DEVELOPMENT OF THE FUTURE GENERATION OF SMART HIGH VOLTAGE CONNECTORS AND RELATED COMPONENTS FOR SUBSTATIONS, WITH ENERGY AUTONOMY AND WIRELESS DATA TRANSMISSION CAPABILITY

Akash Kadechkar

Universitat Politècnica de Catalunya
Electrical Engineering Department

DEVELOPMENT OF THE FUTURE GENERATION OF SMART HV CONNECTORS AND RELATED COMPONENTS FOR SUBSTATIONS, WITH ENERGY AUTONOMY AND WIRELESS DATA TRANSMISSION CAPABILITY

SmartConnector

Author: Akash Kadechkar

Advisor: Dr. Jordi-Roger Riba Ruiz

Dr. Manuel Moreno Eguílaz

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Dedicated to my beloved parents Kashinath and Laxmi Kadechkar,

my brother Akshay and the entire Kadechkar family.

One man's "magic" is another man's engineering.

—ROBERT A. HEINLEIN

ABSTRACT

The increased dependency on electricity of modern society makes reliability of power transmission systems a key point. This goal can be achieved by continuously monitoring power grid parameters, so possible failure modes can be predicted beforehand. It can be done using existing Information and Communication Technologies (ICT) and Internet of Things (IoT) technologies that include instrumentation and wireless communication systems, thus forming a wireless sensor network (WSN). Electrical connectors are among the most critical parts of any electrical system and hence, they can act as nodes of such WSN. Therefore, the fundamental objective of this thesis is the design, development and experimental validation of a self-powered IoT solution for real-time monitoring of the health status of a high-voltage substation connector and related components of the electrical substation. This new family of power connectors is called *SmartConnector* and it incorporates a thermal energy harvesting system powering a microcontroller that controls a transmitter and several electronic sensors to measure the temperature, current and the electrical contact resistance (ECR) of the connector. These measurements are sent remotely via a Bluetooth 5 wireless communication module to a local gateway, which further transfers the measured data to a database server for storage as well as further analysis and visualization. By this way, after suitable data processing, the health status of the connector can be available in real-time, allowing different appealing functions, such as assessing the correct installation of the connector, the current health status or its remaining useful life (RUL) in real time. The same principal can also be used for other components of substation like spacers, insulators, conductors, etc. Hence, to prove universality of this novel approach, a similar strategy is applied to a spacer which is capable of measuring uneven current distribution in three closely placed conductors. This novel IoT device is called as *SmartSpacer.* Care has to be taken that this technical and scientific development has to be compatible with existing substation bus bars and conductors, and especially to be compatible with the high operating voltages, i.e., from tens to hundreds of kilo-Volts (kV), and with currents in the order of some kilo-Amperes (kA). Although some electrical utilities and manufacturers have progressed in the development of such technologies, including smart meters and smart sensors, electrical device manufacturers such as of substation connectors manufacturers have not yet undertaken the technological advancement required for the development of such a new family of smart components involved in power transmission, which are designed to meet the future needs.

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1. INTRODUCTION

We are witnessing a fundamental change in the electricity sector: deregulation and privatization of the electricity market, distributed generation with renewable energies, generation of energy in remote locations and a growing demand for electrical energy. Global climate change poses new challenges for the generation and transmission of electrical energy. Innovative solutions are required to improve the efficiency of the electrical system, reduce CO_2 emissions and optimize the use of energy sources. The most crucial points are sustainability, safety of supply and the efficiency of the electrical system. One of the bets to achieve these goals is the High Voltage Direct Current (HVDC) technology, which allows the interconnection of Alternating Current (AC) networks or renewable sources with the public network and at the same time, it allows increasing the power transmission of electrical energy [1], minimizing also the possibility of faults and increasing the efficiency and stability of the electrical system. The development strategy of large power systems is focused on the Smart Grids, which consist of AC / DC interconnections and highways of point to point electrical transmission with bidirectional power flow. These hybrid AC / DC systems offer significant advantages in terms of technology, economics and security of supply, allowing transmission costs to be reduced and bypassing the overloaded AC systems.

In future, for the coordination in the Smart Grid, it will be essential to have transmission information services of the various components of the system in real-time [2]–[4]. There must be a coordination between the generation, distribution and consumption, through the use of Information and Communication Technologies (ICT), so areas that include instrumentation, synchronization for protection, control, and energy quality or energy management are found connected in a global management system. According to [5], during 2017, 36.7 million people were affected by power outages only in US, with estimated costs around $150 billion. Although it is impossible to avoid completely power outages, their effects can be greatly reduced. In addition, to the development of the new Smart Grids, it is important to have electrical components such as connectors, spacers and conductors that incorporate sensors and by means of wireless links they can transmit information in real time, which can be useful to make a diagnosis of their state of health, level of load, etc., to facilitate predictive maintenance tasks and to be able to contribute to the control of electrical installations in a more reliable, fast and efficient way [6][7].

1.1 BACKGROUND

1.1.1 Wireless Sensor Network using Internet of Things devices

Internet of Things (IoT) devices are hardware components consisting of different types of sensors that wirelessly transmit data from the sensors to another hardware system for real-time monitoring. Wireless sensor networks (WSN) are being developed worldwide [4], [8]–[21] using IoT devices for real-time monitoring of several parameters in diverse applications, to enable them to be more controllable and reliable. It is expected that Industrial Internet of Things (IIoT) can create $12 trillion of global GDP by 2030 [22]. It has been proven that IoT solutions allow drastically improving power system reliability and availability by determining the health condition of vital elements [18], [20], [23]–[25]. By this way, early failure symptoms can be diagnosed, thus allowing to apply suitable measures to anticipate further degradation [26]. Figure 1-1 represents the proposed WSN for the future Smart Grids.

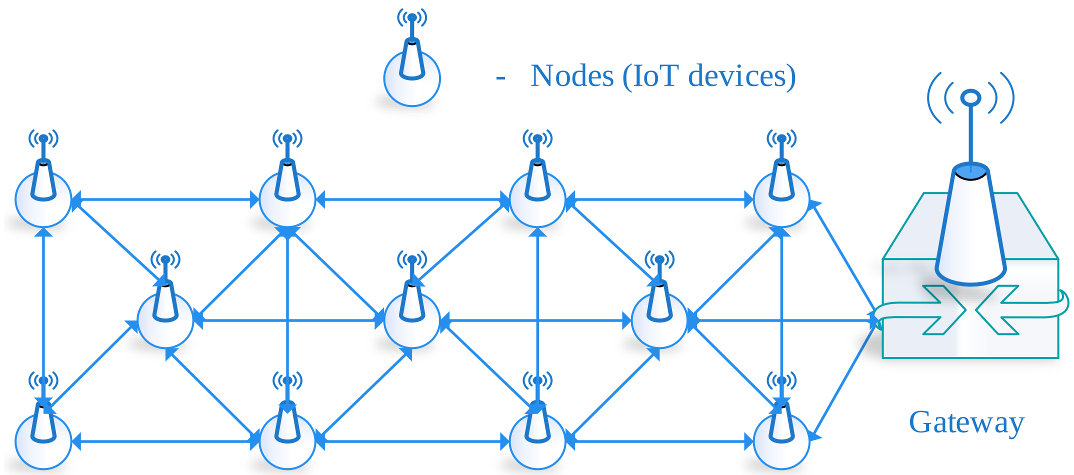


Figure 1-1. Smart Grid based Wireless Sensor Network using Internet of Things devices. Source: own.

In this thesis it is proposed that electrical components like connectors, spacers and conductors can act as nodes for such WSN. Thus, this project is focused on the design, development and validation of an IoT system to be integrated with substation connectors, spacers and conductors which can acquire the data in real time for predictive maintenance. This new family of electrical components will be called *SmartConnector*, *SmartConductor and SmartSpacer*, respectively. This thesis is mainly focused on the development of *SmartConnector*. However, by using the same strategy, the *SmartConductor and SmartSpacer* are developed. Although there exist many IoT devices in the market, this is a very specific application in a very particular High Voltage (HV) environment. So it is necessary to study the environment in order to develop a suitable IoT solution.

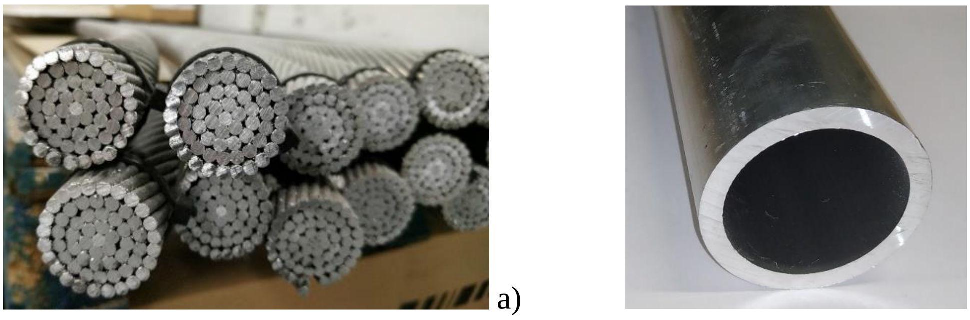
1.1.2 Electrical Substations

Depending on the application, electrical substations are located in the vicinity of a production plant, at the point of distribution to the end user or at the points of interconnection between the electrical lines. Substations employ various devices for safety, switching, voltage regulation, and measurement. Substation are usually located in an outdoor environment, thus being susceptible to harmful environmental conditions such as rain, solar heat, snow, wind, moisture, dust, etc. Moreover, substations themselves are hazardous zones, as they operate in the range of 10-400 kilo-Volts and carry current in the order of kilo-Amperes. Figure 1-2 represents an actual outdoor substation. This thesis is mainly focus on developing smart devices for HV substations.

Figure 1-2. Part of an Electrical Substation. Source: SBI catalogue.

1.1.3 Electrical Conductor and Bus Bar

Conductors are the primary elements for the transfer of power, which occupy a major area of the substation. Conductors can be of different types, like stranded conductors or bus bars as shown in Figure 1-3. But, within a substation, bus bars are the main current carrying conductors because they are rigid and provide mechanical stability. Substation bus bars are commonly made of aluminum, and are supplied in many configurations, including rectangular bars, round tubing, square tubing, etc. The challenge for substation conductor design is to meet dimensional, mechanical and electrical constraints to avoid vibration, corona, thermal expansion and overheating.



a) b)

Figure 1-3. a) Stranded Conductors b) Tubular hollow bus bar. Source: SBI catalogue.

1.1.4 Electrical Connector

The definition of an electric connector, according to the ANSI/NEMA CC 1-2009 standard, is “a device that joins two or more conductors for the purpose of providing a continuous electrical path” [27]. Thus, substation connectors are the joints that physically link the power transmission line and the substation conductors and bus bars. They are usually divided into different categories, depending on the physical junction between the connector and the conductor: mechanical, welded, and compression type are the most common ones. Substation connectors considered in this thesis are aluminum alloy devices of mechanical type. This means that the coupling parts, that is, the parts which transmit electrical power, are mechanically joined by applying a specific torque by means of bolts and nuts, with the aim to ensure an adequate contact resistance between the connector and conductor or bus bar. Mechanical type substation connectors have a wide range of geometries and sizes. Figure 1-4 shows three types of substation connectors belonging to SBI Connectors Spain catalogue.

a) b) c)

Figure 1-4. Mechanical-type substation connectors from SBI catalogue. a) Expansion connector (Conductor to bus bar), b) Straight connector (Bus bar to bus bar), c) Terminal connector (Conductor to bushing terminal). Source: SBI catalogue.

Electrical connectors are key elements of substations, playing a critical role in their reliability and efficiency. Failure of such elements can cause severe outages with catastrophic and costly consequences [28]–[31]. Utilities and system operators must ensure a safe, reliable and continuous delivery of power to customers, while trying to minimize any outage in the service [32]. In addition, some substations are located in remote places, so they are not easily accessible. Nowadays, many maintenance plans are almost corrective, so remedial actions are applied after failure occurrence, since no updated daily data is available for these devices. In order to make a transition towards predictive maintenance plans, daily data such as temperature, contact resistance or vibrations of such devices is required. To this end, they must incorporate sensors and wireless communication systems to transmit this data to a data analysis center to facilitate the application of condition monitoring programs. Thus, it is highly desirable to acquire real-time data to monitor the current health status of power connectors [33]–[35] for a real-time diagnosis and to predict the failure in advance, while estimating the reliability and useful lifetime [36]–[44]. This approach allows optimizing the life cycle management by considering different aspects such as efficiency, power losses and costs points [45].

1.1.5 Intra Phase Spacer for Conductors

Spacers considered in this work are intra phase spacers. These spacers are used to maintain a minimum distance between two or more conductors as shown in Figure 1-5.


a)

b)

Figure 1-5. a) Spacer with three conductors and terminal connectors b) Spacer. Source: SBI catalogue.

Spacers are also used as dampers for preventing Aeolian vibration. The main objective of the spacer is to maintain the distance among conductors of the same bundle, to avoid collision of the neighboring conductors and minimize galloping effects. Galloping creates more mechanical stress in the conductor and in the supports, which can reduce the distance between the conductor and the ground, and ultimately it could lead to short circuit. Also, if the conductors are not symmetrically placed at equal distances, it can create an uneven current distribution among the three conductors, leading to premature ageing of some of them, which it could result in the failure of the system as a whole.

1.1.6 Testing Standards

International standards should be applied to conduct the experiments and to evaluate the performance of the substation connector. The main reference standard for substation connector is the American National Standards Institute (ANSI) / National Electrical Manufacturers Association

(NEMA) CC1 standard[27]. ANSI NEMA CC1 standard contains the procedure to be followed for proper evaluation of the electrical and mechanical characteristics of substation connectors. ANSI NEMA CC1 standard is primarily studied and used in this thesis to perform temperature rise tests and to correctly install substation connectors. ANSI C119.4 standard [46] is another standard which has been studied and applied in this thesis to evaluate the thermal behavior of the conductor and connector when subject to thermal heating and cooling cycles for a long period of time i.e., aging.

1.2 OBJECTIVES

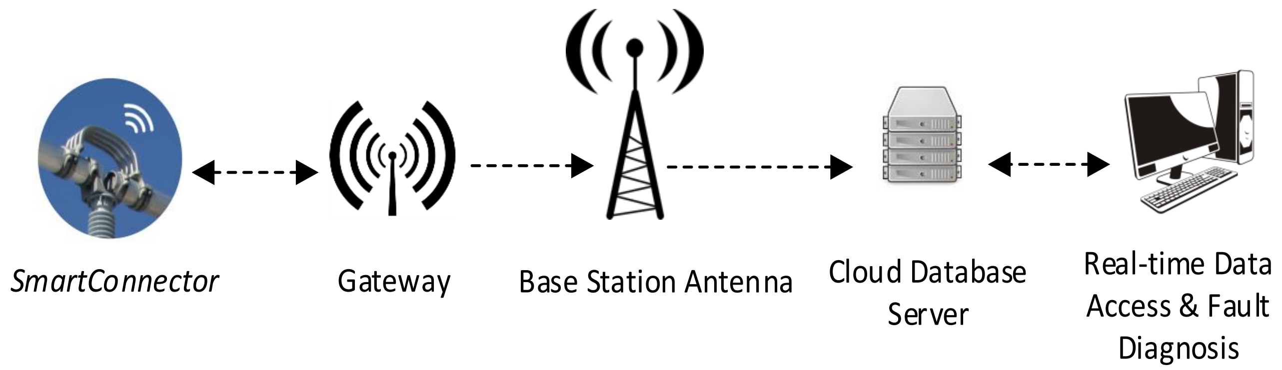


Figure 1-6. Proposed Wireless Sensor Network of *SmartConnector*. Source: own.

The main objective of this work is to build smart IoT devices for substations to form a WSN as shown in Figure 1-6. A summary of the challenges involved in order to accomplish the objectives are described below.

- Selecting the appropriate electronics for this special application. It means that the electronic system should be low cost, small size, robust, reliable under high operating temperature and extreme weather, and most importantly, compatible with both AC and DC electrical systems [47].
- Measure critical physical parameters such as temperature, current, vibration and contact resistance using a combination of sensors and novel data processing techniques.
- Moreover, in High Voltage (HV) facilities human intervention is restricted, being necessary to design an energy harvesting system, which can generate enough power from the environment to extend the lifetime of the IoT device, while avoiding periodic battery replacements.
- Selection of a suitable microcontroller and wireless communication system for reliable data acquisition and transmission.

- Simultaneously, an appropriate gateway must be selected and programmed for receiving data from the *SmartConnector* and sending the data to the cloud in real time using Ethernet, optical fiber, 4G or 5G network, etc.
- Suitable protection of the electronics to be able to operate in a high electric field environment.
- Other objectives include identifying and analyzing the key design parameters for developing the *SmartConnector* by means of both, simulations and experimental tests.

Therefore, it is necessary to build a self-powered low cost IoT system to be integrated within the substation connector, which is capable of acquiring meaningful data and wirelessly sending it to the cloud in real time for an extended period, focused to enable predictive maintenance plans [48]–[50].

SmartConnector electronic system includes three main parts:

1. Sensors
2. Wireless communication system (microcontroller with wireless communications)
3. Power management system (supervises in energy generation, storage and consumption)

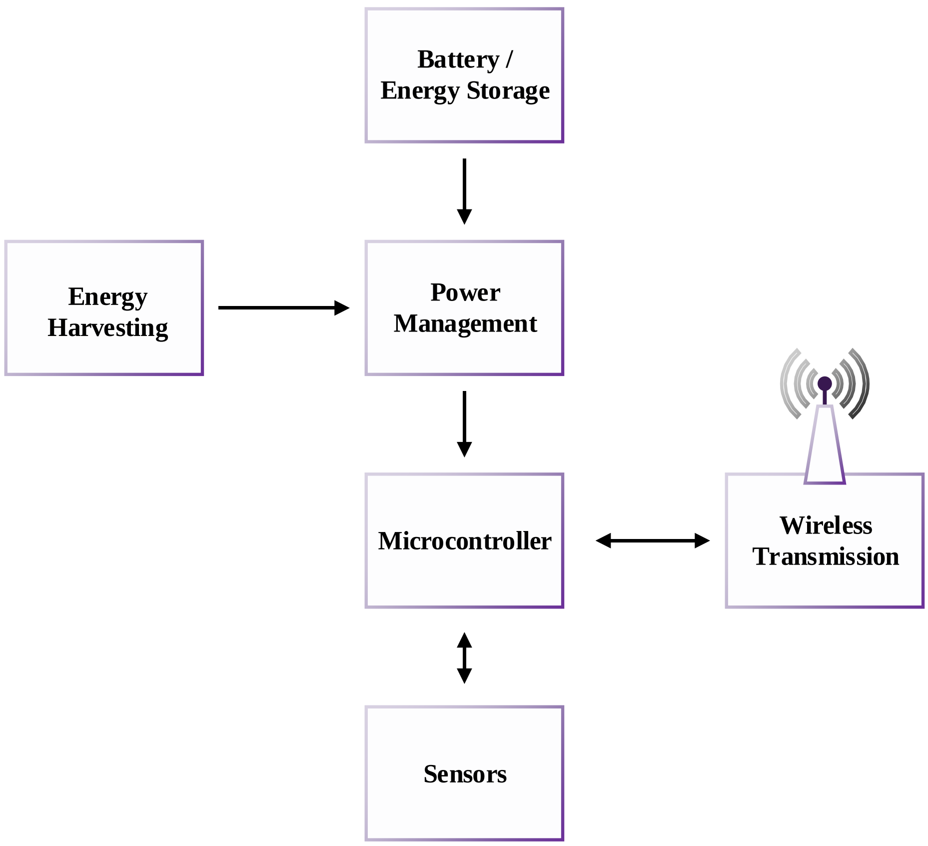


Figure 1-7. Block diagram of the *SmartConnector* electronic system. Source: own.

2. Smart Sensors for Measuring Critical Parameters

This chapter introduces both the background study of the critical parameters affecting the efficiency of the electrical grids, particularly substation connectors, and the importance of monitoring such parameters in real time using different technologies.

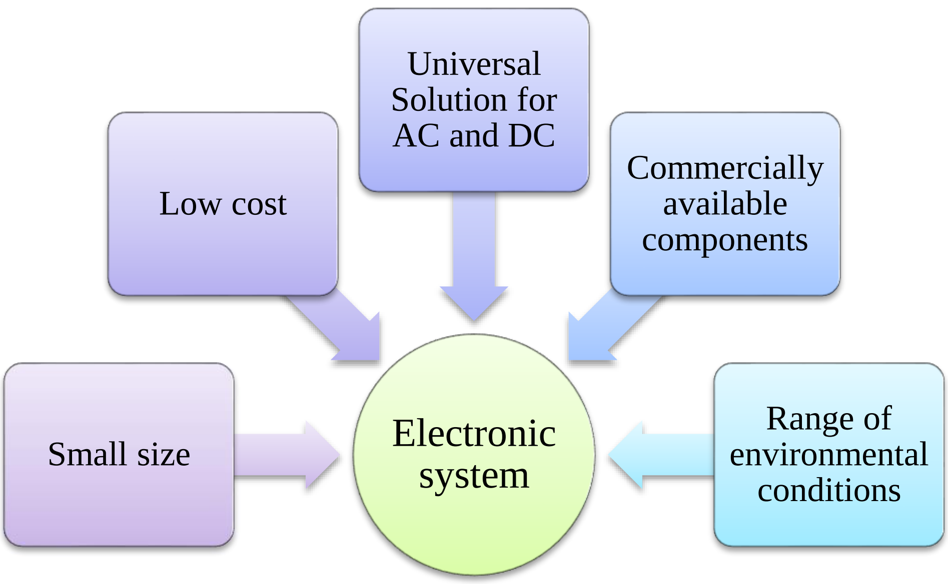


Figure 2-1. Different parameter for selection and development of the electronic system. Source: own.

Furthermore, the sensors to be used for the proposed electronic system are studied and identified in this section. Since, the aim of this thesis is also to satisfy the industry requirements, the selection of components should be done based on certain factors, such as low cost, low maintenance, universal solution, small size, reliability, robustness, range of environmental conditions at which they can operate, etc. as shown in Figure 2-1. New sensors can be developed to fulfill these requirement, but it would be time consuming and expensive for manufacturing. There exist already many commercial sensors available in the market, which can be applied for this application. For example, the sensors which are being used in the automotive industry normally can work under high temperature and high vibration conditions. So, it is better to use the already existing sensors to apply for this application. From the state of art [51], it is known that temperature, current, electrical contact resistance or vibration, are among the main factors affecting the efficiency of the substation and hence, the same parameters are required to be measured in real time.

Section 2.1 describes the importance of temperature measurement. Section 2.2 demonstrates current measurement using Hall effect and Magnetoresistive sensors. Section 2.3 shows the novel developed technique to measure the contact resistance in real-time. Section 2.4 details the method to eliminate the proximity effect on the current measurement. Finally, Section 2.5 explains the effect of vibration on the contact resistance.

2.1 TEMPERATURE MEASUREMENT

Temperature is one of the major causes of failure in an electrical grid. Joule effect is the primary reason for the increase in temperature and losses in electrical grid. Joule heating describes the process by which the energy of an electric current is converted into heat as it flows through a resistance. When the current flows through a body with finite conductivity, the conducting electrons impact with the atoms, thus releasing energy in the form of heat and increasing the temperature of the conducting body like bus bar, conductor, connector, etc. Thus, if more current passes though the conducting body than its nominal current rating, then the conducting body can reach inappropriate temperature point leading to failure of the electrical grid. For the same reason, power transmission is done at high voltage levels, allowing by this way decreasing the current circulating through the network and, therefore, also reducing the necessary cross section of the conductors, while limiting the maximum operating temperature. One could suggest that the voltage could be raised at a much higher level in order to drive electric current almost to 0 A. Unfortunately, high voltage levels close to and over the dielectric strength of the air insulation surrounding the conductor, produce losses in the form of corona effect, which is explained in detail in the section 3.3 .

The change in temperature due to current cycling causes thermal expansion and contraction of the electrical components. This effect is more pronounced in flexible conductors like cables. Hence, the contact resistance between the connector and conductor tends to change due to the expansion and contraction effects because of the thermal cycling, which can affect the temperature, as the electrical resistance is linearly proportional to the temperature, as shown in equation (1). Thus, it is necessary to

3. Wireless Communication

As already mentioned in Section 1.2 , wireless communication is the most important aspect of IoT technology. In order to predict the failure of the substation, it is necessary to collect suitable real-time data from the connector. This data can be any physical quantity such as temperature, electrical current, contact resistance or vibrations level among others. The data can be acquired using suitable sensors detailed in Section 2 and installed in close contact with the connector and further transmitted wirelessly for being monitored, processed and analyzed.

The existing IEC 61850 standard [164]–[166] for communications within substations does not include any wireless communication protocol. It may have been avoided in the standard due to reliability issues, since high-voltage substations and transmission lines tend to produce radio interference (RI) due to corona discharge processes, thus affecting telecommunications reliability. However, with the improvement of low-cost low power electronics including wireless transmission and reception capabilities, it is possible to measure many parameters in the substation by minimizing cabling and maintenance costs.

Hence, in this work, a suitable wireless communications system is selected for data transmission from the *SmartConnector* and related devices to the cloud database server based on the use of low-power IoT devices in-line with smart grid applications [2]–[4], as shown in Figure 1-6. Recent studies suggest to use edge computing for IoT devices that need real-time response. Edge computing is a decentralized cloud processing closer to IoT devices, which reduces the computing, communication bandwidth, latency, and storage burden on cloud servers, thus increasing efficiency and quality of services [167], [168]. Therefore, to test the wireless communication, an entire IoT system is needed and hence, a suitable microcontroller for data acquisition from the sensors is selected, which along with a local gateway that computes the temperature, current, ECR and battery state of charge (SoC) values from the data received by the *SmartConnector* and transmits the processed values to the cloud server via Ethernet, 3G, 4G, etc. for being monitored in the IoT platform. Moreover, the performance of the entire IoT system is tested under high electric field and different corona discharge severity conditions occurring in High Voltage Alternating Current (HVAC), Positive High Voltage Direct Current Positive (HVDC+) and Negative High Voltage Direct Current (HVDC-).

Section 3.1 details the literature review of the state of the art and the different wireless technologies along with their comparison on the important parameters to be considered for its implementation in a substation. Section 3.2 describes the proposed IoT system based on Bluetooth 5 wireless communication. Section 3.3 presents an experimental set up to study the impact of corona on the Bluetooth 5 wireless communication and finally, Section 3.4 provides the solution for the shielding the *SmartConnector* along with the design of a suitable corona protection.

3.1 LITERATURE REVIEW

3.1.1 Related Work

This section reviews the previous works related to the use of wireless communication in HV. In [169], a feasibility study of wireless communications in high-voltage substations is explained. However, issues arise when the transmission frequency of the wireless device is in the same range as that of the RI frequency range. The radiation levels associated to the electrical discharges in HV environment have wide frequency spectrum. The discharge noise will affect the frequency bands operating below 1 GHz, although interference power levels gradually decrease with increasing frequency [170]. Similar results are found in [171], [172] and [173]. Hence, previous studies report that RI mostly occurs with stronger amplitude at lower frequencies whereas trending wireless communication devices use the 2.4 GHz unlicensed ISM band. Results from [174] show that extremely high-voltage (EHV) transmission lines generate corona noise up to 2 GHz. In [175], it is concluded that the inter-electrode distance is an important parameter, since larger inter-electrode distances increases the RI power while shifting its spectrum towards the wireless communication bands.

In [176], the classic Bluetooth was tested in a vacuum switch cabinet, proving that breakdown radiation signals produced in the vacuum gap overlap with the ISM frequency band used by the Bluetooth communication system, thus decreasing the data transfer rate. However, the Bluetooth device is bulky and consumes more power compared to BLE devices, hence being not feasible for long term testing in substation environments, which usually are powered through energy harvesting systems. Simulation results from [177] conclude that the impulsive nature of the noise signals generated in electrical substations is unlikely to obstruct the deployment of classic Bluetooth devices. The wireless local area network (WLAN) proposed in [178] to monitor leakage currents in electrical substation does not show any evidence that the noise due to energized high-voltage equipment interferes WLAN sensors, although the experiments were only conducted under AC energization and not at a very high-voltage levels. In [179], it is proved that the ZigBee communication link is prone to transceiver malfunction and disruption when exposed to strong levels of interference. In [180], it is stated that 5 GHz Wi-Fi (IEEE 802.11a) provides improved interference immunity compared to ZigBee (IEEE 802.15.4) and 2.4 GHz Wi-Fi (IEEE 802.11g). The model presented in [181] to compute corona RI levels in HVDC transmission lines is useful for selecting appropriate wireless communications. In [182], it is proved that the corona current frequency of an ultra-high-voltage (UHVDC) transmission line increases with the voltage, as well as the amplitude of audible noise in the 6–20 kHz frequency band. It is also known that the speed of wireless communication changes under AC corona discharges [183].

3.1.2 Wireless Technologies

Low-power electronics industry is evolving at a very fast pace. This is an advantageous situation to implement small-size low-power electronic devices with wireless capabilities for industrial applications, thus promoting the development of the internet of things (IoT) market. Low-power long-range wireless devices to serve the need of the emerging industrial IoT (IIoT) market are collectively known as low-power wide-area network (LPWAN). LPWAN devices are connected directly to a sensor and send the data to a base station which then transmits the data to the cloud. These devices can be deployed in the field and will continue to function based on battery power for around 10 years, depending on the quantity of the transmitted messages.

Some of the latest LPWAN systems are cellular (NB-IoT, LTE-M/Cat-M1) and non-cellular (SigFox, LoRa, Weightless, etc.) technologies. Table 3-1 compares different LPWAN options. Narrowband IoT (NB-IoT) is a new cellular technology introduced in 3GPP Release 13 for providing wide-area coverage for the IoT [184]. Unlike LTE based IoT networks, in NB-IoT, the data from the sensors are sent directly to the main server, thus eliminating the gateway. Cellular based IoT technologies are expensive, as they use licensed bands. These technologies have been deployed by the existing telecommunication companies to extend their market in the IoT sector, using the existing infrastructure.

Non-cellular LPWAN systems such as SigFox, LoRa and Weightless use free ISM radio bands to avoid the expensive license fees required for exclusive use of frequencies. However, by using unlicensed radio bands, the control over the entire bandwidth is lost. At present, SigFox is the most popular LPWAN in the IoT market. However, SigFox is not an open protocol, since it is restricted to SigFox networks with very low data transfer rate. Long Range (LoRa) is an open standard, since it belongs to a private network. SigFox and LoRa are not appropriate for the cases where downlink communication is important. Table 3-1 compares the different wireless commercially available communication networks.

TABLE 3-1. COMPARISON OF DIFFERENT WIRELESS COMMUNICATION NETWORKS

Communication Protocol	Data Transmission Capacity	Typical Range	Regulation	Cost	Maximum Output Power	Backup Possibility
Bluetooth 5	Moderate	0.4-1 km	License free	Low	0.003 W	Yes
SigFox	Very Low	20-25 km	License free	Low	0.025 W	No
LoRa	Low	5-10 km	License free	High	0.025 W	Yes
NB-IoT / Cat-M2	Low	10-15 km	Expensive dedicated channel	Moderate	0.200 W	Yes
LTE Cat-M1	Low	10-15 km	Expensive dedicated channel	High	0.200 W	Yes
Weightless	Moderate	2 km	License free	Moderate	0.050 W	Yes

LoRa is optimum when the coverage area is large and the required data transfer rate is low. However, in the case of electrical substations, the coverage area is not very large and it is required to collect a relatively large amount of data from the substation for a real-time monitoring and to take immediate action to avoid unwanted power failures. From the above mentioned disadvantages of LPWANs, a different IoT solution is needed for substations. Therefore, it is proposed to use Bluetooth 5 which is a low-power technology with low cost, high data rate and short range, which can be increased when required by Bluetooth mesh networking. Also, with Bluetooth 5 it is possible to have bi-directional communication, whereas the software can be updated over the air (OTA).

3.1.3 Bluetooth Classic versus Bluetooth Low Energy

Table 3-2 summarizes the difference between wireless Bluetooth classic and Bluetooth Low Energy (BLE) based on Bluetooth 5. Bluetooth classic is very different from Bluetooth 5, which is a new generation wireless communication protocol based on Bluetooth Low Energy (BLE), i.e., BLE consumes less power as compared to Bluetooth classic.

Depending on the application, a choice has to be made, because both are used for very different applications. Bluetooth classic is used for transfer of large amount of data and hence, it consumes more battery and also costs more. On the other hand, BLE is used to transfer small amounts of data at periodic intervals, to reduce battery consumption, so it is cheaper as compared to Bluetooth classic. In the proposed application, power consumption is a critical parameter, whereas the size of data to be transmitted is very small. Therefore, Bluetooth 5 wireless communication is selected for the *SmartConnector* application.

TABLE 3-2. DIFFERENCE BETWEEN BLUETOOTH CLASSIC AND BLUETOOTH 5

Parameters	**Bluetooth Classic**	**Bluetooth 5**
Connection speed	Discovery on 32 channels leads to slower connections	Discovery occurs on 3 channels, hence connection is faster
Number of channels	79 RF channels	40 RF channels
Power requirement	High	Low
Protocols	Profiles define their own protocols	Profiles are built on top of GATT/ATT
Applications	Audio streaming and file transfer	Sensor data and low-bandwidth applications

3.2 BLUETOOTH 5 BASED IOT SYSTEM

A suitable Bluetooth 5 module is needed for implementation in electrical substations. After extensive market research it was found that there exist many commercially available Bluetooth 5 modules in the market. All of them come integrated with an Arm® Cortex™ CPU, which is an advantage in terms of size, cost, programming requirements and power consumption. There are several Bluetooth module manufacturers like Nordic Semiconductor, Cypress Semiconductor, NXP, Laird, Texas Instruments, Microchip, Adafruit, Panasonic, Seed Studio, STMicroelectronics, Silicon Laboratories, etc. providing Bluetooth modules with similar characteristics in terms of generous RAM, Flash, operating temperature, inbuilt ADC, input voltage, cost, etc.

However, the nRF52832 (System on Chip) SoC Bluetooth device from Nordic Semiconductors includes low power consumption modes, which can be vital in the proposed application [185]. Also,

4. POWER MANAGEMENT

Power management is the most important aspect for long term functioning of any IoT device, including the *SmartConnector*. The sensors required to sense the physical variables and microcontroller used to acquire and transmit the data, need a suitable power supply. Due to the constraints existing in high-voltage electrical substations, human intervention must be minimized to apply customary condition monitoring programs. Since the sensors are installed on the connector or the bus bars, dedicated cables are unfeasible. Also, many of the already installed connectors have more than 25 years lifetime expectancy [194]. In addition, some are placed in inaccessible locations where it is almost impossible the access to existing power sources, so their continuous supply becomes very difficult and challenging.

Moreover, the sensing and wireless communication systems must be non-intrusive, with minimum impacts on the host equipment. Therefore, such electronic systems must be miniaturized, and must have long-live operation without the need of periodic battery replacements. Such smart IoT devices cannot be fed by batteries since their discharge cycle is limited. Therefore, *SmartConnector* and related IoT devices applied to HV substation must be powered autonomously, and thus, an ambient energy harvesting system is an appealing solution [195]. This approach allows maximizing the time interval between consecutive maintenance operations of the electronics.

Section 4.1 details the literature review of the state of the art and the different energy harvesting techniques along with a comparison of the important parameters to be considered for its implementation in a substation for long term operation. Section 4.2 presents the energy consumed by the *SmartConnector*. Section 3.3 describes the proposed thermal energy harvesting for the *SmartConnector* and its feasibility by performing different experimental tests. Finally, Section 4.4 explores possibility of a solar energy harvesting unit powering the *SmartConnector*.

4.1 LITERATURE REVIEW

4.1.1 Related Work

Diverse strategies have been analyzed such as harvesters based on the electric field, magnetic field, vibrations, solar radiation or thermal energy [195], [196]. However, when dealing with HVDC (high-voltage direct current) power systems, electric and magnetic field based harvesting systems are unfeasible, whereas in indoor substations solar or vibrations based energy harvesting systems present inherent difficulties. Previous energy harvesting research for high-voltage and high-current applications is reported in [195]–[198]. In [195] a hybrid solution is proposed, which increases the cost and size of the energy harvesting system along with the complexity, [170] does not provide a universal solution for AC and DC systems, [197] proposes the use of solar energy harvesting which requires periodic maintenance, whereas [198] implements a heat dissipater in a rectangular bus bar, which requires liquid refrigeration and a big corona protection, thus making difficult its application.

4.1.2 Energy Harvesting Techniques

This section compares different energy harvesting techniques, which are well suited to be applied in high-voltage electrical substations. These technologies can be broadly classified as solar photovoltaic, thermal, magnetic/electric field, vibrations and radio-frequency (from ambient or specially radiated from an external antenna for the application) energy harvesting, whose main features are summarized in Table 4-1.

TABLE 4-1. COMPARISON OF DIFFERENT ENERGY HARVESTING TECHNIQUES FOR ELECTRICAL SUBSTATIONS

Harvesting Techniques	Devices Used	AC & DC Compatibility	Cost	Installation	Maintenance	Continuous Energy
Solar	Solar PV cells	Yes	Low	Moderate	Very high	No
Thermal	Peltier	Yes	Moderate	Moderate	Low	Yes
Electric field	Capacitor	No	High	Difficult	Low	Yes
Magnetic field	Inductor	No	High	Difficult	Low	Yes
Vibration	Piezo crystals	Yes	Low	Difficult	High	No
Radio frequency	Antenna	Yes	Low	Low	Low	No

From the comparison shown in Table 4-1, the only technologies simultaneously compatible with alternating current (AC) and direct current (DC) are solar photovoltaics, thermal, vibrations and radio frequency energy harvesting.

Although sun is the main source of energy that exists, some substations are indoors, and thus, their effectiveness is limited. In outdoor substations, it is not possible to harvest during the night, and in some countries, there is almost no light during the whole day during some months of the year. Another problem of the solar photovoltaic energy harvesting is soiling, the accumulation of dust, dirt, and pollen, which reduces the amount of sunlight on the surface of the solar cells, thus requiring periodic cleaning. Vibrations from the wind or another origin can also be used for energy harvesting. However, in indoor substations, the potential of this technology is very limited and also in outdoor substations, since in some calm days the energy generated by this technology is very reduced, since the power generated is usually below 1 mW [199]. Another possibility is harvesting energy from the nearby radio waves using an antenna. But near to substation, it is not always feasible to find a continuous supply of radio waves, the antenna required to capture the radio waves is sometimes incompatible with corona requirements, and the power harvested is often in the range of the µW [200].

Electrical bus bars are very common in electrical substations, and their temperature increase due to Joule losses. Owing to the abovementioned reasons, it seems that the most universal energy harvesting solution compatible with HVAC and HVDC systems is the thermal energy harvesting, taking advantage of the temperature gradient between the ambient temperature and that of the reference bus bar of the substation connector. It can work for both indoor and outdoor applications, thus being feasible in a wide range of applications. This technology will always be able to generate electrical power as long as there is a sufficient current flowing through the bus bars.

4.1.3 Energy Balance

Even if there exist a suitable Energy Harvesting System (EHS) to power the *SmartConnector*, it will not be sufficient to power the entire *SmartConnector* to send the data continuously every second. Moreover, for this specific application, continuous data transmission is not required, because the connector, once installed, has a life expectancy of around 25 years. So, to trace the evolution of the *SmartConnector*, data transmission per second is not required. Therefore, a suitable strategy is applied, as shown in Figure 3-4, where the *SmartConnector* is in sleep mode for most of the time, while consuming very low power and then wakes up frequently for data acquisition and transmission. To make possible the long term operation of the *SmartConnector*, it is necessary to calculate the frequency

5. CONCLUSION

This thesis is a combination of several fields of research studies. Each chapter of this thesis represents a different field of research area. Therefore, each chapter of this thesis contributes individually in its particular research area. Section 5.1 describes the general conclusion of this thesis, Section 5.2 details the main contributions and finally, Section 5.3 explains the future scope of this work.

5.1 GENERAL CONCLUSION

The main objective of this thesis was to develop a low cost self-powered IoT device which can be applied to connectors and related components like conductors, bus bars, spacers, etc. for high current and voltage substations to acquire meaningful information from such components in real time. Therefore, different fields of research areas have been identified, studied and applied in this thesis in order to fulfill the objective of the project.

In chapter 1, different components involved in the substation were analyzed. The critical parameters needed to be measured for evaluating the conditions of the electrical components were identified. Standard tests needed to perform the experiments were also detailed. The objectives of the thesis were described in detail in this chapter along with the list of the publications carried out during the course of this thesis.

In chapter 2, the operating conditions and environment of the substation were studied. Different stresses encountered by the electrical connectors, conductors and bus bars in the form of Aeolian vibrations, high temperature and uneven current distribution were studied, analyzed and estimated by performing different experiments. Specific sensors (current, temperature, vibration sensors and instrumentation amplifier) were selected, depending on the accuracy, range, cost, size, power consumption, operating temperature, etc. for measuring the contact resistance of the connector using a novel method along with other critical parameters like current, temperature and vibration. Different experiments were performed to test the accuracy, robustness and repeatability of the selected sensors to validate their applicability for the *SmartConnector*, and finally, the results conclude that the selected sensors are suitable for the *SmartConnector.*

In chapter 3, the wireless communication of the entire IoT system was described in detail. Electrical components of the substation are non-moveable assets. Bluetooth 5 wireless communication was selected for implementation in *SmartConnector*. After through market research, Nordic Semiconductors nRF52832 microcontroller with System on Chip (SoC) Bluetooth 5 module was selected because of its small size, cost, RAM memory, inbuilt Bluetooth 5 module, 8 ADC inputs, low power consumption modes, etc. The sensors included in the *SmartConnector* combined with the nRF52832 microcontroller, being an integral part of *SmartConnector,* were tested in both high voltage and high current laboratories to verify the impact of high voltage and high current on the wireless communications and the sensors outputs. After analyzing the results, a shielding enclosure and corona protection were added to the electronic circuit to minimize the effect of high current and high voltage on the *SmartConnector*. The data acquired by the *SmartConnector* is sent through Bluetooth 5 wireless communication to a local gateway (Raspberry Pi) which then computes the contact resistance, current, temperature and battery state of charge in real-time. Finally, the Raspberry Pi sends the final values to the SICAME IoT platform for monitoring purposes.

In chapter 4, solar and thermal energy harvesting systems were selected to extend the lifetime of the *SmartConnector* because of their compatibility with both AC and DC substations. Different experiments were performed to validate the feasibility of the *SmartConnector*. First, the energy consumption of *SmartConnector* prototype was measured. Next, both the solar and thermal energy harvesting systems were tested to estimate the average daily energy harvested to determine the data transfer rate. Results concluded that *SmartConnector* can transmit in real-time data with acceptable error under high current and high current environment by extending its lifetime by harvesting energy from the increment of temperature of the bus bar or conductor due to the Joule effect and from the solar radiation as well.

5.2 MAIN CONTRIBUTIONS

- Selection and validation of the suitable sensors and electronic components required for the wireless communication system and the energy harvesting system.
- Estimating the expected range of temperature, current and vibration in the bus bars of the substation.
- Strategy to measure the contact resistance of the connector in AC using three novel methods.
- Algorithm to validate correct installation of the connector and to measure the contact resistance of the connector in real-time in both AC and DC power systems.

- Cancelling the impact of the proximity effect on the current distribution measurement in parallel conductors using a combination of current sensors and a mathematical model.
- Design of an experiment to analyse the impact of Aeolian vibrations on the contact resistance of the connector.
- Programming the microcontroller of the *SmartConnector* for acquiring data from the current, temperature, vibration sensors, and instrumentation amplifier and from the battery.
- Programming the Bluetooth stack of the *SmartConnector* to send more than 27 bytes of data.
- Programming the microcontroller of the *SmartConnector* to enter different power modes, according to the designed power management algorithm.
- Designing the electronic system of the *SmartConnector* and *SmartSpacer* prototypes.
- Programming the Raspberry Pi to act as a gateway and to receive data from multiple *SmartConnectors* according to the designed power management algorithm.
- Based on the guidelines of edge computing, programming the Raspberry Pi to compute in real-time the values of contact resistance, current, temperature and battery state of charge from the data received by the *SmartConnector* and sending the final values to the cloud.
- Design of an electromagnetic shielding solution for the *SmartConnector.*
- Estimating the minimum temperature difference required between the bus bar and the ambient to enable thermal energy harvesting by performing several experiments.
- Calculating the data transfer rate desired for both solar and thermal energy harvesting options for the *SmartConnector* for extending its lifetime.
- Design and development of the PCB of the *SmartConnector* and the *SmartSpacer* prototypes along with some modifications of the SICAME IoT platform, which was done in collaboration with the SICAME IoT team.
- Design, simulation and development of the corona protection and the installation structure, in collaboration with SBI connectors.

5.3 FUTURE SCOPE

The *SmartConnector* can have a deep impact because of the potential improvement on power system availability and reliability, as well as on economic benefits derived from such improvements and its compatibility with the application of predictive maintenance plans. This thesis provides the solution for real-time data acquisition from the critical locations of the substation. Now, the next logical step is to utilize the received data in order to diagnose the present health status of the connector, predict the future condition of the connector and also the Remaining Useful Life (RUL) of the connector.

Nowadays, RUL is used for predictive maintenance tasks to improve efficiency and productivity, thus, avoiding delays on schedules of industries or projects. Data alone will not be sufficient to allow the prediction. Different types of diagnostic models must be developed based on the behaviour of the connector in different conditions and under different stresses (thermal, mechanical and corrosion) by performing practical experiments.

IoT is an emerging market and its application in the electrical grid is just evolving, based on the guidelines of the smart grid. Using the selection criteria and the key points identified in this thesis, a similar approach can be applied to develop IoT devices and diagnostic models for the other components of the HV power grid. This strategy will ease to apply condition monitoring and predictive maintenance tasks.

Data security and data protection are the other important issues that should be addressed in the near future, before the actual implementation of IoT devices in power grids. Other functionalities like data encryption, Over the Air (OTA) firmware update, and increased range of the wireless communication can be added to the *SmartConnector*.

In future, IoT devices will be the most commonly used data acquisition equipment for monitoring and control purposes. Therefore, a similar strategy proposed in this thesis can also be applied to develop IoT devices for industry sectors other than the power grids.

BIBLIOGRAPHY

[1] Siemens, “HVDC PLUS - The Smart Way,” 2015.

[2] V. C. Gungor, B. Lu, and G. P. Hancke, “Opportunities and Challenges of Wireless Sensor Networks in Smart Grid,” *IEEE Trans. Ind. Electron.*, vol. 57, no. 10, pp. 3557–3564, 2010.

[3] V. C. Güngör *et al.*, “Smart grid technologies: Communication technologies and standards,” *IEEE Trans. Ind. Informatics*, vol. 7, no. 4, pp. 529–539, 2011.

[4] E. U. Ogbodo, D. Dorrell, and A. M. Abu-Mahfouz, “Cognitive Radio Based Sensor Network in Smart Grid: Architectures, Applications and Communication Technologies,” *IEEE Access*, vol. 5, pp. 19084–19098, 2017.

[5] Eaton, “EATON Blackout Tracker Annual Report 2018,” 2018. [Online]. Available: https://switchon.eaton.com/plug/blackout-tracker.

[6] A. B. B. Wireless, T. Differentiators, and N. Cip, “Substation automation Lowering substation retrofit cost with wireless communication.”

[7] R. K. Mobley, *An Introduction to Predictive Maintenance (Second Edition)*. Butterworth-Heinemann, 2002.

[8] R. Medina-Gracia, A. D. R. G. De Castro, J. Garrido-Zafra, A. Moreno-Munoz, and E. Canete-Carmona, “Power Quality Sensor for Smart Appliance’s Self-Diagnosing Functionality,” *IEEE Sens. J.*, vol. 19, no. 20, pp. 9486–9495, 2019.

[9] N. Erratt and Y. Liang, “The design and implementation of a general WSN gateway for data collection,” *IEEE Wirel. Commun. Netw. Conf. WCNC*, pp. 4392–4397, 2013.

[10] F. Dowlatdad, J. Abouei, R. Saadat, and A. Anpalagan, “A Markov-Middleton model for corona noise in WSN transmission line monitoring,” *2015 IEEE Electr. Power Energy Conf. Smarter Resilient Power Syst. EPEC 2015*, pp. 440–445, 2016.

[11] P. Rajgarhia, P. James, V. Nainwal, P. Sowjanya, and S. S. Koshy, “Development of an Ultra-low power WSN gateway for outdoor deployments,” *2014 Int. Conf. Inf. Commun. Embed. Syst. ICICES 2014*, no. 978, 2015.

[12] M. Hajikhani, L. Fabrice, and B. L. Agba, “An Autonomous Wireless Sensor Network in a Substation Area Using Wireless Transfer of Energy,” *IEEE Access*, vol. 6, pp. 62352–62360, 2018.

[13] H. Wu and M. Shahidehpour, “Applications of Wireless Sensor Networks for Area Coverage in Microgrids,” *IEEE Trans. Smart Grid*, vol. 9, no. 3, pp. 1590–1598, 2018.

[14] L. S. I. Sensors *et al.*, “Perovskite PV-Powered RFID : Enabling,” *IEEE Sens. J.*, vol. 20, no. 1, pp. 471–478, 2020.

[15] W. K. Lee, M. J. W. W. Schubert, B. Y. Ooi, and S. J. Q. Ho, “Multi-Source Energy Harvesting and Storage for Floating Wireless Sensor Network Nodes with Long Range Communication Capability,” *IEEE Trans. Ind. Appl.*, vol. 54, no. 3, pp. 2606–2615, 2018.

[16] M. Ayaz, M. Ammad-uddin, I. Baig, and el-H. H. M. H. M. Aggoune, “Wireless sensor’s civil applications, prototypes, and future integration possibilities: A review,” *IEEE Sens. J.*, vol. 18, no. 1, pp. 4–30, Jan. 2018.

[17] H. C. Lee and K. H. Ke, “Monitoring of Large-Area IoT Sensors Using a LoRa Wireless Mesh Network System: Design and Evaluation,” *IEEE Trans. Instrum. Meas.*, pp. 1–11, 2018.

[18] D. Douglass *et al.*, “Real-Time Overhead Transmission-Line Monitoring for Dynamic Rating,” *IEEE Trans. Power Deliv.*, vol. 31, no. 3, pp. 921–927, 2016.

[19] M. G. Vidrascu and P. M. Svasta, “Maintenance-free IOT gateway design for bee hive monitoring,” *2017 IEEE 23rd Int. Symp. Des. Technol. Electron. Packag. SIITME 2017 - Proc.*, vol. 2018-Janua, pp. 189–193, 2018.

[20] Y. W. Kuo, C. L. Li, J. H. Jhang, and S. Lin, “Design of a Wireless Sensor Network-Based IoT Platform for Wide Area and Heterogeneous Applications,” *IEEE Sens. J.*, vol. 18, no. 12, pp. 5187–5197, 2018.

[21] Z. J. Chew, T. Ruan, and M. Zhu, “Strain Energy Harvesting Powered Wireless Sensor Node for Aircraft Structural Health Monitoring,” *Procedia Eng.*, vol. 168, pp. 1717–1720, 2016.

[22] A. Espírito-Santo, R. Abrishambaf, V. Paciello, and V. Huang, “The need for standardisation in low power smart sensing,” *Proc. IECON 2018 - 44th Annu. Conf. IEEE Ind. Electron. Soc.*, pp. 3870–3875, 2018.

[23] S. Daozong, W. Weixing, L. Jianqing, and L. Zuanhui, “Design of WSN nodes and network performance analysis in a tea plantation,” *Wirel. Sens. Network, 2010. IET-WSN. IET Int. Conf.*, pp. 144–147, 2010.

[24] A. Qandour, D. Habibi, and I. Ahmad, “Applied application of sensor networks in underground mines,” in *Proceedings of 2012 9th IEEE International Conference on Networking, Sensing and Control, ICNSC 2012*, 2012, pp. 256–260.

[25] Y. Xiang, K.-L. Chen, Q. Xu, Z. Jiang, and Z. Hong, “A Novel Contactless Current Sensor for HVDC Overhead Transmission Lines,” *IEEE Sens. J.*, vol. 18, no. 11, pp. 4725–4732, Jun. 2018.

[26] Z. Li, Q. Li, Z. Wu, J. Yu, and R. Zheng, “A Fault Diagnosis Method for On Load Tap Changer of Aerospace Power Grid Based on the Current Detection,” *IEEE Access*, vol. 6, pp. 24148–24156, 2018.

[27] A. National, S. Ansi, A. Date, S. Rosslyn, and C. October, “ANSI / NEMA CC 1-2009 Electric Power Connection for Substations,” no. October, 2012.

[28] P. G. Slade, *Electrical Contacts: Principles and Applications, Second Edition*. 2017.

[29] K. Chen, C. Huang, and J. He, “Fault detection, classification and location for transmission lines and distribution systems: A review on the methods,” *High Volt.*, vol. 1, no. 1, pp. 25–33, 2016.

[30] F. Capelli, J.-R. J.-R. Riba, and J. Sanllehí, “Finite element analysis to predict temperature rise tests in high-capacity substation connectors,” *IET Gener. Transm. Distrib.*, vol. 11, no. 9, pp. 2283–2291, Jun. 2017.

[31] J. J.-A. Wang, J. Jy-An, J. K. Chan, and J. A. Graziano, “The Lifetime Estimate for ACSR Single-Stage Splice Connector Operating at Higher Temperatures,” *IEEE Trans. Power Deliv.*, vol. 26, no. 3, pp. 1317–1325, Jul. 2011.

[32] F. de Paulis, C. Olivieri, A. Orlandi, and G. Giannuzzi, “Detectability of Degraded Joint Discontinuities in HV Power Lines Through TDR-Like Remote Monitoring,” *IEEE Trans. Instrum. Meas.*, vol. 65, no. 12, pp. 2725–2733, Dec. 2016.

[33] K. Perdon, M. Scarpellini, S. Magoni, and L. Cavalli, “Modular online monitoring system to allow condition-based maintenance for medium voltage switchgear,” *CIRED - Open Access Proc. J.*, vol. 2017, no. June, pp. 346–349, 2017.

[34] F. Alhebshi, H. Alnabilsi, J. Alzebaidi, A. Bensenouci, T. Brahimi, and M. A. Bensenouci, “Monitoring the operation of transmission line in a smart grid system through IoT,” *2018 15th Learn. Technol. Conf. L T 2018*, pp. 139–146, 2018.

[35] J. G. Olazarri, A. J. Mazon, S. Rementeria, I. Albizu, and E. Fernandez, “Performance of dynamic line rating systems for wind integration,” *5th Int. Conf. Clean Electr. Power Renew. Energy Resour. Impact, ICCEP 2015*, pp. 567–573, 2015.

[36] P. Dehghanian, Y. Guan, and M. Kezunovic, “Real-Time Life-Cycle Assessment of High-Voltage Circuit Breakers for Maintenance Using Online Condition Monitoring Data,” *IEEE Trans. Ind. Appl.*, vol. 55, no. 2, pp. 1135–1146, Mar. 2019.

[37] B. Sun *et al.*, “Remaining useful life prediction of aviation circular electrical connectors using vibration-induced physical model and particle filtering method,” *Microelectron. Reliab.*, vol. 92, no. June 2018, pp. 114–122, 2019.

[38] International Electrotechnical Commission, “IEC TS 61586:2017 Estimation of the reliability of electrical connectors.” IEC, pp. 1–55, 2017.

[39] Zhu Chongyang, Feng Qiang, Sun Bo, Z. Chongyang, F. Qiang, and S. Bo, “Lifetime prediction for electrical connector under the action of random vibration loading,” in *Proceedings of the IEEE 2012 Prognostics and System Health Management Conference (PHM-2012 Beijing)*, 2012, pp. 1–5.

[40] L. Qingya, G. Jinchun, X. Gang, J. Qiuyan, and J. Rui, “Lifetime prediction of electrical connectors under multiple environment stresses of temperature and particulate contamination,” *J. China Univ. Posts Telecommun.*, vol. 23, no. 5, pp. 61–81, Oct. 2016.

[41] L. A. Escobar and W. Q. Meeker, “A Review of Accelerated Test Models,” *Stat. Sci.*, vol. 21, no. 4, pp. 552–577, 2006.

[42] R. S. S. Mroczkowski, “A perspective on connector reliability,” *Proc. 50th IEEE Holm Conf. Electr. Contacts 22nd Int. Conf. Electr. Contacts Electr. Contacts, 2004.*, vol. 00, no. C, p. 7862, 2004.

[43] Y. Zhou, Y. Su, Q. Li, Q. Jin, and J. Gao, “A New Lifetime Prediction Method Based on

Particulate Contaminants for Coaxial Connectors," no. Amsm, pp. 331–334, 2016.

[44] C. Abomailek Rubio, "Development of reduced-scale tests for HTLS substation connectors," *TDX (Tesis Dr. en Xarxa)*, Sep. 2018.

[45] I. E. Martínez García, A. S. Sánchez, and S. Barbati, "Reliability and Preventive Maintenance," in *MARE-WINT*, Cham: Springer International Publishing, 2016, pp. 235–272.

[46] ANSI, "ANSI C119.4 - 2016.pdf." 2016.

[47] B. L. Agba, F. Sacuto, M. Au, F. Labeau, and F. Gagnon, *Wireless communications for power substations : RF characterization and modeling*. .

[48] A. Kadechkar, M. Moreno-Eguilaz, J.-R. Riba, and F. Capelli, "Low-Cost Online Contact Resistance Measurement of Power Connectors to Ease Predictive Maintenance," *IEEE Trans. Instrum. Meas.*, pp. 1–9, 2019.

[49] A. Kadechkar, J. Sanllehi, M. Moreno-Eauilaz, and J.-R. Riba, "Feasibility Analysis of Bluetooth 5 for Real-Time Data Transmission in High-Voltage AC and DC Substations," in *IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society*, 2018, pp. 5228–5233.

[50] A. Kadechkar *et al.*, "Feasibility Study on Thermal Energy Harvesting for Low Powered Electronics in High-Voltage Substations," in *IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society*, 2018, pp. 4224–4229.

[51] P. G. Slade, *Electrical Contacts: Principles and Applications, Second Edition*, 2nd Editio. CRC Press, 2017.

[52] IEEE Power and Energy Society, *605-2008 IEEE Guide for Bus Design in Air Insulated Substations*. IEEE, 2010.

[53] Nedal, "Technical Specifications Nedal Busbars." .

[54] TE Connectivity, "PTF-FAMILY Platinum Temperature Sensors Product Description," 2016.

[55] International Electrotechnical Commission, "IEC 60751 Edition 2.0 2008-07," 2008.

[56] P. Technology, "USB TC-08 Thermocouple data logger | Pico Technology." .

[57] C. Meetoo, S. Bahadoorsingh, N. Ramsamooj, and C. Sharma, "Wireless residential power monitoring system," *2017 IEEE Manchester PowerTech, Powertech 2017*, 2017.

[58] A. Bernieri, L. Ferrigno, M. Laracca, and A. Rasile, "An AMR-Based Three-Phase Current Sensor for Smart Grid Applications," *IEEE Sens. J.*, vol. 17, no. 23, pp. 7704–7712, Dec. 2017.

[59] S. Lee, Y. Ahn, T. Kim, N. Kim, and S. Lee, "A Superpositioning Technique for Accurate Open-Type Current Sensing in Three-Phase Electrical Switchboards," vol. 18, no. 22, pp. 9297–9304, 2018.

[60] J. Han, J. D. Jeong, I. Lee, and S. H. Kim, "Low-cost monitoring of photovoltaic systems at panel level in residential homes based on power line communication," *IEEE Trans. Consum.*

Electron., vol. 63, no. 4, pp. 435–441, 2017.

[61] G. Geng, J. Wang, K. L. Chen, and W. Xu, “Contactless Current Measurement for Enclosed Multiconductor Systems Based on Sensor Array,” *IEEE Trans. Instrum. Meas.*, vol. 66, no. 10, pp. 2627–2637, 2017.

[62] T. Asada *et al.*, “An Overview of Integratable Current Sensor Technologies,” *38th IAS Annu. Meet. Conf. Rec. Ind. Appl. Conf. 2003.*, vol. 2, pp. 1251–1258, 2003.

[63] F. Xie, R. Weiss, and R. Weigel, “Giant-Magnetoresistance-Based Galvanically Isolated Voltage and Current Measurements,” *IEEE Trans. Instrum. Meas.*, vol. 64, no. 8, pp. 2048–2054, 2015.

[64] S. D. T. Dewi, C. Panatarani, and I. M. Joni, “Design and development of DC high current sensor using Hall-Effect method,” *AIP Conf. Proc.*, vol. 1712, pp. 1–6, 2016.

[65] H. Zhang, F. Li, H. Guo, Z. Yang, and N. Yu, “Current Measurement with 3-D Coreless TMR Sensor Array for Inclined Conductor,” *IEEE Sens. J.*, 2019.

[66] X. P. Xu, T. Z. Liu, M. Zhu, and J. G. Wang, “New Small-Volume High-Precision TMR Busbar DC Current Sensor,” *IEEE Trans. Magn.*, vol. 56, no. 2, 2020.

[67] A. Bernieri, L. Ferrigno, M. Laracca, and A. Rasile, “Eddy Current Testing Probe Based on Double-Coil Excitation and GMR Sensor,” *IEEE Trans. Instrum. Meas.*, 2019.

[68] J. G. Deak, Z. Zhou, and W. Shen, “Tunneling magnetoresistance sensor with pT level 1/f magnetic noise,” *AIP Adv.*, vol. 7, no. 5, p. 056676, May 2017.

[69] R. Portas and L. Colombel, “Accuracy of Hall-Effect Current Measurement Transducers in Automotive Battery Management Applications using Current Integration,” in *Automotive Power Electronics*, 2007, pp. 1–8.

[70] T. Instruments, “Hall effect sensor-DRV5053.” .

[71] X. Liu, P. W. T. Pong, and C. Liu, “Dual Measurement of Current and Temperature Using a Single Tunneling Magnetoresistive Sensor,” *Proc. IEEE Sensors*, vol. 2018-Octob, no. 2, pp. 1–4, 2018.

[72] W. Miao, X. Liu, K. H. Lam, and P. W. T. Pong, “DC-arcing detection by noise measurement with magnetic sensing by TMR sensors,” *IEEE Trans. Magn.*, vol. 54, no. 11, pp. 1–5, 2018.

[73] Honeywell, “1-and 2-Axis Anisotropic Magnetic Sensors.”

[74] N. Corporation, “AA/AB-Series Analog Giant Magnetic Sensors.”

[75] MultiDimension, “Large Dynamic Range TMR2104 linear sensor.”

[76] M. Park, S. Byun, W. Kim, J. Lee, K.Choi, and H. Lee, “Non-Contact Measurement of Current Distribution in Parallel Conductors by Using Hall Sensors,” *IEEE Trans. Appl. Supercond.*, vol. 18, no. 2, pp. 1135–1138, Jun. 2008.

[77] National Instruments, “USB-6000 - National Instruments.” [Online]. Available:

http://www.ni.com/es-es/support/model.usb-6000.html. [Accessed: 25-Jan-2019].

[78] National Instruments, "Getting Started with SignalExpress TM," 2013.

[79] Raytech, "Micro-Centurion-II." [Online]. Available: http://www.raytech.ch/Products/Micro-Ohm/Micro-Centurion-II.

[80] Fluke, "Fluke i6000sFlex AC Current Probe." [Online]. Available: https://www.fluke.com/en/product/accessories/current-probes/fluke-i6000sflex.

[81] V. Pascucci *et al.*, "A Standardized Reliability Evaluation Framework for Connections," in *SMTA International*, 2016, pp. 1–10.

[82] E. Carvou, R. El Abdi, J. Razafiarivelo, N. Benjemaa, and E. M. Zindine, "Thermo-mechanical study of a power connector," *Measurement*, vol. 45, no. 5, pp. 889–896, Jun. 2012.

[83] R. Tzeneva, "Investigation of High Power Bolted Busbar Connectors with Longitudinal Slots," *Przegląd Elektrotechniczny*, pp. 223–226, 2012.

[84] W. E. Wilson, S. V. Angadi, and R. L. Jackson, "Surface separation and contact resistance considering sinusoidal elastic–plastic multi-scale rough surface contact," *Wear*, vol. 268, no. 1–2, pp. 190–201, Jan. 2010.

[85] J.-R. Riba, A.-G. Mancini, C. Abomailek, and F. Capelli, "3D-FEM-Based Model to Predict the Electrical Constriction Resistance of Compressed Contacts," *Measurement*, vol. 114, no. January 2018, pp. 44–50, 2018.

[86] I. M. G. González-Díaz, D. Pastor, E. García-Hemme, D. Montero, R. García-Hernansanz, J. Olea, A. del Prado, E. San Andrés, "A robust method to determine the contact resistance using the van der Pauw set up," *Measurement*, vol. Online, pp. 1–18, 2017.

[87] S. Kasi and L. Herron, "Theory of the Effect of Torque and Re-Torque Practices on Electrical Connectors with Clamping Fasteners," in *Power India International Conference (PIICON), 2016 IEEE 7th*, 2016, pp. 1–6.

[88] F. Capelli, J.-R. Riba, E. Rupérez, J. Sanllehí, E. Ruperez, and J. Sanllehi, "A Genetic-Algorithm-Optimized Fractal Model to Predict the Constriction Resistance From Surface Roughness Measurements," *IEEE Trans. Instrum. Meas.*, vol. 66, no. 9, pp. 2437–2447, 2017.

[89] C. Zhai, D. Hanaor, G. Proust, and Y. Gan, "Stress-Dependent Electrical Contact Resistance at Fractal Rough Surfaces," *J. Eng. Mech.*, no. 5, p. B4015001, 2015.

[90] M. Ciavarella, G. Murolo, and G. Demelio, "The electrical/thermal conductance of rough surfaces—the Weierstrass–Archard multiscale model," *Int. J. Solids Struct.*, vol. 41, pp. 4107–4120, 2004.

[91] L. Washer and C. L. Cells, "LCWD Series."

[92] U. Khayam, B. Sutrisno, M. Fauzan, Suwarna, and A. Risdiyanto, "Measurement and Analysis of Contact Resistance of New Designed Connection," in *Joint International Conference on Electric Vehicular Technology and Industrial, Mechanical, Electrical and Chemical Engineering (ICEVT & IMECE)*, 2015.

[93] J. Wu, X. Cui, and Y. Xu, “A novel RFID-based sensing method for low-cost bolt loosening monitoring,” *Sensors (Switzerland)*, vol. 16, no. 2, pp. 1–15, 2016.

[94] K. He and W. D. Zhu, “Detecting Loosening of Bolted Connections in a Pipeline Using Changes in Natural Frequencies,” vol. 136, no. June 2014, pp. 1–8, 2016.

[95] M. Zhuo, L. Yang, and L. Yu, “Thermally Induced Variation of Bolt Load Considering Thermal Contact Resistance,” *2016 IEEE Int. Conf. Mechatronics Autom.*, pp. 1822–1827, Aug. 2016.

[96] S. M. Y. Nikravesh, M. Goudarzi, S. M. Y. Nikravesh, and M. Goudarzi, “A Review Paper on Looseness Detection Methods in Bolted Structures,” *Lat. Am. J. Solids Struct.*, vol. 14, no. 12, pp. 2153–2176, Dec. 2017.

[97] Y. Gotoh, Y. Teshima, and N. Takahashi, “Electromagnetic Inspection Method of Slack of High Tension Bolt,” vol. 47, no. 10, pp. 2566–2569, 2011.

[98] T. Nguyen, T. Huynh, J. Ryu, J. Park, and J. Kim, “Bolt-loosening identification of bolt connections by vision image-based technique.”

[99] M. Jalalpour, J. J. Kim, and M. M. R. Taha, “Monitoring of L-Shape Bolted Joint Tightness Using Thermal Contact Resistance,” 2013.

[100] I. Argatov and I. Sevostianov, “International Journal of Engineering Science Health monitoring of bolted joints via electrical conductivity measurements,” *Int. J. Eng. Sci.*, vol. 48, no. 10, pp. 874–887, 2010.

[101] J. H. Park, T. H. Kim, and J. T. Kim, “Image-based Bolt-loosening Detection Technique of Bolt Joint in Steel Bridges,” no. 1, 2015.

[102] D. Gonzalez, F. Berger, M. Hopfeld, and P. Schaaf, “Model switch experiments for determining the evolution of contact resistance of electrical contacts in contactors,” *Electr. Contacts, Proc. Annu. Holm Conf. Electr. Contacts*, vol. 2016-Decem, pp. 129–134, Oct. 2016.

[103] F. Capelli, J.-R. Riba, and D. Gonzalez, “Thermal behavior of energy-efficient substation connectors,” in *10th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG)*, 2016, pp. 104–109.

[104] D. Gonzalez, M. Hopfeld, F. Berger, and P. Schaaf, “Investigation on Contact Resistance Behavior of Switching Contacts Using a Newly Developed Model Switch,” *IEEE Trans. Components, Packag. Manuf. Technol.*, vol. 8, no. 6, pp. 939–949, Jun. 2018.

[105] Q. Shen, K. Lv, G. Liu, and J. Qiu, “Dynamic Performance of Electrical Connector Contact Resistance and Intermittent Fault under Vibration,” *IEEE Trans. Components, Packag. Manuf. Technol.*, vol. 8, no. 2, pp. 216–225, Feb. 2018.

[106] Q. Shen, K. Lv, G. Liu, and J. Qiu, “Impact of Electrical Contact Resistance on the High-Speed Transmission and On-Line Diagnosis of Electrical Connector Intermittent Faults,” *IEEE Access*, vol. 5, pp. 4211–4232, 2017.

[107] C. Farges, M. Chevrie, J. Sabatier, L. Pradere, and F. Guillemard, “Detection of Electric Contact Resistance Variations in Automotive Connectors,” *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 9469–9476, Dec. 2017.

[108] J. Qu, X. Li, and Q. Wang, “Experimental study on electric resistance of tilted contact in air circuit breaker,” in *2016 IEEE 62nd Holm Conference on Electrical Contacts (Holm)*, 2016, pp. 115–118.

[109] J. S. Bobowski, M. S. Ferdous, and T. Johnson, “Calibrated Single-Contact Voltage Sensor for High-Voltage Monitoring Applications,” *IEEE Trans. Instrum. Meas.*, vol. 64, no. 4, pp. 923–934, Apr. 2015.

[110] E. Grundkotter, P. Weskamp, and J. Melbert, “Transient Thermo-Voltages on High-Power Shunt Resistors,” *IEEE Trans. Instrum. Meas.*, vol. 67, no. 2, pp. 415–424, Feb. 2018.

[111] Analog Devices, “AD627, Micropower, Single-and Dual-Supply, Rail-to-Rail Instrumentation Amplifier.”

[112] A. Laor, P. J. Herrell, and M. Mayer, “A Study on Measuring Contact Resistance of Ball Bonds on Thin Metallization,” *IEEE Trans. Components, Packag. Manuf. Technol.*, vol. 5, no. 5, pp. 704–708, May 2015.

[113] F. Capelli, J.-R. Riba, and J. Pérez, “Three-Dimensional Finite-Element Analysis of the Short-Time and Peak Withstand Current Tests in Substation Connectors,” *Energies*, vol. 9, no. 6, p. 418, May 2016.

[114] K. Wang, G. Gong, G. Chen, Y. Xiao, and H. Lu, “Online Measurement Method of Phase Difference of Current Sensor based on CCA,” 2017, no. Icsai, pp. 242–246.

[115] E. Kona, “Stationary VRLA battery health estimation by resistance measurement - comparison of dc and ac test methods,” *2016 IEEE Int. Conf. Power Electron. Drives Energy Syst.*, pp. 1–5, 2016.

[116] D. Belega, D. Petri, and D. Dallet, “Amplitude and Phase Estimation of Real-Valued Sine Wave via Frequency-Domain Linear Least-Squares Algorithms,” pp. 1–13, 2018.

[117] S. Lipschutz *et al.*, *SCHAUM’S outlines Linear Algebra Fourth Edition Schaum’s Outline Series*, 4th ed. McGraw Hill, 2009.

[118] J.-R. Riba, “Analysis of formulas to calculate the AC resistance of different conductors’ configurations,” *Electr. Power Syst. Res.*, vol. 127, 2015.

[119] International Electrotechnical Commission, “IEC 62271-1:2017. High-voltage switchgear and controlgear - Part 1: Common specifications for alternating current switchgear and controlgear.” International Electrotechnical Commission, p. 260, 2017.

[120] National Instruments, “Specifications USB-6000 8 AI (10 kS/s), 4 DIO USB Multifunction I/O Device.” pp. 1–8, 2018.

[121] E. Journal *et al.*, “Calculation of the ac to dc resistance ratio of conductive nonmagnetic straight conductors by applying FEM simulations,” *Eur. J. Phys.*, vol. 36, no. September, pp. 1–10, 2015.

[122] V. T. Morgan, “The Current Distribution, Resistance and Internal Inductance of Linear Power System Conductors—A Review of Explicit Equations,” *IEEE Trans. Power Deliv.*, vol. 28, no. 3, pp. 1252–1262, Jul. 2013.

[123] A. Itzke, R. Weiss, T. DiLeo, and R. Weigel, "The Influence of Interference Sources on a Magnetic Field-Based Current Sensor for Multiconductor Measurement," *IEEE Sens. J.*, vol. 18, no. 16, pp. 6782–6787, Aug. 2018.

[124] G. D'Antona, L. Di Rienzo, R. Ottoboni, and A. Manara, "Processing magnetic sensor array data for AC current measurement in multiconductor systems," *IEEE Trans. Instrum. Meas.*, vol. 50, no. 5, pp. 1289–1295, 2001.

[125] A. Itzke, R. Weiss, and R. Weigel, "Influence of the Conductor Position on a Circular Array of Hall Sensors for Current Measurement," *IEEE Trans. Ind. Electron.*, vol. 66, no. 1, pp. 580–585, Jan. 2019.

[126] N. George and S. Gopalakrishna, "Development of a New Low-Cost and Reliable Core-Less Current Probe for Conductor With Reduced Access," *IEEE Sens. J.*, vol. 17, no. 14, pp. 4619–4627, Jul. 2017.

[127] A. Paraschiv-Ionescu, C. Jutten, and G. Bouvier, "Source separation based processing for integrated Hall sensor arrays," *IEEE Sens. J.*, vol. 2, no. 6, pp. 663–673, Dec. 2002.

[128] D. Dai, X. Zhang, and J. Wang, "Calculation of AC Resistance for Stranded Single-Core Power Cable Conductors," *IEEE Trans. Magn.*, vol. 50, no. 11, pp. 1–4, Nov. 2014.

[129] W. T. Weeks, L. L.-H. Wu, M. F. McAllister, and A. Singh, "Resistive and Inductive Skin Effect in Rectangular Conductors," *IBM J. Res. Dev.*, vol. 23, no. 6, pp. 652–660, Nov. 1979.

[130] *WG B2.55 Conductors for the Uprating of Existing Overhead Lines*. .

[131] IEEE, "IEEE Std 100-2000 The Authoritative Dictionary of IEEE Standards Terms, Seventh Edition," *IEEE Std 100-2000*. pp. 1–1362, 2000.

[132] G. Rosen, A. Coghill, and N. Tunca, "Prediction of connectors long term performance from accelerated thermal aging tests," in *Electrical Contacts - 1992 Proceedings of the Thirty-Eighth IEEE Holm Conference on Electrical Contacts*, 1992, pp. 257–263.

[133] Y. He *et al.*, "Research on the Temperature Real-time Monitoring Technology of High Voltage Disconnectors," in *2017 4th International Conference on Electric Power Equipment - Switching Technology (ICEPE-ST)*, 2017, pp. 1–5.

[134] R. D. Malucci, "Stability and contact resistance failure criteria," *IEEE Trans. Components Packag. Technol.*, vol. 29, no. 2, pp. 326–332, Jun. 2006.

[135] A. Risdiyanto, M. Arifin, U. Khayam, and Suwarno, "Study on temperature distribution at busbar connection based on contact resistance of different plating contact surface," *Proc. 2013 Jt. Int. Conf. Rural Inf. Commun. Technol. Electr. Technol. rICT ICEV-T*, pp. 1–6, 2013.

[136] Y. Ren *et al.*, "A Novel Model of Reliability Assessment for Circular Electrical Connectors," *IEEE Trans. Components, Packag. Manuf. Technol.*, vol. 5, no. 6, pp. 755–761, Jun. 2015.

[137] Wei-Jen Lee and L. D. Swift, "Direct current busing system design," in *2001 IEEE Industrial and Commercial Power Systems Technical Conference. Conference Record (Cat. No.01CH37226)*, pp. 97–103.

[138] B. . Sotskov, I. Y. Dekabrun, R. S. Kuznetsov, and Z. S. Kirllova, *Electric Contacts*. National Aeronautics and Space Administration, 1965.

[139] T. Israel, M. Gatzsche, S. Schlegel, S. Grosmann, T. Kufner, and G. Freudiger, “The impact of short circuits on contact elements in high power applications,” *Electr. Contacts, Proc. Annu. Holm Conf. Electr. Contacts*, pp. 40–49, 2017.

[140] A. Ksiazkiewicz, G. Dombek, and K. Nowak, “Change in electric contact resistance of low-voltage relays affected by fault current,” *Materials (Basel).*, vol. 12, no. 13, 2019.

[141] R. Fu *et al.*, “Vibration-Induced Changes in the Contact Resistance of High Power Electrical Connectors for Hybrid Vehicles,” *IEEE Trans. Components, Packag. Manuf. Technol.*, vol. 2, no. 2, pp. 185–193, Feb. 2012.

[142] R. El Abdi and N. Benjema, “Mechanical wear of automotive connectors during vibration tests,” *U.P.B. Sci. Bull*, vol. 71, no. 2, 2009.

[143] Z. Kadhim and H. Mery, “Influence of Vibration on Free Convection Heat transfer from Sinusoidal Surface,” *Int. J. Comput. Appl.*, vol. 136, no. 4, p. 6, 2016.

[144] C. B. Freimark *et al.*, “An Introductory Discussion on Aeolian Vibration of Single Conductors, PES-TR17.” IEEE Power & Energy Society, pp. 1–38, 2015.

[145] G. T. Flowers, F. Xie, M. Bozack, and R. D. Malucci, “Vibration Thresholds for Fretting Corrosion in Electrical Connectors,” in *Proceedings of the Forty-Eighth IEEE Holm Conference on Electrical Contacts*, 2002, pp. 133–139.

[146] D. A. Hoble and C. O. Sta, “Study on the Influence of Vibrations on Electrical Contact Resistance,” in *2015 13th International Conference on Engineering of Modern Electric Systems (EMES)*, 2015, pp. 15–18.

[147] B.-H. Wu *et al.*, “Study on the Contact Performance of Electronic EON Connectors Under Axial Vibration,” *IEEE Trans. Components, Packag. Manuf. Technol.*, vol. 8, no. 12, pp. 2090–2097, Dec. 2018.

[148] T. Gissila, “Connectors and Vibrations – Damages in Different Electrical Environments,” Blekinge Institute of Technology, 2013.

[149] N. Hadziefendic, J. Trifunovic, and M. Kostic, “Effects of a Reduced Torque on Heating of Electrical Contacts in Plugs and Receptacles,” *IEEE Trans. Components, Packag. Manuf. Technol.*, pp. 1–9, 2018.

[150] D. Szabó *et al.*, “Inspection of conductor connectors in the medium voltage grid,” *2017 IEEE Electr. Insul. Conf. EIC 2017*, no. June, pp. 270–273, Jun. 2017.

[151] D. Stengel, R. Bardl, C. Kuhnel, S. Grosmannn, and W. Kiewitt, “Accelerated electrical and mechanical ageing tests of high temperature low sag (HTLS) conductors,” *2017 12th Int. Conf. Live Maintenance, ICOLIM 2017*, no. 612748, pp. 1–6, 2017.

[152] P. J.-L. Lilien, “Power Line Aeolian Vibrations,” Université de Liege, 2013.

[153] ELECTRA, “Overhead Conductor Safe Design Tension With Respect To Aeolian Vibrations,”

CIGRÉ, no. June. CIGRÉ, pp. 1–42, 2005.

[154] SBI Connectors, SICAME GROUP, SALVI, Politecnico di Milano, and Stellenbosch University, “Bus bar damper.”

[155] P. F. Sensors and H. Sensativity, “Meas piezo-fillm datasheet,” pp. 1–4, 2008.

[156] M. S. Inc., “Piezo film sensors,” *Technical manual*. p. 2016, 2016.

[157] S. Measurement, “Piezo Film Sensors Technical Manual,” *Measurement*, no. March. p. 57, 2006.

[158] V. P. Uccello and M. Tel, “Piezo Film Sensors Technical Manual,” no. March, 2008.

[159] Measurement Specialties, “MiniSense 100 Vibration Sensor,” *Data Sheet*. p. 4, 2009.

[160] TDK, “MPU-9250 | TDK.” [Online]. Available: https://www.invensense.com/products/motion-tracking/9-axis/mpu-9250/. [Accessed: 11-Oct-2019].

[161] N. Semiconductors, “Nordic Thingy 52.” [Online]. Available: https://www.nordicsemi.com/Software-and-tools/Prototyping-platforms/Nordic-Thingy-52. [Accessed: 26-Apr-2020].

[162] Sicame, “Vibration analysis for rigid tubular busbars for outdoor substation.” [Online]. Available: http://www.sicame.com.ua/damper-en/.

[163] W. Xie, T. Peng, K. Xiao, and J. Zhang, “The Damper Performance Tests for the Aeolian Vibration of Overhead Lines,” *Int. J. Eng. Technol.*, vol. 9, no. 5, pp. 366–369, 2018.

[164] IEC 61850, *Communication networks and systems in substations*. 2003.

[165] M. Adamiak, D. Baigent, and R. Mackiewicz, “IEC 61850 Communication Networks and Systems In Substations: An Overview for Users,” *Prot. Control J.*, pp. 61–68, 2009.

[166] A. M. Gaouda *et al.*, “A Smart IEC 61850 Merging Unit for Impending Fault Detection in Transformers,” *IEEE Trans. Smart Grid*, vol. 9, no. 3, pp. 1812–1821, 2018.

[167] D. Liu, Z. Yan, W. Ding, and M. Atiquzzaman, “A survey on secure data analytics in edge computing,” *IEEE Internet Things J.*, vol. 6, no. 3, pp. 4946–4967, 2019.

[168] W. G. Soliman and D. V. R. K. Reddy, “Microprocessor-Based Edge Computing for an Internet of Things (IoT) Enabled Distributed Motion Control,” in *Advances in Computing and Data Sciences*, ICACDS 19’., vol. CCIS 1046, M. Singh, P. Gupta, V. Tyagi, J. Flusser, T. Ören, and R. Kashyap, Eds. Singapore: Springer, 2019, pp. 22–31.

[169] B. L. Agba, S. Riendeau, H. Bertrand, J. Béland, I. D. R. Hydro-québec, and L. V. Q. Canada, “The Deployment of Wireless Networks in High Voltage Substations : A Feasibility Study,” pp. 46–50, 2012.

[170] D. Moongilan, “Corona noise considerations for smart grid wireless communication and control network planning,” *IEEE Int. Symp. Electromagn. Compat.*, pp. 357–362, 2012.

[171] S. Tenbohlen, D. Denissov, S. Hoek, and S. M. Markalous, “Partial discharge measurement in the ultra high frequency (UHF) range,” *IEEE Trans. Dielectr. Electr. Insul.*, vol. 15, no. 6, pp. 1544–1552, 2008.

[172] Q. Shan, I. A. G. R. Rutherford, S. B. R. Atkinson, and I. E. P. P. J. Moore, “Detection of Ultra-Wide-Band impulsive noise in a 400 KV air insulated electricity substation,” in *20 th International Conference on Electricity Distribution*, 2009, no. 0174, pp. 8–11.

[173] M. Au, B. L. Agba, and F. Gagnon, “A Model of Electromagnetic Interferences Induced by Corona Discharges for Wireless Channels in Substation Environments,” *IEEE Trans. Electromagn. Compat.*, vol. 57, no. 3, pp. 522–531, 2015.

[174] W. E. Pakala and V. L. Chartier, “Radio noise measurements on overhead power lines from 2.4 to 800 kV,” *IEEE Trans. Power Appar. Syst.*, vol. PAS-90, no. 3, pp. 1155–1165, 1971.

[175] F. Sacuto, B. L. Agba, F. Gagnon, and F. Labeau, “Evolution of the RF characteristics of the impulsive noise in high voltage environment,” *2012 IEEE 3rd Int. Conf. Smart Grid Commun. SmartGridComm 2012*, pp. 686–691, 2012.

[176] L. Zhaoxi *et al.*, “Experiment on the application of bluetooth in vacuum switch cabinet,” *3rd Int. Conf. Deregul. Restruct. Power Technol. DRPT 2008*, no. April, pp. 1982–1986, 2008.

[177] S. a. Bhatti, A. Glover, R. Atkinson, J. M. R. de s Neto, and J. S. da Rocha Neto, “Vulnerability of bluetooth to impulsive noise in electricity transmission substations,” in *IET International Conference on Wireless Sensor Network 2010 (IET-WSN 2010)*, 2010, pp. 53–58.

[178] N. Harid, A. C. Bogias, H. Griffiths, S. Robson, and A. Haddad, “A wireless system for monitoring leakage current in electrical substation equipment,” *IEEE Access*, vol. 4, pp. 2965–2975, 2016.

[179] F. Sallabi, A. Gaouda, A. El-Hag, and M. Salama, “Evaluation of ZigBee Wireless Sensor Networks Under High Power Disturbances,” *IEEE Trans. Power Deliv.*, vol. 29, no. 1, pp. 13–20, 2014.

[180] A. Abdrabou and A. M. Gaouda, “Uninterrupted Wireless Data Transfer for Smart Grids in the Presence of High Power Transients,” *IEEE Syst. J.*, vol. 9, no. 2, pp. 567–577, 2015.

[181] C. Tejada-martinez, F. P. Espino-cortes, S. Ilhan, and A. Ozdemir, “Computation of Corona Radio Interference Levels in HVDC Transmission Lines,” pp. 206–210.

[182] Y. Liu, L. Zhou, Y. Liu, H. Yuan, and L. Ji, “Method for calculating corona inception voltage of ultra-high-voltage direct current transmission lines with frequency-domain characteristics of corona current,” *IET Gener. Transm. Distrib.*, vol. 11, no. 15, pp. 3783–3790, 2017.

[183] L. Shi, C. Xie, W. Zhu, H. Deng, and D. Dai, “Study on the Characteristics of Wireless Network Communication under AC Transmission Line Corona Discharge,” *Ichve 2016*, pp. 4–7, 2016.

[184] Y. P. E. Wang *et al.*, “A Primer on 3GPP Narrowband Internet of Things,” *IEEE Commun. Mag.*, vol. 55, no. 3, pp. 117–123, 2017.

[185] N. Semiconductor, “nRF52832 - Product Specification v1.0,” p. 544, 2016.

[186] Raspberry Pi, "Products Archive - Raspberry Pi." [Online]. Available: https://www.raspberrypi.org/products/. [Accessed: 25-Jan-2019].

[187] A. John, R. Varghese, S. S. Krishnan, S. Thomas, T. A. Swayambu, and P. Thasneem, "Automation of 11 kv substation using raspberry pi," *Proc. IEEE Int. Conf. Circuit, Power Comput. Technol. ICCPCT 2017*, 2017.

[188] Y. Cheng, H. Saputra, L. M. Goh, and Y. Wu, "Secure smart metering based on LoRa technology," *2018 IEEE 4th Int. Conf. Identity, Secur. Behav. Anal.*, pp. 1–8, 2018.

[189] GlobTek Inc., "Nickel Metal Hydride Battery Safety Notes." [Online]. Available: https://en.globtek.com/nimh-battery-safety-notes/.

[190] Raspberry Pi Stack Exchange, "How much energy does the Raspberry Pi consume in a day? ." [Online]. Available: https://raspberrypi.stackexchange.com/questions/5033/how-much-energy-does-the-raspberry-pi-consume-in-a-day. [Accessed: 14-May-2020].

[191] SICAME, "Sun4all." [Online]. Available: http://africa.sicame.info/Nos-solutions/Energies-renouvelables. [Accessed: 14-May-2020].

[192] Z. F. Mian, B. McKenney, and R. E. Spoor, "US20160020812A1 - Wireless Transmission Through Faraday Cage Enclosure," 2016.

[193] NFPA, "NFPA 70 - National Electrical Code - 2008 Edition," pp. 1–840, 2008.

[194] R. Bergmann, H. Löbl, H. Bohme, and S. Großmann, "Calculation of the lifetime of electrical busbar joints," *Eur. Trans. Electr. Power*, vol. 7, no. 6, pp. 403–408, Sep. 1997.

[195] F. Yang, L. Du, W. Chen, J. Li, Y. Wang, and D. Wang, "Hybrid energy harvesting for condition monitoring sensors in power grids," *Energy*, vol. 118, pp. 435–445, 2017.

[196] F. Guo, H. Hayat, and J. Wang, "Energy harvesting devices for high voltage transmission line monitoring," *2011 IEEE Power Energy Soc. Gen. Meet.*, vol. 43210, pp. 1–8, 2011.

[197] S. M. V. S. M. V. S. M. V Semedo, J. E. G. J. E. G. Oliveira, and F. J. A. Cardoso, "Remote monitoring of high-voltage disconnect switches in electrical distribution substations," in *2014 IEEE 23rd International Symposium on Industrial Electronics (ISIE)*, 2014, pp. 2060–2064.

[198] Q. Chen, G. Zhang, J. Liu, Y. Geng, and J. Wang, "Design of passive wireless temperature measurement system for high voltage power equipment," *2017 1st Int. Conf. Electr. Mater. Power Equip.*, vol. 2, pp. 659–663, May 2017.

[199] S. Du, Y. Jia, and A. A. Seshia, "An Efficient Inductorless Dynamically Configured Interface Circuit for Piezoelectric Vibration Energy Harvesting," *IEEE Trans. Power Electron.*, vol. 32, no. 5, pp. 3595–3609, May 2017.

[200] J. C. Kwan and A. O. Fapojuwo, "Radio Frequency Energy Harvesting and Data Rate Optimization in Wireless Information and Power Transfer Sensor Networks," *IEEE Sens. J.*, vol. 17, no. 15, pp. 4862–4874, Aug. 2017.

[201] B. Fluke, "Fluke 289 True-RMS Industrial Data Logging Multimeter | Fluke." [Online]. Available: https://www.fluke.com/en-us/product/electrical-testing/digital-multimeters/fluke-

289. [Accessed: 25-Jan-2019].

[202] C. Arnoux, “Chauvin Arnoux K2 micro-clamp.”

[203] O. Najera-Ruiz, I. Martinez-Gamboa, S. Sellschopp-Sanchez, G. Santana, G. Escalante, and C. Alvarez-Macias, “Efficiency improvement of photovoltaic cells by cooling using Peltier effect,” in *2018 IEEE 7th World Conference on Photovoltaic Energy Conversion, WCPEC 2018 - A Joint Conference of 45th IEEE PVSC, 28th PVSEC and 34th EU PVSEC*, 2018, pp. 438–441.

[204] M. Nesarajah and G. Frey, “Thermoelectric Power Generation : Peltier Element versus Thermoelectric Generator,” in *Industrial Electronics Society , IECON 2016 - 42nd Annual Conference of the IEEE*, 2016, pp. 1–6.

[205] D. M. Rowe, “Thermoelectrics, an environmentally-friendly source of electrical power,” *Renew. Energy*, vol. 16, no. 1–4, pp. 1251–1256, Jan. 1999.

[206] S. Lineykin, I. Ruchaevsky, and A. Kuperman, “Analysis and optimization of TEG-heatsink waste energy harvesting system for low temperature gradients,” in *2014 16th European Conference on Power Electronics and Applications*, 2014, pp. 1–10.

[207] B. Haug, “Harvesting energy from thermoelectric generators,” *Ieee power Electron. Mag.*, no. December, pp. 24–32, 2017.

[208] D. Salerno, “Ultralow Voltage Energy Harvester Uses Thermoelectric Generator for Battery-Free Wireless Sensors,” *J. Analog Innov.*, vol. 20, no. 3, pp. 2–11, 2010.

[209] B. Sümer, E. K. San, and K. Sancakdar, “Design of a Thermoelectric Energy Harvesting Module for a Wireless Pressure Measurement in Vehicles,” *Procedia Eng.*, vol. 168, pp. 63–66, 2016.

[210] J. M. Lopera, H. Arco, J. Maria, and P. Pereira, “Wireless Sensors Supplied by Energy Harvesting Thermoelectric Generators,” in *METC*, 2016, pp. 1–8.

[211] I. Advanced Thermal Solutions, “How Air Velocity Affects The Thermal Performance of Heat Sinks : A Comparison,” *Qpedia*, no. 2, pp. 1–19, 2008.

[212] L. Edmunds, “Heatsink Characteristics,” *Int. Rectifier AN-1057*, pp. 1–17, 2004.

[213] Advanced Thermal Solutions, “ATS-1101-C1-R0 58.0 x 37.0 x 22.9 mm maxiFLOW™ Power Brick.” [Online]. Available: https://www.qats.com/Product/Heat-Sinks/maxiFLOW™/Power-Brick/ATS-1101-C1-R0/3310.aspx. [Accessed: 25-Jan-2019].

[214] CCIC, “CCI11 heat sink.” pp. 1–3.

[215] Chaun-chcung technology corp., “Welcome to CCI.” [Online]. Available: http://www.ccic.com.tw/product_list.php?groupid=15. [Accessed: 25-Jan-2019].

[216] L. T. Corporation, “LTC3109,” pp. 1–24.

[217] Linear Technology Corporation, “Demonstration Circuit 1664A featuring the LTC3109.” [Online]. Available: https://www.analog.com/media/en/dsp-documentation/evaluation-kit-manuals/dc1664a.pdf.

[218] N. V. Desai, Y. Ramadass, and A. P. Chandrakasan, “A bipolar ±40 MV self-starting boost converter with transformer reuse for thermoelectric energy harvesting,” *Proc. 2014 Int. Symp. Low power Electron. Des. - ISLPED ’14*, pp. 221–226, 2014.

[219] J. P. Im, S. W. Wang, S. T. Ryu, and G. H. Cho, “A 40 mV transformer-reuse self-startup boost converter with MPPT control for thermoelectric energy harvesting,” *IEEE J. Solid-State Circuits*, vol. 47, no. 12, pp. 3055–3067, 2012.

[220] K. Taeda and H. Koizumi, “A bipolar self-Start up boost converter for thermoelectric energy harvesting,” *2017 IEEE Energy Convers. Congr. Expo. ECCE 2017*, vol. 2017-Janua, pp. 4747–4752, 2017.

[221] Y. K. Ramadass and A. P. Chandrakasan, “A battery-less thermoelectric energy harvesting interface circuit with 35 mV startup voltage,” *IEEE J. Solid-State Circuits*, vol. 46, no. 1, pp. 333–341, 2011.

[222] C. INC, “Series : Cp85 Peltier Module.” pp. 1–10, 2018.

[223] J. H. Meng, X. X. Zhang, and X. D. Wang, “Dynamic response characteristics of thermoelectric generator predicted by a three-dimensional heat-electricity coupled model,” *J. Power Sources*, vol. 245, pp. 262–269, 2014.

[224] S. Microelectronics, “SPV1040.”

[225] Adafruit, “INA219 High Side DC Current Sensor Breakout .” [Online]. Available: https://www.adafruit.com/product/904. [Accessed: 04-May-2020].

[226] P. Instruments, “Photovoltaic meter PCE-SPM .” [Online]. Available: https://www.pce-instruments.com/espanol/instrumento-medida/medidor/medidor-fotovoltaico-pce-instruments-medidor-fotovoltaico-pce-spm-1-det_388373.htm. [Accessed: 04-May-2020].

[227] S. microelectronics, “STEVAL-ISV006V2: solar battery charger using the SPV1040.”

[228] the Aluminium Association, “Aluminium Electrical Conductor Handbook.” 1989.

[229] H. B. Dwight, “Skin Effect and Proximity Effect in Tubular Conductors,” *Trans. Am. Inst. Electr. Eng.*, vol. XLI, pp. 189–198, 1922.