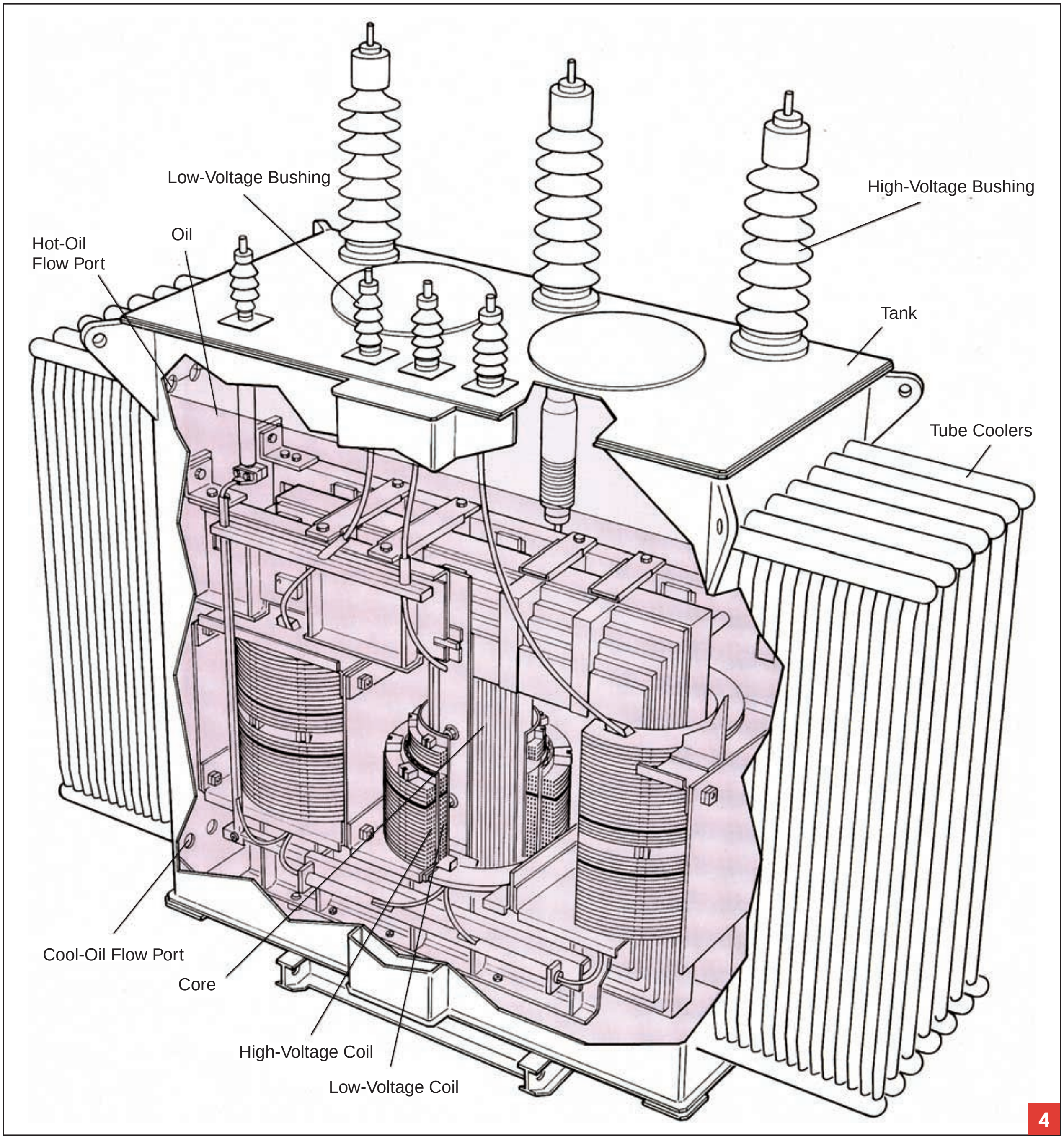
The next leap forward in core technology had its roots in the early 1930s, when the American metallurgist Norman P. Goss of the Cold Metal Process Company found that combined rolling and heat treatment of silicon iron produced a sheet with outstanding magnetic properties in the direction of the rolling. Goss did not realize it, but the effect of the process was to align the major axes of the iron crystals in the same direction, producing a cooperative magnetic interaction. When a core made from such a material was oriented properly in a transformer, the saturation improved 50%, the hysteresis losses dropped by a factor of four, and the permeability increased fivefold.

Again, the translation of that discovery into a method of production of satisfactory iron sheet was long and painful. The Westinghouse Electric Corporation and the American Rolling Mill Company (ARMCO) teamed up to develop suitable processes, as did the General Electric Company and the Allegheny Ludlum Steel Company. Cross-licensing between the two groups enabled transformer manufacturers to exploit one another's advances.

The requirement for a specific orientation of the metal in the core also necessitated substantial changes in the manufacturing of the core. No longer could a simple **E** form be stamped out of an iron sheet; in order to achieve optimal results, each leg of the **E** had to be made from a separate punching. Altogether, Goss's discovery did not become commercial reality until 1941, but its subsequent effect on transformer improvement was substantial.

Insulation And Cooling

Also bearing on the transformer's performance are electrical insulation and cooling systems. These two systems are intimately related because the amount of heat the core and conductors generate determines the longevity of the insulation, and the insulation itself—whether solid, liquid, or gas—serves to carry off some of the heat. Temperatures inside a transformer unit typically reach 100 ºC, the



The typical modern transformer is submerged in oil for insulation and cooling and is sealed in an airtight tank. Low- and high-voltage power lines lead to and from the coils through ceramic bushings. Inside the transformer, coils and core are packed close together to minimize electrical losses and material costs. The oil coolant circulates by convection through external radiators. In large transformers cooling is expedited by attaching fans to the radiators and circulation the oil with pumps.

boiling point of water. Under such conditions, deterioration of the insulating materials can limit the lifetime of a transformer.

Air provided the only insulation and cooling in the first Stanley transformers; the cotton that covered the conductors served mostly to hold them apart. Soon afterward, George Westinghouse immersed the entire transformer in a tank of oil and spaced the laminations in the core so that the oil could circulate by convection among them. The insulating properties of oil-soaked cotton turned out to be superior to those of dry cotton in air, and the combination of circulating oil and a variety of oil-impregnated cellulose materials, such as Kraft paper, became a standard that is still widely employed today (Fig. 4).

Although oils are inexpensive and effective as insulators and coolants, their flammability makes them unacceptable for units placed inside buildings. Chlorinated hydrocarbon liquids (PCBs), introduced in 1932, are not flammable and were once used extensively, but the recent discovery that such compounds have long-term toxic effects has prompted a ban on their use. Some transformers rely on air or nitrogen and glass-based insulators. These are essentially fireproof and can be installed indoors. The breakdown strength of the gas is sometimes enhanced by the addition of small quantities of fluorocarbons. Other dry transformers depend on cast-resin insulation made of polymerizing liquids that harden into high-integrity solids.

Technical progress in heat removal is largely responsible for reducing the overall size of the transformer assembly. At first, transformers insulated with oil relied on natural convection to circulate the coolant, but now, rather elaborate means of removing heat from the oil have been devised. Many units have fan-cooled, external radiators through which the oil-circulates by convection or pumping.

Engineers have also been experimenting for many years with vapor cooling, in which a nonconducting liquid with a low boiling point vaporizes when it comes in contact with hot parts, is transported as a gas to a separate compartment, and condenses there. Several transformers that have vapor-cooling systems are in operation, but their cost is not yet competitive with that of conventional units. The technology still holds promise and is being actively pursued.

The Future

As the transformer enters its second century of service, it is not easy to predict how its evolution will proceed. Research on amorphous metals (metals that essentially have no crystal structure) has elicited some very promising magnetic properties, but economical methods of producing such materials have yet to be demonstrated. Superconducting transformers, whose coils have no electrical resistance, have been built for demonstration in laboratories, but they must be operated at cryogenic temperatures so they, too, are still impractical. Even though such experiments promise technical advances, the overcapacity that has characterized the electric power industry during the last decade or so has discouraged moves to radically change the way transformers are made. The present increased demand for electric power may change this situation.

Finally, one might ask, "Is the transformer here to stay?" Solid-state circuitry has greatly reduced or eliminated the need for transformers in small electronic apparatus, such as radios, sound systems, and television sets. The availability of much larger solid-state devices has made it feasible, in some cases, to transmit high-voltage electric power as dc rather than ac, although transformers are still required in the conversion process. These are hints, however, that solid-state devices could take over some of the jobs of transformers in power systems.

The recent breakthroughs in high temperature superconductivity have raised hopes that materials might be found that are superconducting at room temperature. If they are, and if they can carry very large currents, the distribution of electricity as low-voltage dc, rather than as ac, might become practical. Even at temperatures presently achievable, it is speculated that superconductor transmission might become economical. The economical feasibility of such a drastic change in the way power is distributed has yet to be demonstrated.

In view of such advances and the unpredictable history of technological change, it would be foolhardy to maintain that the transformer will be here forever. But it seems very likely that the transformer will serve during its second century as it did in its first: silently, efficiently, and unobtrusively supporting the electric power systems on which so much of modern life depends.

Further Reading

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