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Introduction

In 1911, the physicist H.K. Onnes, of Leiden Laboratory in the Netherlands, was measuring the resistivity of metals at low temperatures. He discovered that the resistance of mercury completely disappeared when the temperature dropped to that of liquid helium (4.2 K). This phenomenon became known as superconductivity. In 1933, German scientists W. Meissner and R. Ochsenfeld found that the magnetic flux completely disappeared from the interior of materials with zero resistance when cooled to 4.2 K in the magnetic field. This zero magnetic field inside a material became known as perfect diamagnetism and is now called the Meissner effect.

In 1962, B.D. Josephson theoretically predicted the superconducting quantum tunneling effect, known as the Josephson effect. This is where a current flows for an indefinitely long time, without any voltage applied, across a device known as a Josephson junction (JJ) consisting of two superconductors coupled by a weak link. The weak link can consist of a thin insulating barrier (known as a superconductor-insulator-superconductor, or S-I-S) junction, and a short section of non-superconducting (S-N-S) metal. Subsequently, P.W. Anderson and J.M. Rowell experimentally confirmed Josephson's prediction.

Since its discovery, the superconductor and its applications have been one of the most active research fields in modern science and technology, due to its unique physical properties of zero resistance, perfect diamagnetism and the quantum tunneling effect. Superconducting technology is mainly applied in electrical engineering and electronics, and these applications and characteristics are listed in Table 1.1.

Table 1.1 shows that superconducting technology is of great value in the fields of energy resources, transportation, scientific instruments, medical care, national defence and large scientific project. Since its discovery, widespread application of the superconductor has become the pursuit of scientists and engineers. Before the 1960s, practical NbTi and Nb₃Sn superconducting wires were not manufactured until nearly half of a century after the discovery of superconductivity. Since then, superconducting technology and application of superconducting magnets are used for laboratory and practical applications. However, the conventional superconductors have not been widely used in power systems, particularly in alternating current (AC) applications, because of their need to operate at 4.2 K.

With the development of NbTi wires, the Magnetic Resonance Imaging (MRI) system has been increasingly used in hospitals for clinical diagnosis since the 1980s. In 1986, a true breakthrough was made in the field of superconductivity by A. Müller and G. Bednorz, researchers at the IBM Research Laboratory in Rüschlikon, Switzerland. They created a brittle copper oxide ceramic compound, the so-called high temperature superconductor (HTS), which presents superconductivity at temperatures above 40 K. Since then, several kinds of HTS have been discovered and the transition temperature from the normal to superconducting state has reached more than 90 K, which is higher than the liquid nitrogen temperature of 77 K.

Table 1.1 Main applications and characteristics of superconducting technology in electrical engineering

| | Applications | Characteristics |
|-----------------------------------|--|---|
| Superconducting power technology | Transmission power cable | Power transmission with low loss and large capacity |
| | Fault current limiter (FCL) | Safety and stability of grid |
| | Superconducting Magnetic Energy Storage (SMES) | Regulation of power quality and stability of the grid |
| | Transformer | Energy saving and small size |
| | Motor | Higher efficiency and small size |
| | Generator | Higher specific power, higher efficiency and increased grid stability |
| | Current leads | High current density and low heat leakage |
| Superconducting magnet technology | Magnet with high field strength | Large scientific project in particle and nuclear physics, Nuclear magnetic resonance (NMR), scientific instruments, magnetic separation, material preparation, biological and medical science |
| | Magnetic levitation (maglev) | Maglev train, maglev propulsion, flywheel bearing and high precision gyroscope |

Therefore, superconducting apparatus working at temperatures of 77 K made the widespread use of superconducting technology possible. With the great progress in development of HTS materials in the late 1990s, practical HTS tapes were manufactured and commercialized. The application of superconducting power technology was developed on a large scale, with the support of governments and multinational companies. Many prototypes of superconducting power apparatus, such as cable, transformer, FCL, motor/generator and SMES, were developed and demonstrated. At present, commercial superconducting apparatus, particularly the HTSs, are continuing to be developed with increasing investment from governments and companies. It is believed that a major breakthrough in superconducting technology will continue well into the future.

Applications of superconductors in electrical engineering primarily involve superconducting power technology and superconducting magnet technology. With their transition from normal state to superconducting state and then the largely increased current carrying capacity at high current density and zero resistance, superconducting power technology has developed further [1–3]. Table 1.2 lists the main advantages of superconducting apparatus and their influence on the electrical power industry. Other applications include the dynamic synchronous condensers (DSC), magneto-hydrodynamic (MHD) generation of power, cryogenic capacitors, gyrotrons, and superconducting induction heaters [4–14].

Table 1.2 shows that utilization of superconducting power technology cannot only improve power quality, enhance safety, stability and reliability of the grid system, reduce voltage level, and make a super large-scale power grid possible, but also greatly increases apparatus capacity and transmission capacity, and simultaneously reduces loss of power to the grid. Furthermore, the quality of power from renewable energy resources can be improved by using SMES to which a large grid can be effectively connected.

In comparison with a conventional magnet, a superconducting magnet has many unique advantages, such as no energy consumption, small volume, light weight, greater efficiency, greater thermal stability, longer magnetic field life and easier cooling, and also the ability to generate a high magnetic field in a relatively large space. Superconducting magnet technology has been extensively applied in large science projects, scientific instruments, inductive heating, magnetic separation, traffic, biomedicine and the defence industry [15–17].

Because superconductivity appears only at low temperatures, cryogenic technology is an essential prerequisite for any superconducting apparatus. Maintaining the cryogenic temperature consumes more energy and, in particular, maintaining the helium temperature will consume even more energy, which is a major impediment to the commercialization of low temperature superconductor (LTS) technology in AC operation. However, the cooling technology greatly influences customer perception of the superconductor

Table 1.2 Main characteristics, advantages and influences of several superconducting power apparatus

| Apparatus | Characteristics | Advantages and influences on power system |
|---|---|--|
| Cable | (1) High transmission power density (2) Low loss, compact size and light weight (3) Small reactance per unit length | (1) Low voltage, large current and high transmission power density (2) Small occupied urban space |
| Fault current limiter (FCL) | (1) Zero resistance in normal state and large impedance in fault state. (2) Combination of detection, trigger and limiting current (3) Fast response (4) No harmful effect on power grid | (1) Enhanced stability of the grid (2) Improved reliability of power supply (3) Protected electrical apparatus (4) Reduced cost of construction and retrofit (5) Increased transmission capacity of the grid |
| Transformer | (1) High power density (2) Low loss, small volume and light weight (3) Liquid nitrogen cooling and insulation | (1) Reduced area of installation (2) Fulfilling requirements for environmental protection and energy saving (3) Nonflammable |
| Generator | (1) High capacity density (2) Low loss, small size and light weight (3) Low synchronous reactance (4) High overload ability | (1) Reduced energy loss and occupied area (2) Improved stability of the power system (3) Compensated reactive power, improved power quality and stability of grid |
| Motor | (1) High capacity density (2) Low loss, small size and light weight | (1) Reduced energy loss and occupied area (2) Improved efficiency |
| Magnetic Energy Storage (SMES) | (1) Fast response (2) High conversion efficiency (3) Able to provide high power to grid in short time | (1) Fast power compensation (2) Enhanced dynamic stability of the grid (3) Improved power quality (4) Improved reliability of power supply |
| Flywheel energy systems with superconducting bearings | (1) High power density and large capacity (2) High conversion efficiency (3) Low loss | |
| Current lead | (1) Low thermal conductivity (2) High current density | (1) Low heat leakage (2) High efficiency |

product and its operational costs, especially its reliability. Except for certain high-value-added applications, such as MRI or NMR, the potential user is inconvenienced by the requirement to transfer liquid cryogen periodically. HTSs require low maintenance and low cooling costs for commercial acceptability, which is achieved since HTS application requires liquid nitrogen temperatures. The eventual widespread introduction of HTSs to power applications will depend on reliable closed-cycle refrigeration systems.

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