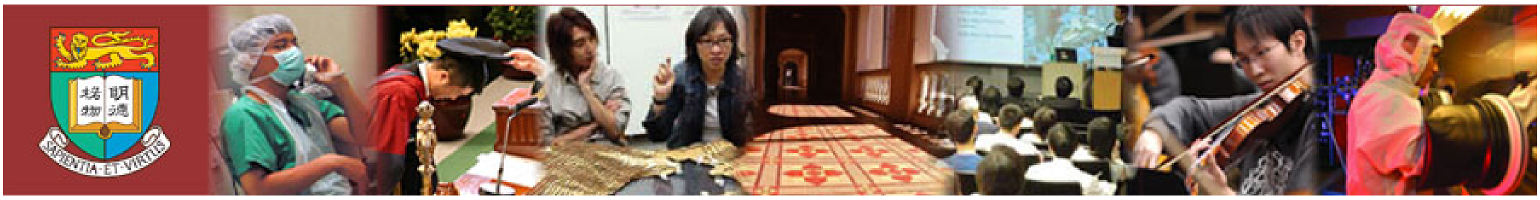

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PAPERS

Magnetics in Smart Grid

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A revolution in power transmission and distribution, driven by environmental and economic considerations, is occurring all over the world. This revolution is spearheaded by the development of the smart grid. The smart grid is bringing profound change to both the power systems and many related industries. This paper reviews the development of the smart grid and its correlation with magnetics, including electromagnetic compatibility issue, magnetic-field-based measurement/monitoring, and magnetic energy storage/conversion. The challenge to the field of magnetics and the usage of the cutting edge magnetics technology in the development of the smart grid are discussed. This paper enables researchers in the magnetics community to be acquainted with the progress in the smart grid and inspires innovative applications of state-of-the-art magnetics technologies in the smart grid.

Index Terms—**Electromagnetic interference (EMI), energy storage, magnetic field sensor, magnetics, smart grid.**

I. INTRODUCTION

ELECTRICITY is an electromagnetic phenomenon in nature. Its generation, transmission, and utilization all rely on the physics of electromagnetics. The modern electric power system has evolved into a highly interconnected, complex, and interactive network. The growing demand in energy independency, modernization of old infrastructure with new technologies, integration of various renewable energy and storage solutions, more efficient utilization of energy and asset, self-healing and resilience to attack and natural disasters, together with the pressure for sustainable development, motivate the development of the smart grid in the 21st century [1]. The smart grid concept has become more consolidated and gained more and more attention since 2009 after many countries or economic union announced their plans for the smart grid. The smart grid is generally envisioned as the platform for implementation of strategic development of power grids and optimized allocations of energy and resources. It is not only a revolution of electric power industry, but also the catalyst to create or breed new industries.

Magnetism, an interaction among the moving charges, is one of the oldest branches of science under constant active study with great implication to energy and environment. The rapid development in its theoretical understanding and experimental study, discovery of new magnetic materials, fabrication of next generation electronics, and applications in various aspects have rendered magnetism a key role in consumer electronics, power grid, energy, and environment. Spintronics integrating magnetism and electronics has enormous applications in novel electronic devices, whereby magnetic field applied on a spintronic device interacts with the spin of the electrons determining the electrical current and thus controlling the resistance of the device [2]. It provides a promising route for smaller, faster, and cheaper devices to record and convey information. In addition, it also largely accelerates the advances of magnetometers [3], [4]. Spintronic sensors including giant magnetoresistance (GMR) and tunneling magnetoresistance (TMR) sensors are vector sensors for magnetic field [5]. Recently, researchers have demonstrated their promising application for monitoring the electric current in overhead transmission lines and underground power cables to enhance situational awareness for the smart grid [6]–[8]. Renewable energy sources are emerging as the future paradigm for sustainable development of human society. Intensive research efforts have been placed on creating new magnetic materials that can improve the efficiency and performance of electric power generation, conditioning, conversion, and transportation. Scientists are fabricating micro- and nano-crystalline powders to create magnets with high energy density [9]. These high-performance permanent magnet materials can be used to create wind turbines with higher efficiency, longer lifetime, and better corrosion resistance [10]. Permanent magnet (PM) materials are critical for realizing electric vehicle technologies as well. Challenges exist for magnetic materials to achieve larger magnetization and coercivity to enhance reliability, power density, and overall energy capacity for motor applications [11]. On the other hand, soft magnetic materials with higher magnetization and permeability, lower coercivity, lower core losses, and lower cost are under active research for more energy-efficient transformers [12]. Environmental magnetism is a new interdisciplinary science involving various subjects such as lakes, marine sediments, loess, soils, biomagnetism, pollution, and archeology. This scientific topic is important for understanding climate change [13]. Magnetism is truly one of the scientific cornerstones of human knowledge and civilization in this modern age, and it plays a critical role in the smart grid.

The rapid development of the smart grid presents both new challenges and opportunities to the magnetism. This paper overviews the features and objectives of the smart grid and discusses the corresponding potential contribution from magnetism. These novel applications of magnetics technology in the smart grid are then described in sequence. Some of these applications described in this paper are still under development. This paper can stimulate the scientists and engineers in the magnetism field to contribute to the development of the smart grid.

II. REVIEW OF THE SMART GRID AND ROLE OF MAGNETISM

In brief, the smart grid is the integration of advanced sensing technologies, communication, computational power,

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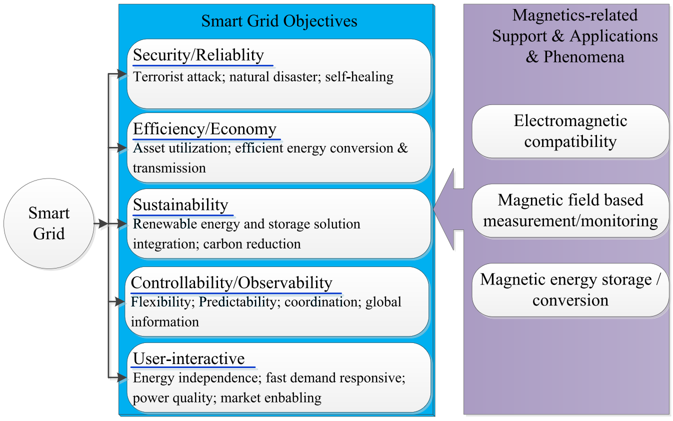

Fig. 1. Smart grid objectives and possible magnetics-related support.

Fig. 2. Example of smart electronics close to HV devices in GIS. (a) HV GIS device. (b) Smart electronics devices.

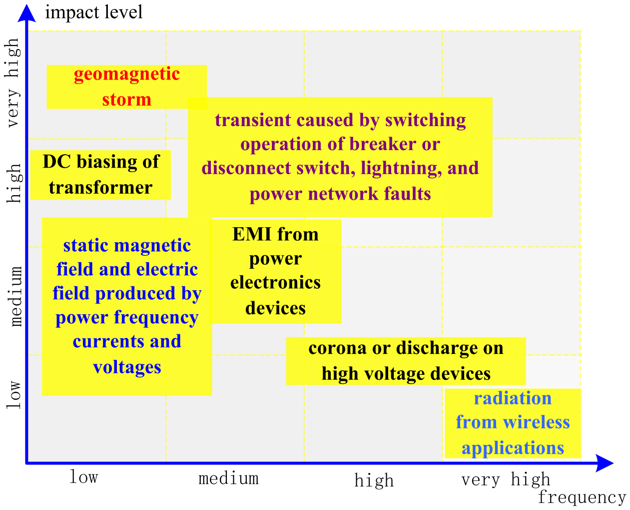

Fig. 3. EMI problems in smart grid and their characteristics.

and control to enhance the overall functionality of the electric power generation and delivery system [14]. The five fundamental objectives of smart grid are summarized in Fig. 1. The first two objectives are the short-term goals to satisfy the immediate needs of the existing power systems on system reliability, security, and cost-effectiveness. The third one for achieving sustainability by implementing renewable energy and carbon reduction is the long-term goal of the smart grid. The last two objectives are the technical approaches for realizing the smart grid. They stress on the observability of power system and the interaction with the users, which heavily rely on sensing and communication technologies.

The magnetics-related phenomena and technologies relevant to the smart grid are categorized into three types. Electromagnetic interaction is the fundamental principle for power generation and transmission. Many electrical events can produce electromagnetic disturbances composing of magnetic field and electric field. Electromagnetic compatibility (EMC) is highly concerned as it is critical for the proper operation of the essential facilities in the smart grid. With the rapid development of magnetic field sensors, the noncontact monitoring by magnetic field measurement can provide an advanced sensing technology for the smart transmission and distribution network. Magnetic field can store energy and act as the media for transferring energy. Magnetic-field-based energy storage /conversion may become one of the solutions for energy generation and delivery in the smart grid.

III. EMC IN SMART GRID

The smart grid faces all the EMC problems in the traditional electric power systems, but some new issues may arise due to the massive deployment of electronic and communication devices in substations and distribution systems. Gas insulated substation (GIS), due to its significant size reduction by adopting the excellent dielectric insulation properties of the sulphur hexa fluoride gas rather than air or oil, is more popularly used in the high-voltage (HV) substations for the development of the smart grid. The combined use of digital substation (or so-called smart substation) and GIS leads to increasing deployment of electronic equipments in switchyards and close to the HV devices. Fig. 2 shows a localized installation of the relay protection (computer-based smart electronics) with a GIS HV device in a smart substation, constituting an integrated primary and secondary systems. Although the possibility of electromagnetic interference (EMI) is decreased using fiber optic communication to transmit the information at process layer, some new EMI problems arise due to the following changes in the smart grid.

1) Electronic transformers are installed closer to the disturbance sources, making the analog/digital converters more susceptible to disturbance.
2) Transferring of secondary devices, such as smart terminals, merging units, relay protection devices, testing, measurement, and control devices, from the control room to the proximity of primary HV devices.
3) Installation of smart secondary devices of circuit breakers and the online monitoring devices in substations enduring harsh EMI environment, caused by HV or large current from power system, especially under fault transient conditions.

The EMI problems generally involve the interference source, the propagation, and finally coupling to the victim circuit. Fig. 3 shows the major sources of magnetics-related EMI in the smart grid according to their frequencies and impact levels.

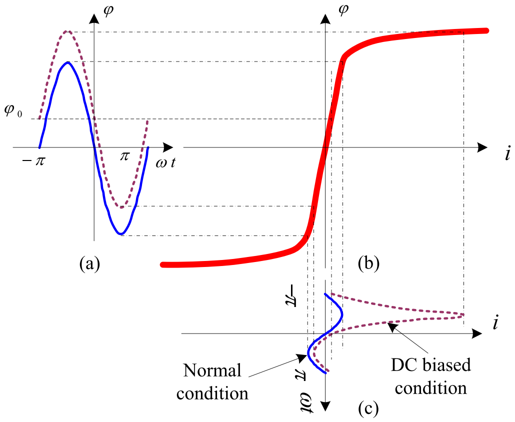

Fig. 4. Effect of dc bias or GIC on power transformer. (a) Flux cycle curve. (b) Flux φ - current i characteristics of power transformer. (c) Excitation current generated under normal condition and dc biased condition.

A. Low-Frequency EMI Caused by Geomagnetic Disturbance and DC Bias

The solar activity is periodic and once occurs it presents serious danger to the power systems. The charged particles of solar wind produce a fluctuating magnetic field that interacts and changes the Earth's protective magnetic field. The (nearly direct) currents induced in long transmission lines from geomagnetic storms are harmful to electrical transmission equipment. These induced currents degrade the performance of generators and transformers by inducing core saturation or overheating [15]. The induced voltage can cause equipment failure in telecommunication and protective relays for power systems [16]. Another type of dc related EMI is the dc-bias magnetization to power transformers caused by widespread use of HV direct current (HVDC) transmission in power systems. A portion of the dc current can intrude into the transformer neutrals of the substations in the vicinity of the electrodes of the HVDC converters. This problem is particularly serious in regions where the earth potentials are high due to soil type, soil moisture, temperature, underlying rock layers, and so on. This may increase the magnetizing current, harmonics leakage magnetic flux, and thus the losses, which in turn results in overheating and insulation ageing [17] From the viewpoint of magnetics, the impact of these two phenomena on the transformers can be explained, as shown in Fig. 4. Due to the saturation of flux φ - current i characteristics of power transformer, large excitation current is generated because of dc bias.

The geomagnetic disturbance (GMD) becomes an important concern in power engineering recently [18], [19]. An analytical model must be developed to facilitate the quantitative analysis of earth surface potential and geomagnetic-induced current (GIC) caused by GMD over a wide geographic area. Novel technology for measurement and evaluation of transformers under dc biased condition need to be developed.

B. Medium-Frequency EMI Caused by Working Current and Transients

The internal sources of EMI include fault conditions at mains frequency (such as short circuit), transients (such as lightning and switching), and power electronics. Typically, GISs occupy an area 20 times smaller than traditional air-insulated substations, hence the space inside a GIS is much more limited. Moreover, there is a prevailing trend to combine and integrate smart electronic components with relay protection in GISs. Thus, electronic devices are being moved closer to HV equipment where the transient EMI (kilohertz to approximately megahertz) might present a serious challenge. Generally, in smart grid systems power electronic converters are applied as interfaces between the renewable sources and grid or between grids to enable flexible regulation of electric energy. The power electronics may cause both conducted (by physical contact) and radiated EMI (by radiation) to power systems, at approximately kilohertz frequency band [20].

C. High-Frequency EMI

Above megahertz level, EMI could be caused by corona or discharge of HV equipment (from approximately megahertz to 400 MHz) [21]. While wireless communication (WC) is prohibited in traditional substations, it is now widely used in the smart grid. The WC at very high frequency (from approximately megahertz to gigahertz) can cause significant interference to the communication or electronic devices [22], [23].

Moreover, to achieve the smart grid objective of enabling end–user interaction, the bidirectional information flow is being established for interaction between the consumers and electricity suppliers. Electronic smart meters with various communication means such as cell and pager networks (from approximately megahertz to gigahertz), radio (approximately megahertz), power line communication (from approximately kilohertz to megahertz), WiFi (approximately gigahertz), and so on, are installed at the consumer sites. This may make the power system even more vulnerable to EMI, and also raise the issue of the potential detrimental effect to human health [24].

Generally speaking, much investigation is needed to develop technologies to measure, characterize and evaluate the effect of EMI in the smart grid. New approaches to analyze the EMI (modeling, propagation behavior, and coupling) should be developed. New standards for testing and evaluating EMI in the smart grid will be developed. In addition, it is expected that new shielding technology that can resist broadband and high-intensity EMI invasion will be in great demand.

D. Shielding of EMI

To avoid the EMI, shielding techniques with high-relative-permeability and high-relative-permittivity materials are adopted. For static or ultralow frequency magnetic field (below 100 kHz), the shielding made of high-relative-permeability material (for example Permalloy and Mu-Metal) can be used. It is based on the magnetic field concentration effect of high-relative-permeability materials. These materials interact with magnetic field and provide a low resistance path to the magnetic flux lines. High-relative-permeability material can be used to make closed containers for reducing the field inside. Fig. 5(a) shows the simulated shielding effect of a cylinder-shaped container made of Mu-Metal (relative permeability $\mu_r = 1 \times 10^4$). While the external magnetic field is 1×10^{-5} T, the inside magnetic field is reduced to 1×10^{-11} T. A multilayer shielding with smaller thickness can be used to obtain comparable shielding effect. Fig. 5(b) shows the simulation result of a double-layer cylinder-shaped Mu-Metal container. With the same external magnetic field 1×10^{-5} T, the magnetic field is reduced to 1×10^{-8} T by the outer layer and then to 1×10^{-11} T by the inner layer.

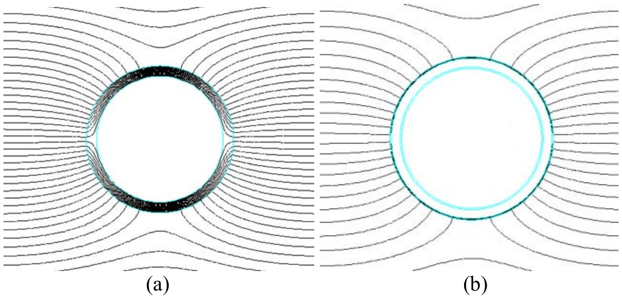

Fig. 5. Simulation results of Mu-Metal cylindrical magnetic shielding. (a) Single layer with 1 cm thickness. (b) Double-layer 1.5 mm thickness each.

For EMI with frequency beyond 100 kHz, since the relative permeability of the shielding decreases rapidly with the increased frequency, it cannot provide a low reluctance path to magnetic flux. Hence, the electric shielding method is adopted instead. For a shielded volume with an ideal conductor, an external high-frequency electric field induces the displacement current inside the conductor, which can counteract the external electric field and significantly reduce its effect. When an external high-frequency magnetic field is applied, eddy current is generated in the conductor, which can cancel the applied magnetic field similar to the case of shielding electric field described above. In the case of high-frequency EMI, the radiation energy of the electromagnetic field is absorbed by the conductor skin as a result of the well-known skin effect. Thus, there is no electromagnetic radiation inside the shielded volume enclosed by a conductor unless the conductor is thinner than the skin depth.

For EMI shielding over megahertz, novel metamaterials are being developed to generate effective shielding effect. Especially for certain frequencies, metamaterials could provide shielding-effect peaks. This property can be used to effectively suppress certain harmonics [25].

IV. MAGNETIC-FIELD-BASED MONITORING IN SMART GRID

A. Monitoring in Smart Transmission Network

To automate the transmission and distribution and establish the ability for the power grid to respond resiliently, it is necessary to deploy various types of advanced sensors in the power system to obtain real-time data for grid condition and predictive response [26]. Due to the causal relation between the electric current and magnetic field, magnetic-field-based measurement technology can play an important role in monitoring and reporting line conditions in real time and enabling rapid diagnosis and precise solutions appropriate to the abnormal events.

Current measurement is one of the fundamental tasks in power system instrumentation, serving for the functionalities such as metering, control, protection, and monitoring. Traditional current measurement based on magnetic-core current transformer (CT) in power system is inadequate for the development of the smart grid due to its intrinsic disadvantages including nonlinearity of the CT magnetic-core characteristic, incompatible with dc, narrow bandwidth (from tens of hertz to hundreds of kilohertz), bulky in size, and requiring regular maintenance for insulating oil [27]. As most of the power electronics devices are working at 20 kHz and above, broadband current measurement with fast response is required to capture the fast-varying (ms or μs) transient waveform for fault analysis, which is not achievable by traditional CTs. In some cases, such as HVDC, the current measurement requires a frequency response extending down to dc [28].

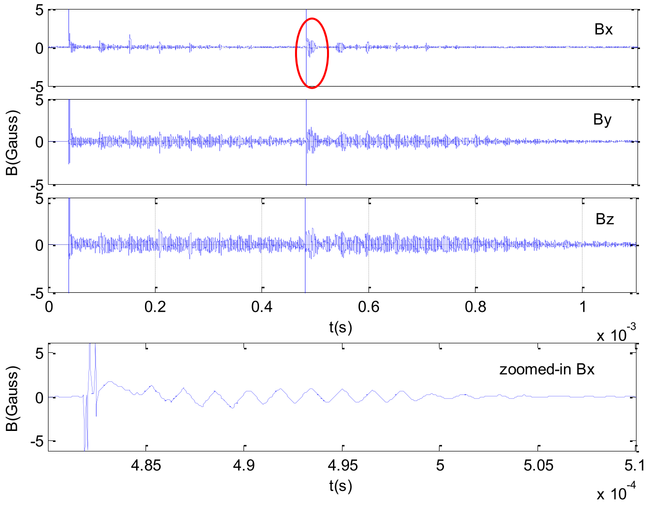

Fig. 6. Transient magnetic field measured during charging busbar in a 110 kV substation.

Magnetic-field-based current measurement can monitor the electrical current without physical contact, providing a novel low-cost and easy-to-install solution. Currently, current measurement with magnetic sensor arrays attracted the attention of many researchers [29]. With the drastic advancement of spintronics technology, high-performance magnetoresistive sensors are emerging. Measurement of current with anisotropic magnetoresistance (AMR) sensors [30] and GMR sensors [31], [32] were investigated. The even more sensitive TMR sensors are highly promising for current sensing [33] because TMR sensors are envisioned to achieve picoTesla sensitivity [4].

A novel approach for fault location of HV transmission line with MR sensors is proposed [34]. This approach is advantageous over traditional impedance-measurement-based and traveling-wave-based approach because it does not need to physically contact the HV transmission line and can accurately locate the fault span. Real-time monitoring of sag and current of a HV transmission line based on magnetic field measurement with MR sensors is also developed [6]. The sag and current can be found by solving the inverse problem analytically from the magnetic field measured by the MR sensors. The scope of this measurement solution is not limited to single target. It can handle multiple targets simultaneously using a MR sensor array to measure the magnetic field distribution. By integrating with the source reconstruction methodology based on stochastic optimization, a range of electrical and spatial parameters of multiple targeting cables can be derived from the measured magnetic field. These types of solutions can even be extended to some complicated application scenarios, e.g., the operation-state monitoring of overhead transmission lines with double circuits [8] and the underground power cables with three-phase conductors [7], which are not possible with the traditional measurement methods. The high-performance magnetic sensor can also facilitate implementation of Poynting vector measurement, which can be used to measure the power system quantities and many other parameters, such as loss, fault, power factor and reactive power, and so on [35]–[38].

B. Measurement of Transient Magnetic Field

Magnetic field measurement may provide solution for the broadband measurement and evaluation of magnetic interference (especially caused by transient) in smart substations, where the secondary systems are placed closer to HV equipments, as described in the previous section. Fig. 6 shows the x-, y-, and z-component of a transient magnetic field waveform recorded during a switching operation to charge a busbar in a 110 kV substation (3 m below the bushing of a transmission line connected to the busbar) with a three-axis AMR magnetic sensor. According to the spectrum analysis, sensing from dc to approximately megahertz frequency band is needed to measure the magnetic interference in substation.

V. MAGNETIC ENERGY STORAGE/CONVERSION IN SMART GRID

The generation, delivery, and conversion of electrical energy are the manifestation of the interaction between electricity and magnetism. Therefore, magnetic energy holds the key to improve the energy efficiency of power generation, transmission, conversion, and consumption, which is one of the most important concerns in the smart grid.

A. PM Generator and Motor

PMs have excellent magnetic properties, such as very high maximum-magnetic-energy-product $(\mathrm{BH})_{\max}$, can endure high temperature (~120 °C), which makes it very suitable for high performance electronic-magnetic devices. For example, large $(\mathrm{BH})_{\max}$ can lead to a much reduced volume of the devices, which is favorable for system integration. The operation loss can also be reduced by its large coercivity (H_c). The recent development of PM motors and generators offer several advantages such as increased power density and efficiency, decreased installation space, high stability at high temperature, and good overload ability, and so on. The PM generators are widely used to replace conventional wind generators (induction motor or doubly fed) because they have the advantages of high efficiency, high power factor, compact size, large rating, high controllability, stable operation, gearbox free (direct drive), additional reluctance torque, and low per unit cost [39]. The emergence of permanent magnetic actuator (PMA) can greatly enhance the intelligence of circuit breakers. The PMA can effectively reduce the closing surge and eliminate reigniting over voltage in interruption, greatly improving the performance of protective devices [40].

B. Magnetic Fault Current Limiter

As the continuing growth of the capacity of power grids, short-circuit current limiting becomes one of the research hotspots in the smart grid for two reasons: 1) the prospective fault current must be limited when a fault occurs (e.g., earth fault in a power transmission network) to protect power devices and 2) the switching capacity of the circuit breakers in power system needs to be reduced to lower the cost. Fault current limiters (FCLs) can realize more flexible and reliable circuit protection and hence contribute to the reliability, resilience, and responsiveness of the smart grid. Currently, there are at least two types of FCLs, including magnetic-saturated-core FCLs (MSCFCLs) and superconducting FCLs, making use of magnetic flux in their operation principle [41]. MSCFCLs were the earliest design [42] and is one of the most widely used today. In an MSCFCL, the electrical cable is wound around two magnetic cores. Each core is wound by another dc coil flowing with a dc current driving the core into saturation. During normal condition, the operating current is low and both the cores are under saturation. Thus, the effective impedance of the system is low. During faulty condition, the large fault current forces each of the cores to come out of saturation in alternate half-cycle. Thus, the effective impedance greatly increases, restricting the flow of the abnormally large fault current. In a superconducting FCL [43], the aforementioned dc current is provided by a superconducting coil [44]. The superconductor quenches when a high fault current begins, leading to the sharp increase in its resistance/inductance and reducing the fault current from what it would otherwise be.

C. Magnetic Energy Storage

In the traditional power system, grid energy is regarded as not storable. However, the integration of renewable energy into current power system infrastructure for sustainability is one of most important tasks in utility industries. Grid-scale energy storage is considered as the ultimate solution for integrating intermittent renewable power sources such as wind power, solar power, and so on into the power grid [45]–[47].

Superconducting magnetic energy storage (SMES) systems store energy in the magnetic field established by the flow of dc in a superconducting coil [48]. The energy stored in the field can be released back to the grid by discharging the coil, with round-trip efficiency greater than 95%. The amount of energy loss in this energy storage process is the least compared with other traditional methods because the electric current encounters almost no resistance in the superconducting coil. Moreover, the energy conversion process in SMES is nearly instantaneous and very high power output can be provided. This is in marked contrast to the other existing methods such as pumped hydro or compressed air [49], which require a substantial time delay to convert the stored energy back into electricity. The SMES can be used to integrate the distributed generation [50] and help shaping the load profile, hence reducing the peak generation capacity demand [51]. It can even be used to control low-frequency oscillation on large-scale power grid by providing damping in the smart grid [52].

D. Wireless Power Transmission

Another promising area is the wireless power transmission (WPT) by induction (short distance), resonance (medium distance), and microwave (long distance). Currently, one of the successful applications of short-distance WPT is the wireless charging of electric vehicles [53]. The transmission is conducted by magnetic induction between the coil on an electric vehicle and the coil laid on the ground. The distance of WPT can be extended to medium distance by adding capacitance to the system. The resulting system exhibits a magnetic resonant frequency that is a product of the inductance and the capacitance of the system. Energy can be transferred from the transmitting coil to the receiving coil if these two coils have the same resonant frequency and they are within meters of each other. This type of nonradiative energy transfer is more confined rather than spreading in all directions [54]. The microwave-based WPT was proposed that can theoretically realize the long-distance delivery over miles. The antennae at the receiving side collect the microwave energy emitted by the transmitter. The diodes connected with the antennae then carry out the rectification to provide dc electricity. A massively parallel receiver on Earth can be used to capture the low-cost solar power from space solar panels in the future [55].

E. Smart Components by Soft Magnetic Material

Microstructures, particularly grain size, determines the hysteresis loop of a ferromagnetic material. Conventionally, good soft magnetic properties require large grains ($D > 100\ \mu$m). However, lowest coercivities can be found in the smallest structural correlation lengths in nanocrystalline alloys for grain sizes $D < 20$ nm. The coercivity demonstrates D^6 dependence at small grain size while the permeability shows an analogous behavior being more or less inversely proportional to coercivity. There are the extraordinary magnetic properties that can be achieved with structural features on the nanometer scale. Therefore, nanocrystalline microstructures are the new materials for the manufacture of common-mode chokes for EMC filters (requiring high permeability) and transformer cores (requiring low coercivity) for their soft magnetic properties. A well known example of such soft magnetic nanocrystalline materials is the Fe-Cu-Nb-Si-B alloy [56]. This nanocrystalline alloy offers the unique advantages of low losses, high permeability, low magnetostriction, and high saturation magnetization of up to 1.3 T. Low magnetostriction is important because it is the primary cause of acoustic noise output from static electrical equipment (e.g., HV transformers). A higher Fe content in these nanocrystalline materials can further boost up the saturation magnetization up to 1.7 T [57]–[59]. There are already commercially available soft magnetic nanocrystalline alloys under various brand names such as NANOPERM, METGLAS, VITROVAC, FINEMET, and VITROPERM, which can be used in constructing smart grid assemblies for ensuring reliable and stable energy management.

VI. CONCLUSION

The smart grid aims to incorporate monitoring, analysis, control, and communication capabilities into the power grids to improve reliability, optimize asset utilization, improve cyber security, increase energy efficiency, and enable diverse generation and storage options. The smart grid will stimulate the development of many industries. Magnetics, as a traditional and still fast-growing branch of science, can significantly contribute to the development of smart grid. The operation mode of smart grid may present many challenges, which may require the use of magnetics related technologies to optimize the design or operation practice. Magnetic-field-based noncontact measurement can revolutionize some of the monitoring practices in the power systems. PM motors and generators can greatly enhance the energy efficiency while current limiters and energy storage systems based on magnetism are important enablers for system reliability and renewable energy. New soft magnetic materials and metamaterials are the fields that the researchers in magnetism should pay particular attention because they can provide innovative solutions for the smart grid.

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