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# A Patent Analysis of Prognostics and Health Management (PHM) Innovations for Electrical Systems

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**ABSTRACT** The use of reliability assessment and prediction in product design, manufacture, and operation has been an evolutionary process. Physics-based modeling and root-cause analysis of failure sites, failure modes, and failure mechanisms have proven to be effective in the prevention and fault detection of product failures over the past decades. Nevertheless, prognostics and health management (PHM) is now the focus of recent activity as noted by the amount of books, articles, and patents. This three-part review aims to give a comprehensive overview of PHM patents from three aspects: PHM for electrical systems, PHM for mechanical systems, and general PHM methodologies. This series of survey papers reviews the history of PHM research in industry and its current status based on U.S. patents from 2000 to 2015; discusses the application of PHM in the design, manufacture, and deployment of equipment in various industries; and presents some of the key research questions which remain to be addressed, with particular attention on the results reported in the last decade. In this part, 114 PHM patents for electrical systems are covered and comprehensively reviewed from the perspective of seven electrical appliances. Several phenomena are summarized through the investigation of U.S. PHM patents from 2000 to 2015. The proportion of the PHM patents for systems increased much more than for components. Compared with single sensor, sensor networks have achieved more applications so that objects are monitored more comprehensively and accurately. In addition, online assessment with on-board solutions is gradually replacing offline assessment of products using downloaded data to realize timely monitoring and troubleshooting.

**INDEX TERMS** Reliability assessment and prediction, prognostics and health management (PHM), application, patents, electrical systems.

## I. INTRODUCTION

Products and their systems are becoming more and more complicated with the continuous development of relevant technologies. Therefore, system reliability is even more urgent, especially given recent accidents in different fields that have caused serious damage. For example, electrical shorts caused mission failures in U.S. missile systems [1]–[3], radar systems [4], and the Galaxy IV and VII satellites [5]; gearbox failure in a 600-kW wind turbine cost over \$150k in 2006, including the cost of materials, labor, access, and downtime [6]; the grounding of 17 Boeing 787 airplanes due to two battery failures cost All Nippon Airways (ANA) alone more than \$1.1 million daily in 2013 [7]; and battery explosions in Samsung's Galaxy Note 7 in 2016 forced a global recall of all Galaxy Note 7s, leading to the ''death'' to this flagship mobile phone, and a loss of \$17 billion [8]. The results of catastrophic accidents are serious not only in terms of severe economic implications but also in human lives.

Failures in battery packs in electric vehicles caused a BYD taxi to catch fire and resulted in the death of 3 passengers [9]; the malfunction of some key sensors caused the Air France Flight 447 disaster that killed 228 people [10]. The cause of these accidents is related to system reliability, which is inseparable from their operational availability ($A_o$).

Operational availability is an indispensable standard technical indicator of product system design. In systems engineering, $A_o$ is defined as the ratio of how long a system has been used to how long the system should be available to use. It is a comprehensive parameter comprising reliability [11], maintainability, and supportability. In another view, $A_o$ is the probability that a system/equipment at any instant in the required operating time operates satisfactorily under stated conditions, where the time considered includes operating, corrective and preventive maintenance, administrative, and logistics delay time. $A_o$ is the function of system design characteristics, operation mission, and maintenance schemes. Practically, $A_o$ is measured by the ratio of the mean time between failures (MTBF, which only applies to repairable products) to the sum of the mean time to repair (MTTR) and the mean logistics delay time (MLDT). From this measure, the increase of MTBF and/or the decrease of MTTR or MLDT can achieve better operational availability. Accurate remaining useful life (RUL) prediction, early failure warning, and preventive maintenance can increase MTBF, which implies a decrease in failure frequency and/or the avoidance of frequent failures.

The decrease of MTTR or MLDT means that the time interval from fault occurring to removal of fault is narrowed. For example, transferring information in time by sensors is an effective way. In addition, advances in maintenance technology and simplified maintenance technology through many aspects in the whole life cycle of the product including product design, maintenance, customer service, and technical support, can all contribute to a decrease of MTTR and thus lead to better operational availability and lower-cost maintainability. A prediction gives information about whether a diagnostic component or system can perform its functionality as expected, including determining the RUL of the component or the length of normal operation time. The system uses the current state as a starting point, then provides a timely warning of subsequent failure so that the user can take timely measures to avoid failures. Accurate life prediction of products can help users maintain or replace old products in advance to prevent the loss caused by unexpected failure and improve the products' operational availabilities. In short, fast and accurate fault diagnosis, maintenance, and prediction are the main ways to facilitate a product's operational availabilities.

Traditional techniques to assess the operational availabilities of systems use handbook-based methods, which fit a constant failure rate model to field failure data. Some examples include the U.S. Military Handbook-217 (MIL-HDBK-217) [12], Telcordia [13], PRISM [14], and FIDES [15] and several other different versions referred to as the MIL-HDBK-217 progeny. However, it has long been known that these methodologies are fundamentally flawed. The assumption of constant failure rates was shown to be incorrect as early as 1961 [16], [17]. Since then this methodology was frequently shown to be either overly optimistic or to severely under-predict reliability [18]–[21]. In fact, several studies have shown that various versions of the MIL-HDBK-217 progeny do not even agree among themselves in their predictions [22]–[25].

Another way to assess product reliability is the *accelerated degradation test* (ADT). The research on ADT began in 1980s. Lu *et al.* [26] first pointed out the reliability of products using performance degradation data and put forward a simple linear model. ADT is based on the degradation data under stress conditions to evaluate the reliability information of the product under normal conditions. ADT research mainly focuses on statistical analysis, modeling of degraded data, and design and optimization of ADT, and identification of failure modes and mechanisms. Product degradation or degradation related parameters are used as functions of time (the function is generally called the "degradation trajectory"). Compared with the handbook-based approach that assumes a constant failure rate, Cox's proportional hazards (PH) model [27] is a kind of semi-parametric accelerated degradation testing model. It can be used to analyze the impact of different factors (e.g., operating and loading conditions) on product degradation. Because the proportional hazard model is used to analyze different factors influencing the survival time, selecting proper factors is first step when PH model is employed in ADT (either for mechanical equipment or for electrical equipment). Usually, analysis of factors generally include the important parameters that characterize the life of the object and environmental factors that effect the life of object, such as vibration, temperature and humidity. Therefore, if an important factor in this link is ignored, it will have an adverse impact on the estimated survival time. On the other hand, only when the dependent variable in the PHM model corresponds to the real degenerate state of the object's health, the PH model is meaningful. It can be seen that the PH model has high dependence on the selection of performance parameters and failure criteria.

A degradation path can be established two ways: First, as mentioned in the previous paragraph, a data curve fitting model can be built directly, which is a kind of experience-based method. The second way is based on physics-of-failure (PoF), physics-of-failure analysis involves the determination of the cumulative damage accumulation in the product due to various failure mechanisms induced by the monitored loads. On the basis of finding out the failure mechanism, the corresponding countermeasures are put forward to eliminate and avoid the failure and improve the reliability of the products. Therefore, PoF is an important part of PHM. PoF leverages the knowledge and understanding of the processes and mechanisms that induce failure to predict reliability and improve product performance. The following steps [28] are necessary when PoF is employed: monitor critical product parameters including environmental (e.g., vibration, humidity) and operational (e.g., temperature, voltage, power); conduct data simplification to make sensor data compatible with PoF model requirements; perform physics-of-failure analysis to determine the time (or cycles) to failure for each load profile and to determine the cumulative damage accumulation for all the load profiles in the life cycle of the product.

With the rapid development of sensing and communication technologies since 2002, PHM has emerged an enabling discipline consisting of technologies and methods to assess the reliability of a product in its actual life cycle conditions. Usually, reliability problems are manifested due to complexities in design, manufacturing, environmental and operational use conditions, and maintenance. PHM aims to determine the advent of failure, mitigate system risks, and trigger early maintenance tasks [29]. In addition, PHM incorporates the sensing, recording, and interpretation of environmental, operational, and performance-related parameters in reliability assessment and prediction. As one of the key enablers for achieving efficient system-level maintenance and lowering life-cycle costs, PHM helps users avoid failures, minimize loss of remaining life, improve repair efficiency, and reduce redundancies, all while targeting the enhancement of operational availability [30]–[33]. In this series of survey papers, patents aim to monitor the healthy state, diagnose fault of the object, or predict life of the object are all regarded as the PHM patents that are further studied and analyzed in this survey.

Data-driven PHM method and PoF PHM method referred above have their distinctive advantages and various constraints. In order to leverage the strength of different PHM methods, an integration or combination of two or more PHM methods, which is called a hybrid PHM or fusion PHM approach, is often exploited for a variety of engineering applications.

PHM benefits object systems by decreasing costs caused by fault, reducing inconvenience (the changes in the two aspects after the emergence of PHM: from regular maintenance to condition-based maintenance; from only detection to failure to the ability to determine the fault location.), and/or increasing safety. Different applications assign value to these benefits based on their own requirements and stakeholders. The challenge is to develop analyses that allow PHM to "buy its way into" particular systems. Nevertheless, there are success stories. NASA [34] reported that the return on investment (ROI) after implementing PHM in an aircraft may be as high as 0.58 over 3 years, assuming a 35% reduction in maintenance requirements. The ROIs resulting from implementing PHM in batteries used in light armored vehicles (LAVs) and the Stryker brigade combat team (SBCT) were estimated to be 0.84 and 4.61, respectively [35]. Goodman and Turner [36] estimated that the ROI for PHM of the electronics in a Eurofighter can be as high as 12.75 for one aircraft. Feldman and Jazouli [37] calculated the ROI for PHM in a Boeing 737 to be greater than 3.17 with an 80% confidence.

**The motivations of this series of reviews are listed as follows**.

1) Patent documents are closely related to industrial applications, compared with academic papers that mainly explore the frontiers of a subject. The review and analysis of patents helps readers know the applications of related technologies in practical industries, thus promoting the development of related disciplines and industrial applications.
2) Current PHM-related review papers are almost all based only on academic papers. This work can fill the knowledge gap of PHM patents review.

The rest of this paper is organized as follows. Section II introduces the basic information about inventors and assignees and how PHM patents have evolved since 2000; Section III classifies patents of electrical systems based on their applied industry, presenting future challenges; and Section IV presents conclusions.

## II. INVENTORS AND ASSIGNEES

A patent is a set of exclusive rights granted by a sovereign state to an inventor or assignee for a limited period of time in exchange for detailed public disclosure of an invention. An invention is a product or a process that solves a specific technological problem. Patents are a form of intellectual property. In U.S. patent law, an inventor is the person, or group of people, who contributes to the claims of a patentable invention. A patent assignee is a person, a group of people, or an entity that has the ownership rights to a patent. The assignee to a patent does not have to be the inventor of the patent.

The selected patents in this series of reviews are authorized patents downloaded from the U.S. Patent and Trademark Office (USPTO) (http://patft.uspto.gov/). They are mainly distributed in the four sections of the USPTO Cooperative Patent Classification (CPC) classification system: B. PERFORMING OPERATIONS, F. MECHANICAL ENGINEERING, H. ELECTRICITY and Y. GENERAL TAGGING OF NEW TECHNOLOGICAL DEVELOPMENTS. Since there is no specific patent category for PHM, three types of PHM patents were retrieved by keyword search. The acquisition of the target patents consisted of the following two steps:

**Step 1:** Keyword searching (keywords included: "issue date" from 1/1/2000 to 12/31/2015 2015, "abstract" included "fault" or "failure" or "health management" or "life prediction" or "fault diagnosis" or "life prediction" or "health monitoring"), then a large number of patents were retrieved.

**Step 2:** Manual screening of patents related to PHM on electrical systems, mechanical systems, and methodologies, which guarantees the integrity of the data in this series of reviews.

PHM patents are divided into three categories: PHM for electrical systems, PHM for mechanical systems, and general PHM methodologies. The classification method is based on the field of patent application. PHM patents for electrical systems refer to the patents that specialize in solving

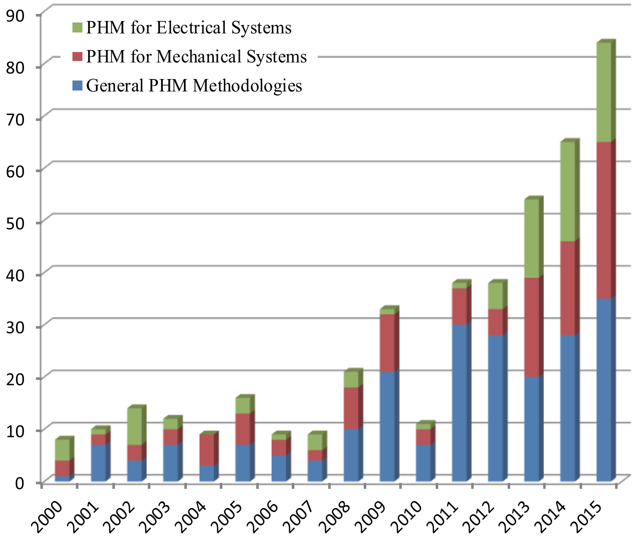


**FIGURE 1.** Number of PHM patents per year.

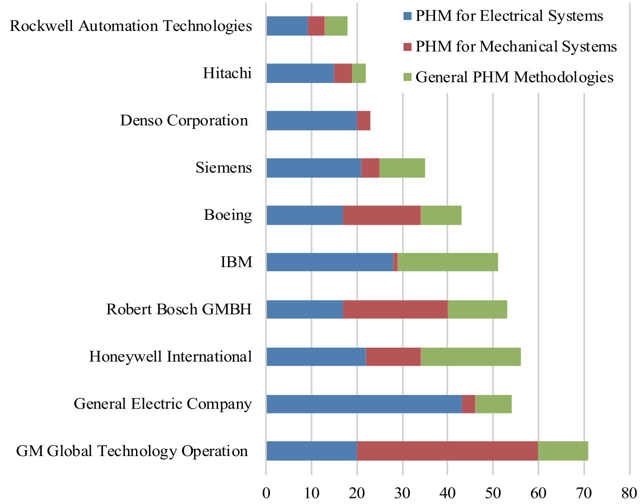


**FIGURE 2.** Top 10 PHM patent holders 2000-2015.

problems related to electrical failures. Similarly, PHM patents for mechanical systems refer to the ones for mechanical failures. For patents with embodiment about mechanical PHM or electrical PHM, the range of applications of the patent will be carefully distinguished. If the patent can be used for applications in different fields (i.e., not limited to the field of electrical or mechanical), the patent will be put into general PHM methodologies.

The number of PHM patents increased by more than 20 times from 2000 to 2015 (see Fig. 1). Before 2002, the backwardness of science and technology restricted the development of equipment, e.g., data acquisition devices (sensors, etc.), data processing and transmission devices (computers, wired networks, wireless networks, etc.) and visualization devices. Therefore, PHM research conducted by commercial companies was limited to a large extent. In addition, at that time, the equipment used for PHM (e.g., microcontrollers, miniaturized sensors, and wireless connections) was too expensive to be installed in all aircraft. McDonnell Douglas, Boeing, Raytheon, and Northrop Grumman dominated the PHM patents, accounting for 21 out of 34 patents (62% of the total patents). These four military-related companies patented PHM for critical applications, more than 70% of which were airplanes and engines. A total of 12 companies obtained PHM patents before 2002, and eight companies, including Rockwell, Honeywell, and Lockheed Martin, share eight of these patents. The PHM patents before 2002 mostly concern mechanical parts and systems.

However, in 2015, the top four companies in all three types of PHM patents (electrical systems, mechanical systems, and general PHM methodologies), GM Global Technology, General Electric, Honeywell, and Robert Bosch, owned only 32 out of 84 patents, with a share declining from more than 60% to 38% in 2015. Thirty-three companies obtained patents before 2015 overall, and 29 companies share 34 of these patents. This figure indicates that PHM research has been conducted by a wider range of companies since 2002. When PHM was first being developed, the assignees of the PHM patents were mainly distributed among military-related companies and the focus was mostly on mechanical components and systems. The assignees of the PHM patents have gradually taken up a growing proportion in small and medium companies. As seen from Fig. 1, the number of PHM patents has grown rapidly since 2010, which indicates that the benefits of PHM are being recognized by industry, and PHM research has successfully attracted more attention.

The 10 companies with the largest number of PHM patents, as of 2000 to 2015, are shown in Fig. 2. All are Fortune 500 companies. GM Global Technology, General Electric (GE), Honeywell International, Robert Bosch, and IBM have the largest PHM-related patent portfolios. For example, GE, which provides diversified offerings in a wide range of industry sectors from airplane engines to wind turbines, owns the most PHM patents. General Electric has been making efforts to integrate PHM techniques with their previous technologies to deliver reliable products with health monitoring capabilities. GE's remote monitoring and diagnostic software, known as Expert-on-Alert (EOA), was first launched and deployed on 200 locomotives in 1998. By 2005, EOA had been used on more than 5,000 locomotives and had reduced the maintenance personnel from 150 to 2 because of the increased uptime, reduced road failures, and improved shop productivity. GE also expanded its PHM techniques to wind farms with an anomaly detection algorithm named PulsePOINT, to GEnx engines with a full authority digital electronic control (FADEC) system [38], and to offshore drilling facilities using a blowout preventer (BOP) and remote monitoring and diagnostics (RM&D) [39]. Honeywell, the company that owns the third largest number of PHM patents, has also conducted extensive research on PHM and integrates PHM technology with their products, such as the corrosion and corrosivity monitoring systems (C2MS) for rotorcraft platforms, expeditionary force vehicle (EFV) drive train prognostics systems (DTPS) for marine/automotive vehicles, and machinery prognostics system (MPROS) for condition-based maintenance and prognostics of mechanical equipment (e.g., engines, generators, and chilled water systems). According to Fig. 2, the total number of PHM patents for applications owned by the top 10 PHM patent holders was more than that of the patents for general PHM methodologies from 2000 to 2015.

By application area, GE leads the PHM patents for electrical systems, while GM Global Technology and Robert Bosch own the most PHM patents for mechanical systems. Other players, such as Honeywell and Rockwell have PHM patents in a range of different application areas.

Concerning PHM for electrical systems, GE, IBM, Honeywell, and Siemens have the most powerful patent portfolios. Siemens, ranking fourth among the assignees of PHM patents in total, has the most patents in PHM for medical care, most of which deal with medical image processing and classifiers that determine cancer survival rates, heart attack rates, and tissue detection. In this class, PHM patents for semiconductor components, computers, and their accessories, such as hard disk drives, memories, and mainboards, account for more than 60% of all PHM patents for electrical systems. Additionally, PHM patents for batteries represent a less than 10% share of patents for electrical systems up to 2015. However, the number of patents for battery monitoring and prognostics is expected to increase due to the hybrid/electric vehicle and smart grid industries, which view safe, smart, and economical batteries as an indispensable energy storage component in revolutionizing the way people use energy. Therefore, research on PHM batteries needs to be strengthened.

In terms of PHM patents for mechanical systems, the top 10 assignees, including GM Global Technology, Robert Bosch, Boeing, GE, Honeywell, and Ford Global Technologies, own almost 45% of the total issued patents in this class. Among them, the four leading companies, GM Global Technology, Robert Bosch, Boeing, and GE, together own 94 PHM patents, accounting for a third of all issued patents for mechanical applications. This indicates that a majority of companies in mechanical system industries have not developed PHM techniques, have not applied PHM to their products, or have not patented their PHM techniques. IBM, Honeywell International, and General Electric dominate the patents of general PHM methodologies because their business spans a variety of industries and requires research on general PHM methodologies and implementation methods.

General PHM methodologies accounts for the largest percentage of all PHM patents since 2008, indicating that an increasing amount of research has been conducted on the fundamental methodology of PHM in a system. The number of PHM patents for other applications such as architecture and medicine has been steadily increasing every year since 2004, which shows that the companies in those industries are using PHM.

The increasing demand for health monitoring, diagnostics, and prediction of useful life is convincing more companies to use PHM methods and applications. A number of companies have determined the value of patents and have been targeting patents for intellectual property (IP) leverage and internal use. While research in PHM is dominated by American and European companies, Asian companies have stepped up their activities since 2007. Samsung has joined the ranks of the 20 leading assignees, and Fujitsu, Toyota, and Taiwan Semiconductor Manufacturing Company (TSMC) have started filing for patents. Interestingly, all of these Asian companies are in the automotive and semiconductor industries, illustrating the fact that Asian companies have gained a large market share in those two industries. More Asian companies, especially Chinese companies, are expected to join the patent number ranking resulting from the transfer of manufacturing to China and industrial upgrading in companies that will need to meet the requirement of higher reliability of their products.

## III. PHM FOR ELECTRICAL SYSTEMS

Electrical systems are present in almost all areas of our daily life and industries. Since unexpected electrical failures in such systems during field operation can have severe implications, their safety and reliability must be ensured. Electrical system degradation is usually triggered by complicated failure mechanisms such as soldering joint problems, improper human operation, aging of system components, environmental conditions, and many other factors. The consequent functional loss, commonly called "failure", may lead to catastrophic results (i.e., open or short-circuit). To address these concerns, various methods have been developed for detecting faulty circuit conditions, isolating fault locations, and even predicting the RUL of electrical systems. The primary difference between PHM for electrical systems and PHM for mechanical systems is that almost every mechanical system requires additional sensors to convert mechanical parameters, such as the rotation speed of a shaft, to electrical parameters, such as a voltage or current, that can be monitored and processed, whereas electrical systems often have electrical outputs that can be used for health monitoring. Companies from all industry sectors, ranging from consumer electronics to aerospace, have been researching PHM for electronics systems to monitor operating states, detect degraded performance, and predict RUL. This paper deals with the PHM implementation methods, algorithms, and apparatus for specific electrical systems, electronic devices, or pieces of equipment. As shown in Fig. 3, these categories are: semiconductor products and computers, batteries, electric motors, circuits and systems, electrical devices in automobiles and aircraft, networks and communications, and others.

### A. SEMICONDUCTOR PRODUCTS AND COMPUTERS

PHM patents for semiconductor components, computers, and their accessories such as hard disk drives, memories, and motherboards account for more than 50% of the PHM patents for electrical systems, which indicates that companies are

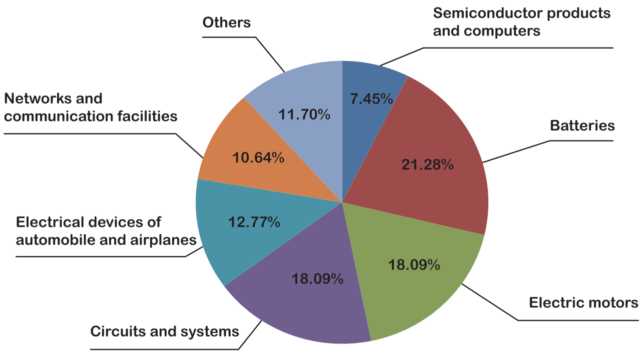


**FIGURE 3.** The main categories of PHM use in electrical systems.

**TABLE 1.** Distribution of typical patents in semiconductor products and computers (D stands for diagnostic, P stands for prognostic, DP stands for diagnostic and prognostic).

| Assignee | 2000-2005 | 2006-2010 | 2011-2015 |
|---|---|---|---|
| Maxsp Corporation | | | [40](D) |
| Sun Microsystems | [42](D) | [41](D) | |
| Toshiba | [43](D) | | |
| IBM | | | [44](DP) |
| Sandisk | | [45](P) | |
| Qualcomm | | [46](D) | |
| Intel | | [47](D) | |
| Fuji Electric | | | [48](D) [49](D) |

investing seriously in these products to improve their reliability. Sun Microsystems and Fuji Electric possess most of the patents related to computer microprocessors. Semiconductors are an inextricable part of computer systems, and semiconductor integrated circuits are currently the most fundamental hardware components in computers. Power semiconductors (i.e., PIN diodes, thyristors, power MOSFET, IGBT, and GTO) are widely employed in converter circuits and controllers. Many big enterprises (Internet companies, financial companies, etc.) have their own servers for the daily operation of the company nowadays. Moreover, more and more enterprises are beginning to dabble in the field of electronic commerce. It can be seen that computers are playing a particularly important role in modern enterprises. It may cause heavy losses to enterprises once the computers fail. Therefore, there is a great demand for PHM of semiconductor products and computers. Table 1 lists the assignees and dates of the patents mentioned in this subsection.

With the current complexity and interoperability of computer hardware and software, the newly installed program will inevitably affect a preexisting program. To overcome this issue, Keith [40] presented an expert system and agents for computer hardware and software diagnostic and report systems. An agent application is first installed on a user's system. The agent application then retrieves problem data from the expert system library pertinent to the user's operating environment. The agent application utilizes discrete scripts to send data to a knowledge base when a problem is discovered, so that the knowledge base is able to generate new discrete scripts using artificial intelligence, which are sent to the expert system library. The user's system is better protected as a result.

Sun Microsystems disclosed a dynamic performance analyzer for computers [41]. The invention relates to techniques for enhancing reliability and availability within computer systems. It proactively monitors faulty computer system components by using three-dimensional telemetric impulsion response fingerprint (3D TIRF) surfaces in combination with a two-dimensional sequential probability ratio test (2D SPRT). Sun Microsystems disclosed another invention [42] that detects a thermal anomaly in a computer system. During operation, the system derives an estimated signal for a thermal sensor in the computer system, wherein the estimated signal is derived from the correlations with other instrumentation signals in the computer system. Each estimated signal is generated by applying predetermined correlations with other signals to the actual measured values for the other signals. Next, the system compares an actual signal from the thermal sensor with the estimated signal to determine whether a thermal anomaly exists in the computer system. If a thermal anomaly exists, the system generates an alarm.

Toshiba proposed a scheme [43] for fault diagnosis in a client-server computer system. In this scheme, a fault occurring in one computer among a plurality of computers (constituting a client-server computer system) is detected while the computers are executing respective processes. The scheme does not judge whether or not the computer with the fault detected is a server.

IBM proposed anomaly-driven software for capturing and automating responses to the anomalies of flash memory [44], which can determine the end-of-life stage and thereby predict the RUL of the flash memory. A counter in the software is associated with the life cycle event (a write cycle to the flash memory or a read cycle from the flash memory) of the flash memory. Based on the counter, the total number of occurrences for the life cycle event is determined. The RUL of the flash memory is identified according to whether the total number of occurrences exceeds the predefined threshold. The user is then notified of the life cycle state of the flash memory.

Sandisk's PHM method for estimating the end of life of a non-volatile memory system is based on the average number of erases per block [45]. A platform provides information on the amount of RUL for a memory device, such as a flash memory card. For example, the user can see the memory card's expected remaining lifetime in real-time units (i.e., hours or days) or as a percentage of estimated initial life. An end-of-life warning is activated if either the expected amount of remaining life falls below a certain level or the number of spare blocks falls below a safe level.

Qualcomm disclosed a unified memory portion [46] with a fault-inhibiting function for wireless mobile communication devices. The unified memory portion can protect itself from operational fault from nocent information. In addition, Intel proposed a complementary metal-oxide-semiconductor (CMOS) technology [47] to solve memory elements' fault.

Fuji Electric disclosed a gate driving circuit that has a fault detection unit for a semiconductor switching device [48]. Some semiconductor switching devices are connected in series in the gate driving circuit. The gate driving circuit can determine a short-circuit fault of the semiconductor switching device by detecting the current passing through the circuit of series connection (e.g., diodes, and resistors) when an OFF command signal is given. Fuji Electric proposed an innovative method of locating the fault position of a semiconductor device [49]. A platform is designed for fault position analysis on a semiconductor device, through which a fault position of a silicon carbide (SiC) semiconductor device can be locked. This fault position analysis method scans and irradiates a semiconductor device and a circuit with a laser beam to heat the device and the circuit. To analyze the fault position, a current is applied to the device and the circuit during heating in order to detect any changes in resistance subject to the current level.

Before the advent of fault detection and fault location technology, it was difficult for human operators to know where and how frequently to check for problem or fault conditions and how to correct such conditions when found. Fault detection and location detection technologies have made great progress. However, some of the diagnostic methods are still very traditional. For example, the PHM methods in [44] and [45] rely on counting, which does not actually reflect the health status of objects accurately. There is a trend in the semiconductor and computer industry to assess the health state in real-time, predict failure dynamically, and isolate errors before actual failure occurs. Since the use of semiconductors will predictably expand from existing computer systems and circuit systems to other products in the future, the development of PHM for semiconductors will continue.

### B. BATTERIES

Batteries are an integral part of a wide range of products from small portable devices to big industrial equipment, including automotive vehicles, aerospace, grids, and other mobile applications. As a core component of a battery-powered system, the health of a battery has a huge effect on the performance of the whole system. Battery degradation and aging can cause early product failure, fire and even explosion as well as incurring high costs. Therefore, batteries or battery packs must be monitored and managed. Battery monitoring includes measurement and reporting of an individual battery's remaining charge, rate of charge/discharge, temperature, and operational state. Battery management mainly refers to connecting/disconnecting the battery, and thereby, the battery state of charge and the state of health are estimated. As a part of PHM, accurate RUL prediction for batteries provides a helpful reference for when to maintain the batteries and facilitates early warning before batteries reach their end of life (EOL) so that the batteries, which are about to fail, can be replaced in time. GM Global Technology and Lapis Semiconductor own most of the PHM-related patents in the battery field. PHM patents in this aspect fall into two main application types: vehicles and electronic devices. Table 2 lists the assignees and dates for the patents mentioned in this subsection.

**TABLE 2. Distribution of typical patents in batteries.**

| Assignee | 2000-2005 | 2006-2010 | 2011-2015 |
|---|---|---|---|
| Sinoelectric Powertrain | | | [51](D) |
| Honda Motor | | | [52](D) |
| BYD | | | [53](D)<br>[54](D) |
| Tesla | | | [55](D)<br>[56](D) |
| LaunchPoint Energy and Power | | | [57](D) |
| NASA | | | [58](D) |
| GM Global Technology | | | [59](D)<br>[60](D) |
| Lapis Semiconductor | | | [62](D)<br>[63](D) |
| Panasonic EV Energy | | | [64](D) |
| Sony Ericsson Mobile Communications | | [65](D) | |
| Hitachi Automotive Systems | | | [66](D) |
| NSK | | | [67](D) |
| JTT Electronics | | | [68](D) |
| GM Global Technology | | | [70](DP) |
| BlackBerry | | | [71](D) |
| Lenovo Enterprise Solutions | | | [72](D) |
| Renesas Electronics | | | [73](D) |
| Samsung | | | [74](D) |
| Dell | | | [75](D) |
| Medtronic MiniMed | | | [76](DP) |
| Denso | | | [77](D) |
| Honeywell | | [78](D) | |
| Panasonic | | | [79](D) |
| Daimler AG | | [80](P) | |
| Individual Patents | | | [61](D)<br>[69](P) |

Electric vehicles are advantageous compared to traditional vehicles owing to their rechargeable batteries. Electric vehicles are inherently more efficient, meaning more energy is used in locomotion than is lost to heat compared to conventional internal combustion engines. Also, electric vehicles do not produce exhaust gases. However, the use of electric vehicles presents technical challenges, mainly for the health management of the batteries or modular batteries. Currently, the two major methods (i.e., method based on PoF model and deterministic regression method based on machine learning) for RUL prediction of batteries are confronted with challenging problems [50]. Sinoelectric Powertrain disclosed a method [51] of handling a fault in a battery pack for electric vehicles. The invention introduces a heartbeat signal that is transmitted from a battery management system (BMS) via a fault bus. The battery module supplies voltage to a high-voltage circuit of a vehicle. If a critical issue arises in the battery module (e.g. over-charging or over-discharging of a battery cell, an isolation fault, short-circuit, over-current, over temperature, or overpower), the battery module terminates the heartbeat signal, thereby preventing the BMS from receiving further signals. In response to not receiving the heartbeat signal, the BMS automatically shuts down the high-voltage circuit, preferably without the need of any software or a complex operating system.

Honda Motor Co. also patented a fault detection system for an automotive battery circuit [52]. A vehicle's electrical system includes an electric power generator arranged to selectively provide electric power to the vehicle's electrical load and charge the battery. A fault detection system detects an open-circuit or high resistance fault in a ground circuit. A controller in the fault detection system controls the voltage output of the generator so as to either restrict or increase battery charging by the generator for a designated test period.

There are usually multiple battery packs in a battery system for storing electrical power and supplying electrical power to a vehicle. BYD determined a severable feature [53] in the electrical connections between at least some of the cells. The electrical connection can be severed locally at the severable feature when there is an impact force that is in excess of a predetermined magnitude or an overcurrent or overtemperature condition. In addition, BYD disclosed methods and systems [54] for detecting internal battery abnormalities during charging and discharging states.

Tesla proposed a detection method [55] of overcurrent shorts in a battery pack using pattern recognition. A condition of a hazardous internal short is identified by comparing patterns of series element voltages to the last known balance condition of the series elements. If the loaded or resting voltage of one or more contiguous series elements uniformly drops from the previously known condition by an amount consistent with an overcurrent condition, an overcurrent internal short-circuit fault is registered. In addition, an integrated thermal management system [56] was invented for battery modules.

LaunchPoint Energy and Power disclosed a fault-tolerant BMS with electric vehicle applications [57] as well. NASA patented a BMS [58] for hybrid cars and aerospace or spacecraft applications that uses a plurality of transformers interconnected with a battery having a plurality of battery cells. Windings of the transformers are driven with an excitation waveform whereupon signals are responsively detected, indicating the health of the battery. GM Global Technology disclosed a battery fault-tolerant architecture for a cell failure modes parallel bypass circuit [59] and a battery fault-tolerant architecture for a cell failure modes series bypass circuit for electrical vehicles [60]. A fault-tolerant modular BMS [61], different from a diagnostic method based on monitoring signals, was disclosed. The battery management control modules are arranged in a redundant topology so that if any one of the components fails, the other components resume the functions of the failing component.

Lapis Semiconductor patented a diagnostic toolkit [62] for a battery cell monitoring system based on a similar principle in which a semiconductor circuit is provided including a comparator section that compares discharge sections with a threshold voltage. The company later disclosed a battery monitoring system [63] that enables appropriate self-diagnosis of batteries connected with a voltage measurement unit for motor drivers of hybrid or electrical vehicles. Panasonic EV Energy disclosed a toolkit [64] for controlling output of a rechargeable battery that prevents the life span of the rechargeable battery from being shortened while ensuring starting of the engine. When an index indicating the charged state of the rechargeable battery satisfies a discharge suspension condition, the controller installed in the vehicle can instruct a vehicle ECU to stop discharging the rechargeable battery. Sony Ericsson Mobile Communications invented a dynamic battery advisor [65] that can provide a recommendation indicative of whether the power available from the battery is sufficient for the function circuitry to carry out the specified function.

Hitachi Automotive Systems disclosed an integrated circuit [66] for controlling battery cell and vehicle power supply systems. The battery cell control device comprises a measurement circuit that measures terminal voltages at the battery cells and an abnormality diagnosis circuit for any abnormality in the battery cell control device. NSK patented a power state diagnosis toolkit [67] that diagnoses the power state of a vehicle. The toolkit consists of an electrical control system and a motor controlled by a vector control method. JTT Electronics disclosed a battery monitoring system [68]; comprising a battery control unit (BCU), a plurality of module control units (MCUs) connectable to battery modules, and a ground fault detection unit that provides a fault signal to the BCU controller. An apparatus was disclosed [69] that includes a resistance measuring unit operable to determine the solution resistance and the charge-transfer resistance of a battery. Then a process is executed to estimate the number of remaining charge cycles before a discharge capacity lower limit is reached. A state of health (SOH) monitoring and prognostic method for a battery was disclosed by GM Global Technology [70], which includes training offline parity-relation parameters between the extracted battery voltage and the current signals during offline battery discharge events.

Several PHM patents related to batteries in electronic devices such as portable devices and computers are included in PHM patents on batteries. BlackBerry disclosed a method and special apparatus [71] for displaying battery fault notifications on wireless devices. Lenovo Enterprise Solutions patented a method [72] for dynamically configuring current sharing and fault monitoring in redundant power supply modules for components of an electrically powered system. Renesas Electronics disclosed a semiconductor integrated circuit de-vice [73] for controlling the power supply voltage of the target circuit. Samsung patented an apparatus for reporting fault information of the battery of a power storage system [74], including a receiving portion configured to receive state information of the battery from the BMS of the power storage system; a controller configured to produce fault information of the battery according to the received state information; and a display that shows the fault information produced by the controller.

As the value and use of information continue to increase, individuals and businesses are seeking additional ways to process and store information. One option available to users is information handling systems. Dell disclosed an information handling system battery [75] that has protective circuits to detect and address specified faults. Medtronic MiniMed disclosed a PHM patent [76] for a portable electronic device, such as a fluid infusion device, which obtains its operating power from a primary battery and a secondary battery. The device can also generate an intelligent battery life indicator that displays an accurate representation of the remaining life of the primary battery by the patented power control techniques. Denso patented a battery fault detection apparatus [77] for industrial uses. The battery fault determination apparatus monitors battery cells and produces an output signal that indicates a monitoring result. Honeywell disclosed a lithium-ion battery prognostic method [78] based on the open-circuit voltage of the battery. The method can also track the full battery capacity as a function of time, and perform trend analysis of the full battery capacity over time to predict the battery's EOL. In addition, Panasonic [79] and Daimler AG [80] both proposed a toolkit for predicting the voltage of a battery and RUL of battery.

The number of patents for battery monitoring and prognostics in hybrid and electric vehicles is exploding. These patents view batteries as an indispensable energy storage component that is revolutionizing the way people use energy. Although the technologies proposed in related patents are constantly being updated, the research on PHM for batteries needs to be strengthened by a combination of experts from different backgrounds, including chemical engineering, materials science, electrical engineering, mechanical engineering, reliability engineering, and computer science. Specifically, an electrochemical model is needed to be developed to achieve more accurate SOH estimation and prediction by relating the inside chemical reaction with the outside voltage and current measurement. Furthermore, an adaptive estimation system should be developed that can improve the accuracy of battery health estimation by taking into account battery dynamics especially when the system is placed under varying loads. Some of patents discussed in this subsection refer to the establishment of fault-tolerant BMSs [57], [59]–[61]. More than two-thirds of the patents establish the PHM equipment or system for monitoring and diagnosis of batteries, in which, it is necessary to try the current popular machine learning algorithms to observe diagnosis accuracy.

### C. ELECTRIC MOTORS

Electric motors used in industrial manufacturing processes such as power generation systems and electric cars are required to function as designed in varying environmental conditions. Manufacturing downtime caused by a failure of an electric motor can reduce productivity and profitability significantly. At the same time, motor failure can cause

**TABLE 3. Distribution of typical patents in electric motors.**

| Assignee | 2000-2005 | 2006-2010 | 2011-2015 |
|---|---|---|---|
| Danfoss Drives | | | [81](D) |
| Rockwell | [82](D)<br>[87](D) | [83](DP) | |
| Robert Bosch | | | [84](D) |
| Korea Electronics Technology Institute | | | [85](D) |
| THK | | [86](D) | |
| Eaton | | [88](D) | |
| GM Global Technology | | | [89](D) |
| International Rectifier Corporation | | [90](D) | |
| Hamilton Sundstrand | | | [91](D)<br>[92](D)<br>[93](D)<br>[94](D) |
| Deere Company | | | [95](D) |
| General Electric | | [97](P)<br>[98](P) | |
| Durr Systems | | | [99](D) |
| Fanuc LTD | | [101](D) | |
| Individual Patents | [100](D)<br>[102](P) | | |

abnormal vibration and noise, thereby resulting in noise pollution to the environment and serious harm to the human body. Electric motors are vital elements of industrial facilities, and the health and condition of these motors must be closely monitored to anticipate and prevent failures that could result in costly unscheduled downtime. Passive monitoring and health assessment methods using sensors and diagnostic algorithms that are isolated from control algorithms are widely used. Nearly all PHM patents for electric motors are based on the measurement of current, since it is closely related to the operation condition of electric motors. Voltage-based measurement is also disclosed for the identification of fault conditions. Patents are introduced according to two different monitoring methods, i.e., the measurements of current and voltage. Rockwell and General Electric possess most of the patents in the electric motors field. Table 3 lists the assignees and dates for the patents mentioned in this subsection.

Danfoss Drives proposed a method for detecting earth-fault or grounding fault conditions in a motor controller [81]. The present invention relates to a method for determining the existence of an earth-fault on a motor controller. A high- and a low-side DC-link and high-or low-side switching elements are included in the motor controller. An earth-fault was detected according to the measured magnitude of a current flowing in that DC-link.

Rockwell disclosed a method [82] for detecting a stator winding fault in an induction motor based on sampling instantaneous signals from the motor and then deriving a total negative sequence current component of the instantaneous signals. The method calculates an expected negative sequence current based on some of the sequence components and then subtracts the expected negative sequence current from the total negative sequence current to determine a fault negative sequence current, wherein the fault negative sequence current is indicative of the fault. Rockwell also disclosed a toolkit [83] for controlling, diagnosing, and prognosing the health of a motorized system. The diagnostics system and the prognostics system employ a neural network, an expert system, and a data fusion component in order to assess and prognose the health of the motorized system according to one or more attributes associated therewith.

Robert Bosch disclosed a method [84] for fault recognition in an electric machine, controlled by an inverter in a motor vehicle. The phase currents of the electric machine are ascertained by measuring. A fault, such as phase overcurrent, is recognized if at least one of the phase currents exceeds a predefined upper threshold value. Then the pulse-controlled inverter is switched into a safe state in order to prevent possible damage to the electrical components.

Korea Electronics Technology Institute disclosed a system [85] for detecting short-circuit fault of a stator coil winding in a permanent magnet motor. This method consists of driving a parallel coil-type motor on the basis of a pre-defined current reference value, detecting a phase current vector of the motor, and calculating a current compensation value for removing a negative sequence component of the motor on the basis of the phase current vector.

THK patented a diagnostic system [86] that monitors the supply current to motors and detects an anomaly waveform of the current. An anomaly detection unit monitors the supply current to the linear motor, thereby detecting the anomaly of a linear motion apparatus based on a waveform of the supply current. The anomaly of the linear motion apparatus can be detected early and accurately.

Rockwell Automation patented an apparatus [87] for monitoring an electrical power converter, which is used in motor drives that control electric energy supplied to an electric motor. The apparatus consists of five current sensors, which indicate the direction of the electric current. A controller then analyzes the five indications to detect when a fault condition occurs in the power converter.

Eaton disclosed a system and method [88] for proactive detection of conditions indicative of potential motor faults, including a plurality of sensors configured to monitor the operation of a motor. A processor disposed within the housing is configured to perform specific analysis to determine a motor fault index of the given motor. GM Global Technology patented a motor phase winding fault detection method and apparatus [89], which measures feedback signals of the machine, including each phase current, and generates reference phase voltages for each phase. International Rectifier Corporation invented a toolkit [90] for detecting multiple overcurrent thresholds using a single comparator device. This invention can provide system protection in motor drive systems by using only one comparator device instead of multiple comparator devices.

Hamilton Sundstrand invented a system [91] for stepper motor phase failure detection. The system comprises a stepper motor, and a controller configured to measure a parameter associated with the current of the stepper motor prior to commanding a step in connection with the stepper motor. The system then commands the step in connection with the stepper motor and measures the parameter subsequent to commanding the step and comparing the measurements of the parameter. Finally, the system determines whether a fault exists with respect to the stepper motor based on a comparison of the measurements. In addition, Hamilton Sundstrand patented a method [92] for detecting an overcurrent fault in a variable-frequency electric power generation system.

Hamilton Sundstrand disclosed a hardware-based, redundant overvoltage protection method [93] for generator system, which includes a generator and a generator control unit (GCU). The GCU is connected to monitor and regulate the generator output voltage. The GCU includes a protection signal processor that receives the monitored generator voltages and executes a program to detect an overvoltage condition. The GCU further includes a fast overvoltage detection circuit that generates an overvoltage fault signal if the peak voltage value measured is greater than the threshold value. Hamilton Sundstrand also disclosed an overvoltage prevention method for an aircraft electrical power generation system [94].

Deere Company patented a method and controller [95] for an electric motor with fault detection, where a measuring circuit is adopted to measure the collector-emitter voltage or drain-source voltage for each semiconductor switch of the controller. When the measured voltage value for the particular semiconductor switch is lower than a minimum threshold, a data processor will determine that a short-circuit in this semiconductor switch is present. A driver simultaneously activates counterpart switches coupled to other phase windings of the electric motor, other than the particular semiconductor switch, to protect the electric motor from potential damage associated with asymmetric current flow. Nidec Motor patented an electric motor system [96] that has substantially independent hardware and software-based pathways for detecting and initiating responses to fault conditions, such as over-current conditions. Each pathway involves comparing a voltage, which is representative of an electric current flowing to the motor, to a predetermined maximum voltage, and if the former exceeds the latter, the motor is shut off using hardware or software. When one pathway detects a fault condition other pathways may be notified, and the notified pathways may also initiate shutting off the motor.

Rather than simply analyzing the operation parameter data, GE disclosed a monitoring system [97], [98] that forecasts both the failure mode and RUL in electric motors by acquiring historical motor data such as historical repair information, obtaining operational parameter data from sensors, conducting failure analysis based on a composite of reliability probability distributions corresponding to predetermined sub-populations of historical motor system failure causes, and performing an integrated causal network and reliability analysis. Durr Systems disclosed a high-voltage controller [99], which is configured to drive a high-voltage generator, with improved monitoring and diagnostics. A toolkit [100] for detection of stator and rotor anomalies was patented by determining residual magnetic fields in dynamo-electric machines. Fanuc LTD disclosed a unit [101] to predict the separation of the wire in the motor driving system before the actual separation of the wire. Thus, an operation failure of the motor driving system could be prevented from occurring. In addition, a diagnostic apparatus for oil burner motor was disclosed in [102] for predicting failures by determining the running and cycle time of oil burner motors. Advance notice of potential failures could be provided by processing data from the monitoring device.

Motors are the core components of application systems, and large-scale and complex applications require motors with high output power. Motor is a device that is very easy to fail in application systems. Therefore, the health status of the motors must be monitored. The above-mentioned patents are introduced from two aspects of monitoring current and voltage related to motors. These two methods are based on comparing of the measured value and the threshold value. However, fault diagnosis for motors becomes more complicated and difficult because of their increasing complexity. Intelligent PHM for motor systems, which owns more advantages than traditional PHM needs to be developed to realize real-time monitoring of motor systems, timely troubleshooting, and life prediction.

### D. CIRCUITS AND SYSTEMS

Circuits and systems play a critical role in industrial applications. Functional loss in electrical systems is inevitable because the system components and devices experience irreversible degradation once they are put into use. For instance, the degradation of electrolytic capacitors in filter circuits (e.g., Sallen-Key bandpass filters and biquad low-pass filters) causes analog electronic filter circuits to fail [103], [104]. Circuits such as driver circuits, excited circuits, switching circuits, power distribution circuits, and transmitting circuits are used extensively in industrial electronic equipment such as controllers, power networks, energy conversion systems, and transportation tools, and in highly critical military and aerospace systems. The PHM patents for circuit systems (e.g., protection systems, ungrounded electrical systems, and power distribution systems.) have been disclosed since the 1980s. Boeing, and Fuji Electric possess most of the patents in the circuits and systems field. Table 4 lists the assignees and dates for the patents mentioned in this subsection.

The PHM patents for circuits with different functions [105]–[115] are discussed in this review. Rockwell disclosed an automation network [105] for error diagnostics and prognostics in motor drives. Boeing disclosed a fault-tolerant synchronous rectifier PWM regulator system [106]. In this system, a force commutated synchronous rectifier is operable to be coupled to an electrical bus and the fuse in the system is operable to open in response to a fault in the electrical bus. Additionally, due to the concern of abnormal power conditions in the system, Boeing patented a fault isolator apparatus [107] for an aircraft electrical bus for protection under various loads, as well as the power distribution equipment. A circuit protection system against arc flash [108] was patented. The protection system can provide a dynamic delay time to an upstream circuit breaker when a fault is detected in a circuit. After the dynamic delay time has elapsed, there is an opportunity for the nearest circuit breaker to clear the fault. LG Chem Ltd. disclosed two diagnostic methods [109], [110] to determine when a voltage driver for an electric vehicle is shorted to a ground voltage on different occasions. Honeywell disclosed an electronics-based system [111] for power conversion and load management, which provides control sequencing, PHM, and diagnostics for fault-tolerant operation of the system. Besides, a prognostic cell [112] for predicting failure of integrated circuits was presented by Ridgetop Group.

**TABLE 4. Distribution of typical patents in circuits and systems.**

| Assignee | 2000-2005 | 2006-2010 | 2011-2015 |
|---|---|---|---|
| Rockwell | | | [105](DP) |
| Boeing | | | [106](D)<br>[107](D) |
| LG Chem Ltd. | | | [109](D)<br>[110](D) |
| Honeywell | | [111](D) | |
| Ridgetop Group | | [112](D) | |
| Intel | [113](D) | | |
| Eaton | | | [116](D) |
| Siemens | | | [117](D) |
| Hitachi | | | [118](D) |
| General Electric | | | [119](D) |
| Ford Global Technologies | | | [120](D) |
| Hamilton Sundstrand | | | [121](D) |
| Individual Patents | [115](D) | [108](D) | [114](D)<br>[120](D) |

Intel disclosed a method [113] for diagnosing open defects in logic circuits. A pair of diagnostic fault models and an associated algorithm are employed to automate the diagnoses of open defects that cause interconnects to be open or high resistance in logic. The diagnostic fault models are used to predict potential logic errors from the outputs of a logic circuit in the presence of an open defect. A diagnostic signature set corresponding to the logic circuit is combined with the predicted errors. The diagnostic signature set is then compared with the set of errors observed during testing using a diagnostic matching algorithm that ranks the presence of open defects in the circuit. In addition, a diagnostic circuit for monitoring an analog-digital converter circuit [114] and a troubleshooting system for an aircraft auxiliary power unit [115] were disclosed.

A ground fault is a typical and common fault type of a transmission line. The corresponding devices and methods to deal with ground faults have been developed steadily. Eaton patented a circuit interrupter [116] that provides grounded neutral protection. The circuit interrupter includes a ground fault detection circuit configured to sense a difference between currents passing through the two conductors in the circuit interrupter and then to output a signal based on the sensed difference. Siemens [117] patented a toolkit for a supervisory circuit of a ground fault detection device. The toolkit is used for a self-test of the ground fault detection device. Hitachi disclosed an electromagnetic load circuit failure diagnosis device [118] for detecting layer short-circuit failures in active device couplers. This device works by comparing the number of on/off operations of chopping of the high-side switch element against a predetermined number called the "failure diagnosis threshold".

Several PHM patents for circuit systems have been disclosed from the 2010s. Direct current (DC) systems are widely used in various fields such as automatic transmission systems, DC micro-networks, and marine systems. In these fields, the DC system usually applies voltage to multiple loads coupled in parallel. However, an overcurrent fault that may be caused by a short-circuit condition, could introduce a cascaded failure to the loads due to the large current in DC bus bars, DC capacitors, and power converters. Overcurrent fault protection is thus one critical challenge for the DC system. Usually a protection system is provided for detecting fault conditions and operating one or more protection devices to isolate the fault area. GE disclosed a toolkit [119] for fault protection in DC systems. Furthermore, a toolkit was patented for ground fault detection and location in ungrounded electrical systems [120]. PHM patents on power distribution [69], [121] are involved as well. Ford Global Technologies patented a power distribution circuit diagnostic system [121]. A line to neutral electrical parameter and a neutral to ground electrical parameter were separately sensed by two sensors in the diagnostic system. Therefore, a fault condition in the line or neutral was identified based on the observed electrical parameters. In many aircraft systems, the quality of the electrical power is critical for flight control and for electrically driven hydraulic pumps. Internal faults can cause loss of power or unacceptable degraded power quality in these flight critical systems. Hamilton Sundstrand proposed a method of detecting and isolating faults [122] within power conversion and distribution systems, which includes a generator circuit, a power converter circuit, and a distribution circuit. A system controller is configured to monitor differential current and power between any two of the three circuits. A current loss fault is detected based on the monitored differential current, and a series arc fault is detected based on the monitored differential power.

Short-circuit faults and the ground faults [109], [110], [116]–[118] appear frequently in the above-mentioned patents, while open-circuit faults are hardly mentioned. Therefore, these three fault types must be comprehensively covered. Fault diagnosis, separation, and prediction circuits or devices are usually proposed to conduct PHM for circuits and systems, which inevitably results in the increase of systems' hardware and software burdens. Establishing an automated network for circuit systems, realizing a comprehensive monitoring of system data, timely detection of system abnormalities, and troubleshooting are all worthy goals.

**TABLE 5. Distribution of typical patents in electrical devices in automobiles and airplanes.**

| Assignee | 2000-2005 | 2006-2010 | 2011-2015 |
|---|---|---|---|
| Robert Bosch | | | [123](D) |
| Toshiba | | | [124](D) |
| GM Global Technology | | [127](D) | [125](D)<br>[126](D)<br>[130](D) |
| Denso | | | [128](D) |
| Ford Global Technologies | | | [129](D) |
| Panasonic | | | [131](D) |
| Hamilton Sundstrand | | | [133](D)<br>[134](D) |
| Boeing | | | [135](D) |
| Individual Patents | | | [132](D) |

## E. ELECTRICAL DEVICES IN AUTOMOBILES AND AIRPLANES

Electrical systems in automobiles and airplane are becoming more and more complicated along the development of these industries. PHM patents for electrical devices in automobiles and aircraft are constantly being proposed. The electrical system in an automobile mainly consists of the power, wires, antilock brake system (ABS), switches, sensors, actuators and control unit. Aircraft electrical systems consist of the aircraft power supply system and a variety of electrical equipment, such as flight control, engine control, avionics, fuel pumps, oil pumps, life support systems, lighting and signals, and anti-icing and heating systems. GM Global Technology holds most of the patents for electrical devices in automobiles and aircraft. PHM patents on electrical devices of automobiles and aircraft are introduced respectively. Table 5 lists the assignees and dates for the patents mentioned in this subsection.

Robert Bosch patented a method [123] for detecting an electrical fault in the electrical network of a motor vehicle, so as to protect the components in the electrical network, in particular, the pulse-controlled inverter. The method detects an electrical fault by comparing the voltage magnitudes of the battery voltage according to a mathematical model, wherein the battery is used as the voltage source for the electrical machine associated with the pulse-controlled inverter or as an energy store in the generator operating mode of the electrical machine. The checking procedure compares whether a specifiable deviation has been exceeded. Toshiba patented a voltage detection circuit [124] for automobiles with an electronic control unit (ECU). An in-vehicle driver with a voltage detection circuit is configured to detect an accidental short-to-power from a power source, in order to protect the circuit unit controlled by an ECU from damage due to the short-to-power. When a short-to-power of a battery or a battery pack occurs, a detection terminal voltage becomes high because the detection terminal input current is increased as the detection terminal voltage increases, resulting in the occurrence of a detection terminal input current. In addition, once the detection terminal voltage reaches a predetermined voltage or higher and exceeds the breakdown voltage of a detection comparator, the detection comparator deteriorates or breaks.

GM Global Technology patented an electric vehicle diagnostic system [125] for diagnosing the performance of an active cooling system that cools down a rechargeable energy storage system (RESS) with a coolant. GM Global Technology also disclosed a control module [126] that includes a global positioning system (GPS) receiver and a diagnostic module that may diagnose faults in various components of a vehicle and in driver interface devices (e.g., accelerator pedal) and sensors (e.g., manifold temperature sensor). The GPS receiver determines the location of a vehicle. The diagnostic module diagnoses the fault in a vehicle component, and the diagnostic data includes both a predetermined diagnostic trouble code associated with the diagnosed fault and the vehicle location when the fault was diagnosed. A reference voltage diagnostic [127] suitable for use in an automobile controller was presented by GM Global Technology as well.

Recently, some inverters for in-vehicle auxiliary units have been directly connected to a power supply for a traction unit. However, if the number of units connected to the power supply increases, stray capacitance between the power supply and the body of the vehicle increases, or the value of dielectric resistance decreases. In this case, the accuracy of diagnosing the insulation failure can be lowered. Denso disclosed an apparatus [128] for insulation failure diagnosis between the body of a vehicle and the connection path to a power supply for a traction unit. The apparatus contains a diagnosis unit, which includes a unit that stores a threshold value for determining the insulation failure. The threshold value is obtained by measuring an electrical state quantity of the connection path depending on stray capacitance.

Ford Global Technologies patented a system for detecting the usage of a mobile phone in an automobile [129]. The detection module generates an output that indicates the detected condition. A controller in the vehicle is configured to receive the output, and control the vehicle in response to the detected condition. GM Global Technology proposed a method [130] for monitoring in-use performance ratios of onboard diagnostic systems for plug-in hybrid electric vehicles. Panasonic presented a power management method [131] for an external storage device was presented. The power supply state is determined by whether or not the data access by the media control section can be performed.

The electrical system architectures in aircraft are becoming increasingly complex and must communicate (i.e., distribute) power in any number of directions. Typically, there may be typically three generators associated with an aircraft, although more may also be utilized. William *et al.* [132] proposed an electrical power supply system that has internal fault protection. Users in aircraft receive power from AC buses, whose power is delivered from the generators. The individual AC buses are connected by a tie bus. The first source of electric power delivers power to the first AC bus, which delivers power to the first set of users. A supply current sensor is between one source of power and the corresponding AC bus. A tie bus output sensor senses power from the AC bus that is delivered to the tie bus. A plurality of user output current sensors sense the current passing to each of the plurality of users. A control is operable to compare a sensed current in the supply current sensor and sum the current in the tie bus output sensor and the plurality of user output sensors. If the sum of the out-put sensors differs by more than a predetermined amount from the current sensed by the supply sensor, the control identifies a fault. This AC bus is then disconnected from the tie bus. A fault detection circuit [133] was disclosed by Hamilton to automatically detect the faults in hold-up power storage devices, which are commonly employed in a variety of applications to keep a unit or device functional for a limited period of time upon power interruption. The fault detection circuit includes a hold-up monitoring circuit connected to monitor the output of the hold-up power storage device. The hold-up monitoring circuit measures the duration of time that the hold-up power storage device provides sufficient power upon power loss, and detects the faults based on the measured duration of time.

Electric power systems, such as those on an aircraft, are susceptible to overvoltage conditions. Vandergrift's proposal [134] relates to overvoltage detection, and in particular to a system and method for controlled overvoltage detection. An overvoltage condition exists when the voltage applied to a load is larger than the voltage the load is rated to handle. These conditions may occur, for example, due to a lightning strike. If the voltage is sufficiently large or exists sufficiently long, the system can suffer permanent damage. Therefore, it is necessary to detect overvoltage conditions so that they may be handled prior to any circuit damage. Boeing disclosed an electrical load management system [135]. A database module stores the configuration and the requirements of an electrical system, and an analysis module determines its performance characteristics based on the con-figuration. In addition, a configuration management module manages the changes to the electrical system configuration. Furthermore, it compares the performance characteristics to the system requirements to enable optimal performance and to provide compliance information.

The PHM of automobile and aircraft electrical equipment is currently not advanced enough to avoid any accident in automobile and aircraft electrical systems. In the future, with the continuous development of computers, electronics, and other technologies, new breakthroughs in the PHM of automotive and aircraft electrical equipment are expected, and the relevant theories and methods will be introduced [136]. On the whole, the development of PHM in this regard tends towards the areas of networking and intelligent, multi-functional, and expert systems. Resource sharing will be achieved with microcomputers and their networks as a

**TABLE 6.** Distribution of typical patents in networks and communication facilities.

| Assignee | 2000-2005 | 2006-2010 | 2011-2015 |
|---|---|---|---|
| Cisco Technology | | | [137](D) |
| Nortel Networks Limited | [138](D) | | |
| Qualcomm | | | [139](D) |
| Huawei Technologies | | | [141](D) |
| Hewlett-Packard Development Company | | | [143](D) |
| IBM | | | [145](D) |
| Individual Patents | | | [140](D) [142](D) [144](D) |

toolkit to organize and integrate a variety of special analytic instruments.

### F. NETWORKS AND COMMUNICATION FACILITIES

Network and communication (particularly wireless) technologies have been largely adopted by industry and are now indispensable in our daily lives and our work. Networks are comprised of a multiplicity of devices such as servers, routers, hosts, switches, repeaters, hubs, encryption devices, and backup devices such as media libraries. Since a network involves a user equipment side, a network side, and a wired network side, network faults are complex and diverse. For example, a network adapter hardware fault, driver inconsistency, an unauthorized Internet protocol, a dummy link, or a serious packet loss may occur on the user equipment side; signal interference, a signal coverage problem, or a network parameter configuration error, may occur on the network side; and a power over ethernet (POE) switch port fault, a wired bearer network fault, or a deficient bearer network bandwidth, may occur on the wired network side. Network administration in core enterprise settings is nontrivial because of the many challenges, such as identifying and securing the network from various sophisticated attacks (e.g., distributed denial of service attacks, worms, port scans, etc.) and dynamically responding to these events. Therefore, high operation and maintenance requirements are imposed on the network, for example, fast locating of a network fault, accurate analysis in fault diagnosis, and timely discovery of a potential network fault. A network anomaly is an unusual event in a network that is of interest to an entity such as a network provider, a network user, a network operator, or a law enforcement agency. A network anomaly may be raised unintentionally as a result of normal network traffic conditions, such as the breakdown in a network resource, or intentionally by a malicious attack through a hacker who tries to damage the network or impair the performance of the network. Table 6 lists the assignees and dates for the patents mentioned in this subsection.

Connection reliability is critical for the overall health of a wireless network. Cisco Technology disclosed a toolkit [137] that facilitates troubleshooting of wireless connectivity issues in a wireless network. The diagnostic supplicant can establish a link to a diagnostic manager via a diagnostic link in response to one or more events, and then the diagnostic supplicant generates and transmits a problem report to the diagnostic manager. The problem report initiates a troubleshooting protocol between the diagnostic manager and the diagnostic supplicant. Nortel Networks Ltd disclosed a toolkit [138] for managing a communication network by storing management information about two or more configuration states of the network. Future states of the network can be predicted based on information about past states. Techniques [139] for supporting fault tolerance in communication systems are presented by Qualcomm Inc. Their invention can minimize service disruption following a fault of critical network nodes, improving overall system robustness and resiliency.

Myriad equipment, such as user equipment (UE) and related software and firmware applications, can affect the performance of a wireless network. Accordingly, telecommunications carriers typically monitor the operation of such equipment and assess performance through multiple key performance indicators (KPIs). Rahman's proposed toolkit [140] diagnoses the performance issues of wireless equipment or a wireless network through an alternative communication channel enabled by an alternative wireless network available to wireless equipment. Huawei Technologies proposed a wireless network fault diagnosis toolkit [141], which can completely diagnose wireless network faults so that corresponding measures are taken against the wireless network faults. The network management server performs area-based wireless network fault diagnosis, rather than single-pointİ fault diagnosis specific to single-user equipment, according to the statistical in-formation corresponding to each area. Therefrom, the fault trend of the user equipment can be fully perceived, so that corresponding measures are taken against wireless network faults to effectively improve the quality of the user experience.

Adams *et al.* disclosed a method and system for processing fault alarms and trouble tickets [142], referred to as electronic telecommunications trouble forms, in a managed network services system. In conventional network monitoring environments, network surveillance engineers receive alarm reports from the telecommunications network and then manually process these alarm reports. As a result, many organizations and businesses have resorted to addressing the daunting, costly task of network monitoring and maintenance on their own. Adams et al.'s invention provides an approach for supporting automated fault isolation and recovery. When an alarm indicative of a fault within a customer network is received, an event within a workflow is triggered in response to the alarm, wherein a new trouble ticket is generated as part of the workflow. Next, the communication with a trouble management system is performed to correlate the alarm with an existing trouble ticket.

Hewlett-Packard Development Company patented an autonomous diagnosis and mitigation of network anomalies [143], which heuristically detects a network anomaly in real time. The invention diagnoses and defends against network anomalies in real time by actively monitoring a wide range of specific administrator-configurable network parameters on an enterprise network scale and quickly localizing problematic parameters. To improve network reliability and management in current high-speed communication networks, the Trustees of Boston University proposed an intelligent system [144] using adaptive statistical approaches. The system learns the normal behavior of the network. Deviations from the norm are detected, and the information is combined. The proposed system is thereby able to detect unknown or unseen faults. This method can detect abnormal behavior before a fault actually occurs, giving the network management system (human or automated) the ability to avoid a potentially serious problem. Systematic analysis of data collected from multiple network resources (i.e., network links, routers, etc.) is a key feature of the invention. By leveraging whole-network data, the invention is able to diagnose a wide-range of anomalies, including those that may span throughout a network. Diagnosis allows the identification of the time when an anomaly is present, the location of the anomaly in the network, and the anomaly type.

Networks are used to communicate data among a plurality of network devices. In many cases, the network is used to transport power from a power supply to one or more of the plurality of network devices. IBM patented a network power fault detection method [145] for networks that are used in networking computers and computer peripherals. Furthermore, IBM proposed an expert system [146] for identifying the failing unit of a switch in a multiplex communications system, where a method for detecting and analyzing errors in a communications system was described. The method employs expert system techniques to isolate failures of specific field-replaceable units and provide detailed messages to guide an operator to a solution.

Although PHM technologies have been matured, PHM patents for networks and communication facilities are currently insufficient [147]. The primary interest in networks and communication industries may not be PHM. However, there will be a lot of patents focusing on anomaly detection or intrusion detection for security, whereas anomaly detection can be performed for monitoring the status of health of networks and communication facilities in the subject to PHM. Therefore, the inclusion of domain knowledge on network and communication into PHM technologies is important for the use of PHM technologies in networks and communication industries. In addition, the current popularity and importance of networks and communication facilities in various industries lead to more stringent requirements for PHM technology [148]. So network fault diagnosis is a potential direction for both enterprises and scholars.

### G. OTHERS

In addition to the given patents, other PHM patents in electrical systems accounted for 10% of total PHM patents from 2000 to 2015. These patents included lighting systems [149]–[151], refrigerators [152], banking machines [153], medical devices [69], [154], magnetic field sensors [155], actuators [156], photovoltaic (PV) installations [157], and airbag [158]. Although the monitored systems are diverse, ranging from flywheels to molding machines, the process and methodology of PHM disclosed in these patents is fundamentally similar except for the input data from sensors. The usage of PHM will be extended to more fields in electrical systems. Table 7 lists the assignees and dates for the patents mentioned in this subsection.

**TABLE 7. Distribution of typical patents in other subsystems.**

| Assignee | 2000-2005 | 2006-2010 | 2011-2015 |
|---|---|---|---|
| Acuity Brands | | [149](D) | |
| CIMCON Lighting | | | [150](D) |
| Honeywell | | | [151](D) |
| Field Diagnostic Services | [152](D) | | |
| Proteus Digital Health | | | [154](D) |
| Allegro Microsystems | | | [155](D) |
| Schneider Electric Industries | | | [156](D) |
| Toshiba | | | [157](D) |
| Freescale Semiconductor | | | [158](D) |
| Medtronic | | | [159](D) |
| Individual Patents | [153](D) | | |

Acuity Brands disclosed a network operation center for a lighting management system [149] that uses networked intelligent luminaire managers. A plurality of networked luminaire managers, each collocated with a respective luminaire, monitors the status of their respective luminaires. The luminaire managers include transmitters for transmitting status information about their respective luminaires and third-party devices to a network server. The network server forwards the received status information from the networked luminaire managers to a computer of an owner of the plurality of luminaires and a third-party user. The luminaire managers communicate with each other, whereby they form a network.

Similarly, CIMCON Lighting patented a fault management method [150] for streetlights, which includes receiving information representative of a location and status of the networked streetlights. Any fault condition of the networked streetlights is detected based on the received status information. Honeywell disclosed a method [151] for health monitoring of light emitting diode (LED) lights, which can be used to illuminate areas for security purposes or to mark runways, taxiways, and approaches at an airport. The method is based on the following information: the junction temperature of an LED, current ambient temperature, and a drive current associated with the LED, thereby determining the performance and RUL of the LED.

Field Diagnostic Services disclosed a method [152] for fault detection and diagnostics of a refrigeration, air conditioning, or heat pump system operating under field conditions. It does so by measuring, for each vapor compression cycle, at least five, and up to nine, system parameters and calculating system performance variables based on the measured parameters. Once the performance variables of the system are determined, the invention provides fault detection to assist a service technician in locating specific problems. This invention also provides verification of the effectiveness of any procedures performed by the service technician, which ultimately will lead to a prompt repair and may increase the efficiency of the refrigeration cycle.

Automated banking machines are widely used now, and a common type of automated banking machine used by consumers is an automated teller machine (ATM). Trelawney et al. disclosed a diagnostic server software component for an automated banking machine [153]. The diagnostic server can periodically retrieve diagnostic messages from a nonvolatile memory of the machine and store the diagnostic messages on the hard drive of the machine. The stored diagnostic messages are then sent to an external computing device. The software is also able to periodically communicate with terminal control software of the machine so that the terminal control software can retrieve the diagnostic messages from the nonvolatile memory.

Most medical devices do not work well with electricity. Bi *et al.* [154] patented an apparatus that enables robust, reliable control for implantable medical devices, including cardiac pacemakers, defibrillators, and cardiac resynchronization devices. A method of stabilizing the external impedance and a system for fault detection and fault recovery for an implantable device were also provided. Magnetic field sensors [155], which use magnetic field sensing elements, are used in a variety of applications, such as a current sensor that senses the magnetic field generated by the current carried by a current-carrying conductor, a magnetic switch that senses the proximity of a ferromagnetic or magnetic object, a rotation detector that senses passing ferromagnetic articles, and a magnetic field sensor that senses density of magnetic field. Moreover, some methods for monitoring power source longevity of an implantable medical device were patented in [69] and [159].

Chelloug [156] proposed a diagnostic method that is a simple, economical, and efficient actuator comprising a coil and its power supply control device. The method can check whether the coil winding is interrupted or short-circuited or if the control electronics are not faulty. Toshiba patented a fault detection apparatus and a fault detection method [157] for a PV electricity-generating system. There are several storage units to store different parameter values such as the output value of the communication unit, an output model indicating the relationship between sunshine conditions and electrical output, a correction unit to correct the sunshine condition, and a detection unit to calculate the expected electrical output for each module based on the corrected sunshine condition and the output model, and to detect a fault in the modules. Edwards and Gray [158] provided an airbag control circuit that includes a self-diagnostic circuitry. After installation into a vehicle, the control circuit allows the airbag to test itself if a sufficient fire current is provided when needed to set off a squib.

From the patents analyzed in this subsection, it can be seen that in the field of electrical systems besides the six major application types mentioned above, PHM also has a share in the non-mainstream electrical applications. In the future, PHM technologies is expected to be applied in more electrical applications to ensure the safe operation of the object.

## IV. CONCLUSIONS

PHM has emerged as an alternative to the traditional approaches for improving the reliability of products. The objective of this paper is to fill the knowledge gap of academia and industries in the subject to PHM. Through a discussion of PHM patents for electrical systems, this paper reviewed different aspects of PHM: i) the current research status; ii) the industrial applications; iii) and the challenges and opportunities in the implementation. Several trends in PHM approaches and implementation were identified, including the following moves: from individual components to systems, from implementation of a single sensor to networked sensors, from offline data analysis to online data analysis, and from monitoring products in the use stage to monitoring over the whole life cycle. In the future development of PHM patents in electrical systems, there are three issues that need to be paid attention to as follows:

1) Networked and distributed fault diagnosis techniques and their applications will be further developed because distributed structures and wireless communication networks are widely used in industrial systems. Correspondingly, networked sensing systems are replacing single sensor measurement because they can provide PHM algorithms with detailed information for a target system from different measurement positions in different units.
2) Data-driven techniques will find more applications because data acquisition systems and smart meters are installed in industrial automation systems to help monitor the health of the device, resulting in a large amount of available data.
3) Active fault diagnosis approaches are far from mature compared with non-invasive diagnosis methods because the increased use of sensors and wireless connections can harm the robustness of the monitoring system. Therefore, further relevant scientific research is needed.

In the future work on two remaining parts, Part II review will focus on PHM for mechanical systems and Part III review will focus on PHM for general PHM methodologies separately.

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