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Asset Management Strategies for Power Electronic Converters in Transmission Networks: Application to Hvdc and FACTS Devices

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ABSTRACT The urgency for an increased capacity boost bounded by enhanced reliability and sustainability through operating cost reduction has become the major objective of electric utilities worldwide. Power electronics have contributed to this goal for decades by providing additional flexibility and controllability to the power systems. Among power electronic based assets, high-voltage dc (HVdc) transmission systems and flexible ac transmission systems (FACTS) controllers have played a substantial role on sustainable grid infrastructure. Recent advancements in power semiconductor devices, in particular in voltage source converter based technology, have facilitated the widespread application of HVdc systems and FACTS devices in transmission networks. Converters with larger power ratings and higher number of switches have been increasingly deployed for bulk power transfer and large scale renewable integration—increasing the need of managing power converter assets optimally and in an efficient way. To this end, this paper reviews the state-of-the-art of asset management strategies in the power industry and indicates the research challenges associated with the management of high power converter assets. Emphasis is made on the following aspects: condition monitoring, maintenance policies, and ageing and failure mechanisms. Within this context, the use of a physics-of-failure based assessment for the life-cycle management of power converter assets is introduced and discussed.

INDEX TERMS Asset management, FACTS devices, HVdc, power electronic assets, physics-of-failure.

I. INTRODUCTION

Significant developments in power semiconductor devices, together with the need for interconnectors and increased transmission capability, have led to a revolution in power electronics assets over the past decades. This transition has caused a paradigm shift from traditional power transmission substation assets to substations incorporating power electronics. Out of these devices, high-voltage dc (HVdc) converters, particularly voltage source converter (VSC) based HVdc and flexible ac transmission systems (FACTS) devices like thyristor-controlled series compensators (TCSCs) and static synchronous compensators (STATCOMs), are frontrunners in the transmission grid. These devices consist of power electronics equipment such as converter valves, cooling systems and auxiliary components. Although strategies for managing traditional transmission assets such as power line conductors, insulators, breakers and transformers have been well studied and are common practice for utilities [1], the increased incorporation of power electronics into the existing grids has become an escalated management challenge [2], [3].

Power electronics device installations in the grid date back to the early years of the 20th century with the invention of the mercury-arc rectifier, marking the beginning of the *"classical era"* of power electronics [3], [4]. Power electronics has emerged as a complex and multidisciplinary discipline following several decades of evolution. It embraces all areas of the power system, thereby ushering in a new kind of industrial revolution due to its significant role in sustainable energy generation, renewable energy systems integration and bulk power transfer [3], [5], [6]. In recent years, an increased number of power electronic assets has been deployed to enable additional power flow capacity through existing transmission assets to circumvent overhead transmission expansion limitations. The proliferated application of power electronics to support renewable generation, to boost power transfer without building new transmission infrastructure, and to facilitate a sustainable evolution towards a low-carbon future has made of these assets prominent members of the power system industry. Therefore, revisited management approaches are required [6], [15].

Significant investment has been taking place around the world for the integration of non fossil fuel resources utilizing power electronic assets, especially HVdc and FACTS, which places new stress on existing equipment and interconnecting systems [3], [6]. For instance, the US nearly doubled their spending on network upgrade and expansion from $28 billion in 2010 to $44 billion in 2013 [7]. It is foreseen that over $300 billion will be invested over the next 20 years for refurbishment and deployment of transmission and distribution assets [7]. Similar scenarios are faced elsewhere. For example, the net investment as per the UK government obligation to meet low carbon network policies is expected to reach £30-50 billion by 2030 as compared to the current value of less than £13 billion [7], [8].

Owing to the fact that in the future a major part of this investment could be made on power flow control devices like HVdc and FACTS, it is a matter of interest to look into their effective management [8], [9]. The inherent capability of these devices to control and stabilize networks has been another aspect that renders their potential application in transmission systems. In addition, they aid to optimally utilize existing assets—thereby increasing capital and operational savings [6]–[9]. However, the need for an effective asset management is high; for instance in the UK the cost of a new HVdc link of 2 GW capacity is around £1 billion and the loss of revenue due to failure can cost £1 million per day as a result of the loss in electricity transmission [7], [8]. Furthermore, a loss of 2 GW transmission capacity can potentially jeopardize the UK network as it signifies a considerable loss of total capacity (80 GW) [8]. These scenarios stem up the ever-increasing demand from utilities around the world to formulate efficient and optimal asset management practices for ageing HVdc and FACTS assets [10]–[15].

It is evident that power converters are subjected to a high level of examination, monitoring and standardized reporting. For instance, CIGRE has produced biannual reports on HVdc converter station reliability and energy utilization [16]. The impact that different components have on the forced energy utilization (FEU) is depicted in Figure 1. Converter valves contribute three fourths of the forced outages, which emphasizes the need for their effective management. The cost breakdown of a new HVdc installation compared to other components is shown in Figure 2. As it can be observed, converter assets incur almost one fourth of the cost [15]. Additional publications and guidelines for HVdc converter reliability based on power electronic components in the substation operation and maintenance can be found in [17]–[20].

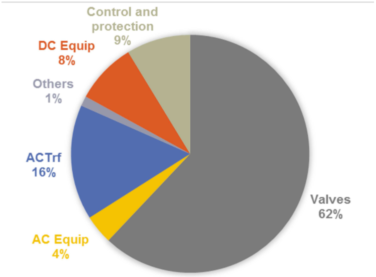

FIGURE 1. FEU breakdown for thyristor HVdc systems (2011-2012).

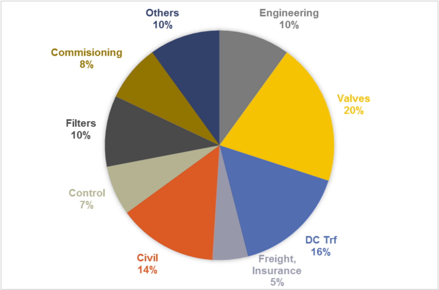

FIGURE 2. Installation cost of an HVdc station.

On the other end of the power transmission spectrum, open market systems and deregulation have encouraged power utilities to find optimal strategies for managing existing and new assets over their lifespan. This has caused asset management to become one of the most prominent sectors [21], [22]. General aspects of asset management practices are well known in power systems. Throughout the last 10 to 15 years, asset management has been adopted as the reigning paradigm for the management of electricity networks, contributing to the understanding of the value of assets [3], [9]. This follows stringent standards like PAS 55 and ISO 55000, which provide clear definitions and requirements for establishing and verifying an optimal management for all kinds of physical assets related to the power industry [9], [30]. To increase the understanding of the effect of emerging capital assets on existing power networks, a roadmap of new research directions considering the power electronic assets should be identified [4]. Through this paper we are trying to bridge this gap by addressing some of the research questions.

Focus has been recently placed on the monitoring, maintenance, and ageing and failure mechanisms, as reported in [23]–[26] and references therein. Qiao *et al.* [23] (and corresponding references) have presented different monitoring and health management approaches to improve the reliability and lifespan of wind energy conversion systems. Similarly, state-of-the-art technologies and best practices in asset management for smart grid networks have been presented in [24]. However, due to the complexity of power converter structures and their degradation mechanisms, interpreting the

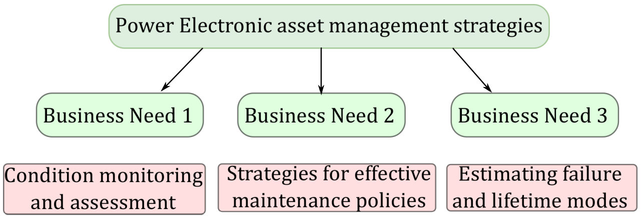

FIGURE 3. Business needs for power electronic asset management.

information obtained through existing techniques and subsequently evaluating their condition is a challenging task (especially for non-experts). Moreover, current asset management systems are mainly focussed on ac substations and, furthermore, there is lack of information, methods and understanding of the impact of new age power electronic devices [27]–[32]. Therefore, there is a need to investigate new techniques and their applications for analysing data and identifying information which, in turn, may improve the design of power converters in terms of reliability. Among these methods, the assessment through physics-of-failure and degradation mechanisms constitute promising options.

Initial efforts on the application of the aforementioned techniques for power electronic device monitoring and diagnosis were reported in [25] and [33]. Nevertheless, such efforts are scattered over different aspects, such as the interpretation of measurement data for diagnosis, maintenance and ageing. There is still lack of a common framework within which new methods can be effectively deployed and executed to perform a unified asset management approach in transmission networks.

In this context, research efforts in this paper focus on presenting the state-of-the-art of asset management strategies in transmission networks. An emphasis is made on the following aspects: condition monitoring, maintenance policies, and the estimation of ageing and failure mechanisms. In addition, existing applications of physics-of-failure based diagnosis and prognosis in power electronic assets condition assessment have been summarized. To provide value, these have been linked to the transmission network asset management regime, with a particular focus on prospective future research roadmaps. Following this line, power electronic assets can be mainly characterized by the following business needs (see Figure 3):

1) Business Need 1: Trends in condition monitoring and assessment.
2) Business Need 2: Strategies for effective maintenance policies.
3) Business Need 3: Estimating failure and ageing mechanisms.

II. CONDITION MONITORING

The technique or process for monitoring the operating characteristics of a component or an equipment, in such a way as to predict the need for maintenance before serious deterioration or breakdown, is known as condition monitoring (CM) [26]–[29]. CM systems have evolved over decades, with an existing HVdc and FACTS asset base spanning over 50 to 60 years. Traditional approaches like keeping maintenance records and visual inspections are probably the best sources of condition assessment. Fortunately, power electronic substations are not much different than standard electrical substations. This means that there is a substantial amount of experience in place already. However, there are some special design characteristics that should be accounted for which are not common for ac substations [15]. In general, present CM systems are mainly focussed on ac substations [27]–[30]; furthermore, the monitoring function is single and completely independent, protocols are not compatible and the interface is not unified [31]–[36].

To address these shortcomings and better satisfy the needs of monitoring levels in power electronic substations, the design and implementation of CM and decision support systems in HVdc and FACTS converter stations are required [34]–[36]. It is relevant to highlight that a recent industry-based survey on advancements in CM practices reported that more than 50% of the participants believed that monitoring techniques and assessment tools should be improved [37]. The report also specified that semiconductor devices are often the weakest link in converters and comprise 30% of the total failures. Thus, it is evident that CM could play a crucial role in optimizing the operation of power electronic based assets. Therefore, in this section the CM and assessment approaches used in power converter based assets are categorized (see Figure 4).

A. TRADITIONAL APPROACH

The traditional CM approach applied to combined ac and dc substation components can be divided into five main categories: visual inspection; monitoring the hot spot temperature; assessment of the vibration of wall and winding; sensor analysis for examining dissolved gases and partial discharges; and the voltage and current signature measurement. To obtain meaningful information from these monitored parameters, data should be analyzed to assess the state of the components [32]–[35]. Each CM data category can be evaluated using condition assessment (CA) techniques, as illustrated in Figure 4. Each CM and CA technique will be discussed in the following subsections.

1) ACOUSTIC MEASUREMENT/VIBRATION MONITORING

Acoustic measurement and vibration analysis constitute the traditionally used approaches for CM of rotating equipment. They have been recently employed in the power converter monitoring discipline due to the advancements in the technology used for CA [30]. Acoustic and vibration sensors have found a place in the market, with the former being attached to components to listen to their state using sound level meters, while the latter being mounted to register local motion [38], [39]. The use of these monitoring and diagnosis devices is well established in the wind turbine converter industry to estimate the health of a

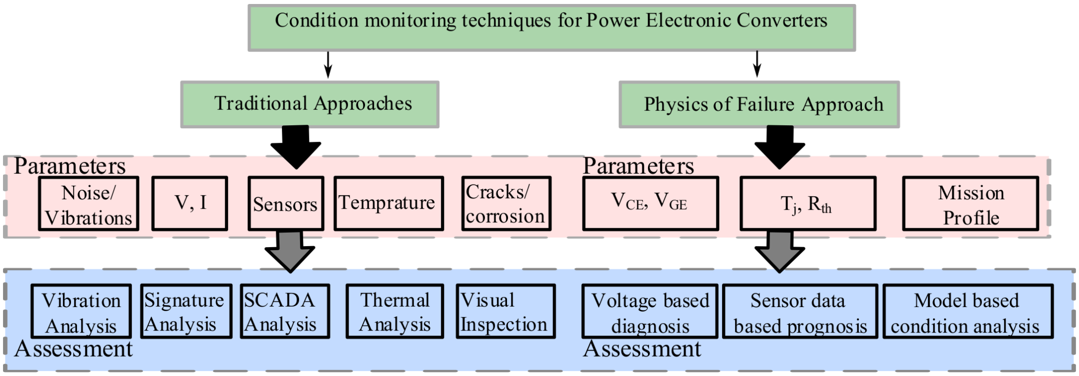

FIGURE 4. CM and assessment methods for power electronic assets.

device [39]. In a dc converter station this analysis has been mainly used to estimate the noises and vibrations generated from filter capacitors, valve cooling systems, valve reactors, converter transformers and switching devices like circuit breakers [38]–[42]. Another important indicator for the noise resulting from dc magnetization are the currents arising due to the asymmetry in the firing of thyristor valves; this in turn depends on the accuracy of the firing control system [38]. Additional estimation methods for diagnosis include the use of root-mean-square value of the signals, frequency response and amplitude, energy, skewness, crest factor, counts and events [39]–[44].

2) SIGNATURE ANALYSIS

Signature analysis (SA) is one of the easiest yet comprehensive CM method employed to predict electrical and mechanical faults. The signals that can be detected may be either electrical (voltage, current, power or flux) or mechanical. Various types of faults can be detected using SA methods, which are mainly categorized as: 1) model reference, or 2) feature extraction methods [28], [38]. The model reference method spots faults by comparing the results of measurements with likelihoods of mathematical-based or artificial intelligence-based models. Conversely, the feature extraction method uses frequency and time-domain signal processing techniques to capture signatures representing normal and faulty performances [28]. The application of SA in estimating the health of thyristor valves has been reported in [43] and [44]. SA can identify misbehavior of valves, such as inconsistency in the conduction and firing sequences due to disturbances in ac or dc systems [43]. Fuzzy logic seems to be suitable for the implementation of the natural language definitions of these misbehaviors [44]. Estimation of the frequency energy levels using frequency spectra characteristics in dc switchyards and valve halls has been applied to analyze the electric and magnetic field strength of HVdc converter valve units [45].

3) SENSOR/SCADA DATA ANALYSIS

Supervisory control and data acquisition (SCADA) systems are collectively used in most transmission networks. Sensor or SCADA-based monitoring is reliable and one of the most cost-effective CM methods since it relies on the interpretation of data only. In a dc sub-station it collects information from key components and converter assemblies using the sensors fitted to valve-based units, heat-sinks, protection and control systems and switches. The status of the valves can be interpreted from operational data and from the measurements of signals, such as temperature, pressure, and current. This information reflects the real-time state of valve units and, by proper assessment, a relationship between different signals can be observed—in turn providing information on the health of the converter [27], [46]. Many wind turbine methods can be effectively used for dc substation CM following an adequate implementation. Given that it was not designed for CM purposes, the main shortfall of SCADA-based analysis is that it cannot be applied systematically as the collected data may not be comprehensive enough to represent the whole dc substation. The variation of SCADA data subjected to operational conditions poses the difficulty of detecting an incipient fault from raw data without an appropriate data analysis tool [48]. Furthermore, the data capture rate of 5 to 10 min is too slow for most fault diagnoses of fast-acting power electronic assets as compared to other equipments such as circuit breakers or transformers [49].

4) TEMPERATURE MEASUREMENT/THERMAL ANALYSIS

Temperature measurement (TM) and thermal analysis (TA) are among the most exhaustive ways for assessing the condition of power electronic devices. TM aids in identifying potential failures related to temperature changes in the equipment due to faults, overloading and deformations. Monitoring is performed using sensors, such as optical pyrometers, resistant thermometers and thermocouples [50]–[53]. TA using infrared (IR) thermography has become one of the most reliable and prominent prognosis methods for asset health monitoring of dc systems [50]. This method covers a wide range of components from HVdc converter stations, including thyristor valves, diodes, snubber circuits, pumps and expansion tanks [51]. Temperature-based CM relies on the fact that all working components emit heat; thus when a component in the system malfunctions, its temperature increases beyond normal values [52]. IR temperature transmitters and high-resolution IR cameras constitute the sensors applied in TA, with results typically interpreted visually. For example, an IR thermal image showing the temperature distribution of the surface between thyristors and the radiator in an HVdc converter has been evaluated in [51] to estimate the temperature distribution among the upper and lower thyristors valves. The measurement of the thyristor valve temperature is kept as the base line for estimating the overload capability and rating of redundant thyristors for a 12-pulse converter scheme subjected to the worst case thermal and voltage stresses [53].

5) VISUAL INSPECTION

One of the most challenging monitoring techniques is the visual inspection (VI) method, which is based on human sensory capabilities. VI may be used as a complement to other CM approaches. It includes touch (temperature and vibration checking), deformation and aspects (DA), and detection of sounds emitted by a functioning system. VI is generally used to monitor thyristor valve cooling system electrodes, water level sensors, corrosion and cracking [54]. In several cases, this method can be very effective in identifying problems that were not previously determined by other techniques. Such cases includes loose parts, connections, terminals, and components; visibly worn or broken parts; excessive temperatures; and oil leakages, corrosion, and leaks on the valve water piping [51]. Since VI is a labor intensive and highly subjective task, the results will depend on the experience and judgement of the inspector [55], [56].

Nowadays, developments in VI technologies have reached the pace of the wind industry. For instance, remote VI technologies have been implemented to inspect gearboxes, wind turbine blades and other critical components [57]. Recent developments include the use of gyroscopes to inspect interior areas that may not be accessible otherwise—aiming to reveal hairline cracks, corrosion, pitting and other defects [58]. Flying remote devices are the latest addition to the VI family, which appear to be effective in reaching out remote and offshore installations [59].

Some of the discussed monitoring methods are still in their infancy or development stages, although a few are mature techniques. The transition from conventional CM approaches is inevitable due to the reliability-based design and physics-based failure mechanisms adopted for modern power converters. Physics-of-failure based monitoring and analysis is discussed in the next subsection.

B. PHYSICS-OF-FAILURE BASED CM

Ensuring a high availability and reliability is the top priority for transmission network operators. To achieve this through power electronic assets, a physics-of-failure (PoF) based assessment during the design stages has been widely accepted. The combination of degradation calculation with root cause failure analyses and probabilistic methods forms the basis of PoF [60], [61]. The PoF approach has mostly taken place within the electronics industry and has focussed on optimizing the reliability of complex circuits [62]. Continuous improvement has reduced failure rates of IGBT modules in traction applications from 1000 failures-in-time (FIT, the number of failures in one billion hours) in 1995 to 20 FIT in 2000, and very few in recent years [63].

Despite the extensive efforts to improve reliability, failures in power electronics have been observed continuously [63]. Surveys indicate that IGBTs have been the most frequently used devices (42%) among power semiconductors, followed by metal-oxide semiconductor field-effect transistors (MOSFETs) (27%), thyristors (14%) and PiN diodes (10%) [37]. Most of the work in recent years has concentrated on IGBTs for power electronic converters [63]. In contrast with traditional CM approaches, PoF based CM focusses on the lifetime estimation of new generation power semiconductor devices such as IGBTs, IGCTs, MOSFETs, SiCs, among others. A threefold process is employed to monitor the strength of power electronic components; this involves diagnosis, prognosis and condition analysis. Figure 5 illustrates a typical life estimation flowchart for voltage-controlled converters in wind turbine applications. The interdependency of different physical models and their relevance in PoF based CM are evident from the diagram.

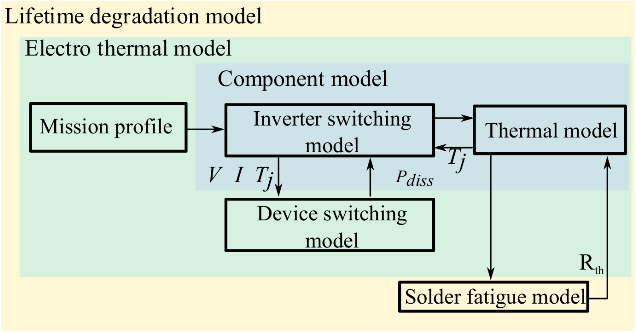

FIGURE 5. PoF based life estimation flowchart for voltage-controlled converters [66].

1) DIAGNOSIS

Diagnosis is used to estimate the root cause failure in a power electronic asset upon occurrence of a fault [63]. Based on the understanding of failure mechanisms, reliability models for these devices can be built to aid the failure analysis and lifetime prediction without performing costly tests. In a diagnosis process, monitoring the contributors for degradation is a vital route to understand the physics behind the damage caused by it [64]. Device parameters are major contributors for component degradation. These include the on-state voltage or resistance (V_{CEsat}/R_{ON}), the internal thermal resistance (R_{th}), and the threshold gate voltage (V_{GEth}) [63]–[66]. Although these parameters are difficult to measure in practice, they may cause changes in the operational characteristics of the devices or converters at system level. Substantial research has been conducted in this area [65], [66]. However, most of the work has looked at a device level instead of system level—which needs considerable attention since health indicators may vary depending on the application (*e.g.* HVdc, FACTS) and mission profile (*e.g.* offshore, onshore). For instance, different types of degradation may influence the forward voltage drop in an IGBT, but a single degradation mechanism may influence several damage indicators. Therefore, the use of a single parameter to monitor degradation is insufficient to develop a complete CM system [65].

2) PROGNOSIS

The process of estimating the remaining useful life (RUL) by predicting the health conditions at some point in the future is known as prognosis. This method has a significant effect in the decision making process as it provides flexibility to determine the RUL while minimizing the risk of failure [33], [68]. Prognostics of IGBTs received attention primarily from mission-critical systems such as avionics, high-speed rail, and offshore wind turbines. In such systems, no failure is desirable until the next maintenance period [33]. The usual prognoses used in power electronics assets are data-driven and model-based approaches [33]. The model-based prognostic approach relies on the physical models that describe the relationship between lifespan and design parameters, material properties, and loading conditions. The damage-based, strain-based, and fatigue life models are widely employed prognosis approaches [70]. Model-based CM is particularly attractive for devices working under variable operating conditions and varying environments, such as HVdc converters, onshore and offshore converter stations and renewable energy systems. Conversely, the data-driven approach exploits component historical data and health condition. These attributes are extracted from the device information without relying on failure modes. The particle filtering method and power-cycling testing are examples of data-driven approaches for prognosis [71].

3) CONDITION ANALYSIS

Condition analysis requires the measurement of one or more damage indicators during the power converter operation. However, simple knowledge is not sufficient to form the overall CM strategy [33], [72]. To lay down the main realistic degradation mechanisms, accelerated ageing tests that apply mission profile-based stresses to the devices are used [72]. Several types of degradation can influence a single damage indicator; for instance, a variation in the forward voltage of an IGBT can be affected by the temperature, the gate oxide integrity, the quality of electrical connections (including bond wire lift-off), and the metallization reconstruction [73]. It is very difficult to measure these indicators in a functional system; for example, it is necessary to estimate the chip temperature to measure the thermal resistance. In a functional system, such measurements would require an interruption of the converter operation, which would lead to a complex monitoring system [74], [75]. The most complex task in condition assessment is the determination of critical contributors to degradation and thereby failure since they are dependent on the application and power module technology. For instance, the bond wire degradation in an IGBT or diode is often determined by an increase of forward voltage V_{fwd}. However, different proposals for a critical level of V_{fwd} have been reported [75].

4) DISCUSSION

PoF based CM represents a new addition to existing monitoring approaches. It has recently received attention in 'mission critical' applications such as offshore wind farms and modular multilevel converter (MMC) based HVdc stations. Application of the PoF approach in wind turbine condition based monitoring and maintenance has been addressed in [87]. Following the threefold process as discussed in previous sections (*i.e.* diagnosis, prognosis and condition analysis), a continuous online estimation of the damage accumulation can be performed using standard converter parameters. Precise assessments may be then carried out in real time considering the probability of failure for specific failure modes and components. In turn, these can reduce the investment cost of additional measurement equipment.

Reliability based design for emerging semiconductor devices in wind turbines and photovoltaics has resulted in the advent of a PoF approach in power systems and power electronic applications [90], [91]. Moreover, new technologies and devices which can effectively monitor, diagnose and even automatically detect and rectify faults have been installed and/or are under research [29]. There is an urgent need for a standard and unified approach for the CM of devices used in the transmission assets, irrespective of them being ac or dc [91]. Multi-vendor devices should follow strict guidelines or type registrations as required by the utilities to have an effective integrated monitoring and prognosis framework. To address this, Section V-A outlines a future perspective on component level asset management which is required for the effective monitoring and diagnosis of converter assets, together with the challenges and opportunities it creates.

III. MAINTENANCE METHODOLOGIES

In offshore wind farms, HVdc stations and FACTS controllers, maintenance of power converters is usually done by manufacturers for an initial period of 5 years. After this, either the operator or third parties perform the job or maintenance contracts with the original equipment manufacturer (OEM) are extended [14], [15], [77].

One of the main driving forces behind the transition from mercury arc to thyristor valves and later onto IGBTs for power conversion in the high voltage power electronic industry was the burden on maintenance requirements [7]–[9]. However, many of the existing and new power electronic assets are equipped with CM systems along with SCADA for operation. This provision provides a platform for the development of intelligent and device dependent maintenance policies. The use of a thyristor monitoring system to aid the HVdc maintenance policy has been reported in [76] and [77].

Therefore, CM leads to the next business need: developing of a proper maintenance strategy which includes corrective, preventive, reliability and PoF centred maintenance. This is shown schematically in Figure 6. The use of PoF as the new indicator for developing maintenance policy for power electronic assets is in its early stages compared to other strategies.

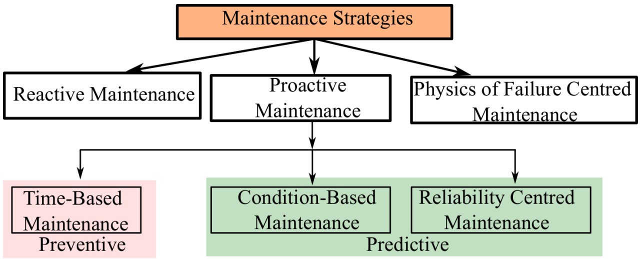

FIGURE 6. **Maintenance strategies.**

A. RUN-TO-FAILURE/REACTIVE MAINTENANCE

This is arguably the oldest and simplest maintenance strategy for low-cost machinery currently used in the industry that does not affect plant reliability. In general, run-to-failure implies refurbishment or replacement once the device has failed to operate. Therefore, a component is allowed to function and is replaced or repaired only upon failure. This strategy cannot be applied for major equipment as their failure would cost much more than their maintenance [16]–[18]. For a long time run-to-failure was the main maintenance activity carried out reduce the downtime of HVdc converters. In some cases, the failure consequences can be catastrophic and thus this type of maintenance has been reserved for non-critical faults. Additionally, it depends on the availability of spare parts [18], [77]. The advantages and disadvantages of run-to-failure are listed below.

Advantages

1) It is an economical way of maintenance requiring only limited man-hours.
2) It reduces unnecessary shut-downs and interruptions, with maintenance only performed when needed.
3) It is a widely understood strategy among maintenance technicians.

Disadvantages

1) Failures in high power converters become costly to repair and may need expensive spare parts.
2) Degradation leading to failures in power electronic assets may sometimes be irreparable if not detected early.
3) Complete shut-down of the plant or station may sometimes happen due to certain failures, which in some cases exceeds the cost of regular inspection—thereby losing revenue.

B. PROACTIVE MAINTENANCE

Safety, reliability and cost effectiveness are the major constraints while developing a maintenance policy for power system assets. Policies should be developed to reduce degradation in equipments and to ensure that the devices operate smoothly throughout their operating lifespan [12], [13]. In line with these objectives, the proactive maintenance (PM) strategy is a combination of preventive and predictive maintenance practices including monitoring, inspection, testing, cleaning, overhauling, and replacement activities (at fixed intervals) [18], [77]. PM not only contributes to an increased availability and efficiency, but also supports maintenance planning and budgeting, as well as contributing to the formulation of effective asset management strategies [78], [79]. Typical PM activities include shutting down the equipments at regular time intervals to perform time-based maintenance (TBM), using CM systems to perform condition-based maintenance (CBM), and using risk-based or reliability-centred maintenance (RCM). The RCM approach combines the benefits of TBM and CBM.

1) TIME-BASED MAINTENANCE OR PREVENTIVE MAINTENANCE

It is the most currently applied maintenance activity for power converter devices in utilities and industries. By carrying out regular maintenance and asset examination at constant intervals [12], TBM may prevent many failures. However, it may also cause unnecessary outages, wasting labor, time, and money if the maintenance interval is too small. In addition, unexpected incidents may still occur if the intervals between maintenance tasks are too large [32]. For a typical HVdc asset, maintenance is performed once every year or every two years, aiming to keep the scheduled energy unavailability to the minimum [12], [77]. Given that the operating conditions and environment boundaries where a VSC performs have been given great importance, CBM and RCM are preferred over TBM due to their more preventive nature and cost versus risk benefits [80]. The benefits and disadvantages of TBM are listed below.

Advantages

1) The procedure is easy to plan and well understood by maintenance engineers and technicians.
2) Fault inception and damage can be incurred if the inspection rates are reduced.
3) The lifespan of assets can be increased due to regular examinations and maintenance.

Disadvantages

1) The procedure is expensive and requires additional man-hours and unnecessary interruptions.
2) In some cases, TBM is unable to detect faults—especially when the inspection interval is large.
3) TBM may produce unnecessary shut-downs and additional maintenance costs, increasing the FEU in HVdc assets.

2) CONDITION-BASED MAINTENANCE OR PREDICTIVE MAINTENANCE

In this strategy, maintenance is carried out in response to the observed degradation in component condition. Surveillance, real-time monitoring, diagnostic, and trending tools are used to assess component ageing and thus plan maintenance accordingly. Maintenance is only performed when needed, so the strategy is very responsive to equipment conditions [55]. For instance, in an HVdc asset specific maintenance work is required depending on the converter topology [35], [77]. In traditional line-commuted converter (LCC) based HVdc systems, TBM is generally preferred over CBM due to its operating experience and low failure rates. However, CBM may be necessary in some cases for a prudent operation of the system following a scheduled maintenance, as described in [81]. Conversely, CBM is preferred over TBM for VSC-based assets. This is due to the smaller amount of implemented projects, the environmental conditions and the degradation phenomena of IGBTs (or other power electronic switches) [82]. The major advantages and disadvantages of using CBM are listed below.

Advantages

1) Maintenance is performed only when it is necessary, thereby providing savings by minimizing unnecessary inspections and man-hours.
2) It reduces unnecessary shut-downs and risks associated with them.
3) A real-time monitoring of the assets condition delivers an increased utilization.

Disadvantages

1) CBM depends on the monitored data, but continuous monitoring is not economical.
2) The processing and extraction of information from the monitored data is not well understood in industry.
3) It requires fast data communication and manipulation facilities for successful on-line monitoring and experienced personnel for the effective interpretation of data.

3) RISK OR RELIABILITY-CENTRED MAINTENANCE

The key objectives of the RCM approach are to optimize maintenance costs, increase system reliability and improve asset utilization [77], [84]. Several utilities have implemented RCM strategies. These are based on the significance and state of a component. During the maintenance policy development stages, the main consideration is given to the current state of the component and the consequences of its failure [78], [83]. Based on these constraints, a risk and criticality list is created and the highest priority in maintenance scheduling is given to components whose state has depreciated considerably and which are at the top in a risk matrix [78]. Existing power converter assets like HVdc converters and wind power installations use RCM as their main maintenance strategy [78], [86]. As compared to traditional approaches, an RCM strategy applied to the converter stations at Manitoba Hydro has increased the availability of the dc transmission system by reducing the number of outages [77], [86]. This approach even reduced the maintenance frequency from being annual to once in four years for major equipment [86]. The advantages and disadvantages of RCM as compared to other maintenance policies are summarized below.

Advantages

1) The probability versus risk approach reduces the cost of maintenance operation, resulting in less shut-downs for low-risk failures.
2) The inspection rates are reduced, thereby saving cost associated with them.
3) As the programme focuses on the reliability of the device, the possibility of high-risk failures can be reduced.

Disadvantages

1) The formulation of risk matrices and the prioritization of components based on them are complex, thus consuming significant time when developing maintenance models.
2) The procedure and processes related with RCM are not well developed, and are thus less understood by the maintenance personnel.
3) Maintenance models require a background of well-judged data and information.

C. PHYSICS-OF-FAILURE BASED MAINTENANCE

The physics behind failure of a device and the development of strategies for maintenance based on these factors is known as PoF based maintenance (PoFBM). Identifying the failure mechanism is the key for developing an effective PoFBM strategy. Compared to other maintenance practices, this is a one-person exercise where the different ways in which a component can physically fail are identified or forecasted [87]. The solution reached through PoFBM can be directly applied to any other identical component regardless of the equipment where it is located at—implying a universal failure addressing nature [88], [89]. PoFBM is an ideal maintenance tactic for power electronic assets where the trade-off between reliability and criticality versus cost has always been a concern for the optimal life-cycle operation and maintenance (O&M) [87]. Control of the O&M cost of power electronic assets is an area of growing interest to utilities as the assets come to the end of manufacturer's warranty. To this end, a maintenance model which considers the constraints and system parameters applied to the physical model of the device under investigation can be developed (see Figure 7). Using this model the damage indicators and critical operating regions of the assets can be identified. PoFBM has been applied to the electronic industry [62], with potential application in wind turbines being discussed in [61] and [90]. In offshore applications, PoFBM can be combined with TBM or CBM to reduce the down-time resulting from outages

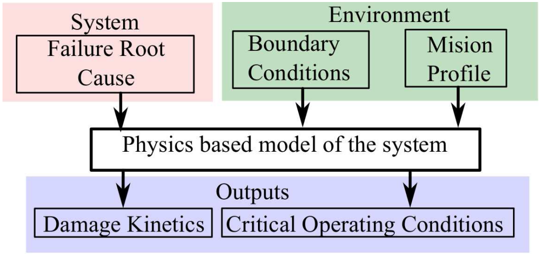

FIGURE 7. PoF centred operation and maintenance model.

and to increase reliability [90], [91]. The major advantages and disadvantages of this approach are outlined below.

Advantages

1) The pre-operational and operational environments are taken into consideration for developing maintenance models of the entire life-cycle.
2) PoFBM provides an early warning of potential failure, thereby minimizing unscheduled maintenance.
3) The use of PoFBM can extend maintenance cycles, thereby maintaining effectiveness through timely repair actions with less unwanted costs related to inspections.
4) It is a single-person process for identifying ways to transfer a common maintenance strategy across every asset into operation; thus, it saves time and avoids repetition.

Disadvantages

1) It is a very recent approach and thus less understood by maintenance engineers and technicians.
2) Uncertainties in loading, mission profile and environmental conditions can be a hindrance for a proper maintenance plan development.
3) In-depth knowledge of the equipment is inevitable for the understanding of physics behind failure.
4) Testing for damage prediction and robust validation, vital for the estimation of the physical life of a device, is resource-consuming.

As previously discussed, the main aim of asset management is to maximize the benefits for any utility subjected to specific constraints. This may not only be achieved through suitable CM techniques, but also through efficient maintenance plans which can maximize the use, reduce the outage time, and increase the lifetime of the assets. However, research directions in asset utilization at a process level need to be revisited. To this end, the roadmap in Section V-B is proposed aiming to achieve a maximum benefit from new and existing asset bases.

Proper management practices to extend the lifespan are related to the way in which the state of assets are monitored, maintained and valued. Based on these assessments the next business need is to estimate the state of health, modes of failures and ageing mechanisms. These aspects discussed in the following sections.

IV. ESTIMATING FAILURE AND LIFETIME MODES

Since their appearance in the transmission regime, manufacturers have claimed an infinite lifespan of semiconductor devices as they have no moving parts and thus no wear and tear. Even CIGRE reported that *"semiconductor devices do not wear out"* [92]. However, refurbishment and replacement strategies for HVdc and FACTS controllers have reached a level in which utilities and manufactures alongside are looking for options to extend their lifespan through upgrades, renovations and extension methods [10]–[15].

The three different concepts of lifetime mechanisms for power system assets can be applied to power semiconductors as well. These are illustrated in Figure 8 and are physical, technical and economic lifetime:

- Physical lifetime: The selection of assets based on the application where they will be used defines the physical lifetime of the equipment. Recent developments in PoF and reliability-based design can extend the physical life of power semiconductor assets.
- Technical lifetime: Rapid technological developments have caused the conventional power electronic assets to be replaced by new large capacity devices. For example, mercury arc valves have been replaced by thyristor valves and IGBTs in HVdc and FACTS applications.
- Economic lifetime: The economical valuation of an equipment depreciates with time even when it is still physically usable. New assets should be installed to enhance the value of existing assets; for example, HVdc interconnectors and FACTS devices may be incorporated to enhance power transfer capabilities.

A. PHYSICAL AGEING MECHANISM

Thanks to developments over 10 decades, the range of power semiconductor devices used in converters for HVdc and FACTS controllers is extensive [91], [92]. The low switching frequency and high power capability of thyristors makes them suitable for HVdc applications, while IGBTs are suitable for motor drives where high switching frequency is favored. For renewable energy converters where maximum power transmission and a limitation of harmonics is desired, IGBTs have been preferred due to their high power capacity and high switching frequencies [91], [92].

The most important design consideration for the lifetime estimation of semiconductor devices is reliability. It is often represented by a bath tub curve, as shown in Figure 9. This is an idealized plot representing the regions of operation of a device over its lifespan [91], [95]. The curve consists of three regions: an initial stage, a normal operating region and a wear out or failure period. The primary stage takes place during the initial years of an installation and includes design faults, packing procedures and installation problems. The normal operating region period includes random failures bounded by environments, which are very low. The final stage considers the total failure resulting from wear out, which causes an increase in failure rates following the normal period [33], [91], [95].

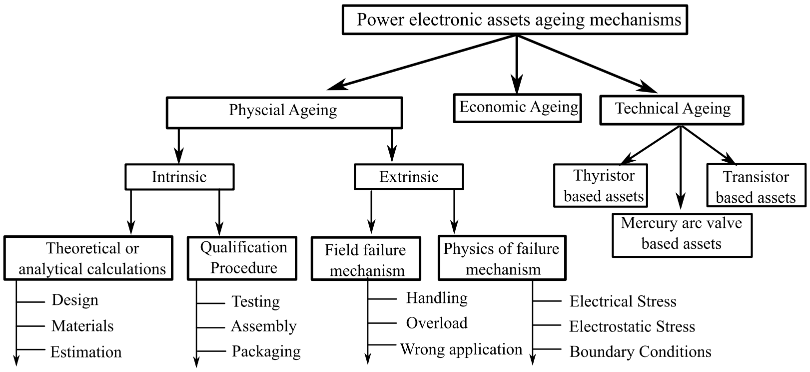

FIGURE 8. Classification of ageing mechanism for power semiconductor assets.

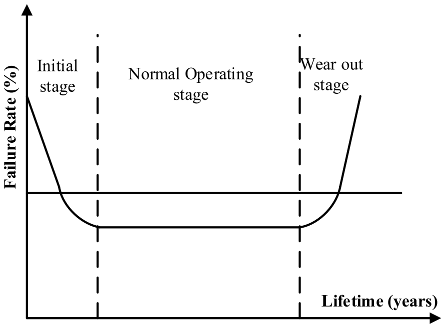

FIGURE 9. Bath tub curve for failure rate estimate over lifetime.

According to CIGRE, the two main types of semiconductor devices used for HVdc and FACTS applications are thyristors and IGBTs [92]. The physical ageing mechanism of these power devices can be categorized as intrinsic or extrinsic (see Figure 8). These mechanisms are graded through qualification procedures, theoretical calculations, field failure experiences and PoF-based processes [87], [96], [97].

1) INTRINSIC AGEING

Degradation and failure analysis have attracted a significant interest with regards to failure modes in semiconductor devices used for high voltage applications [37]. This is explained by the increased deployment of these devices facilitated by undergoing a decrease in size [98]. In this context, understanding the intrinsic ageing mechanism of a device during the design process is of great importance to guarantee a prolonged life-cycle. The intrinsic ageing phenomenon is influenced by the different tests and procedures carried out to qualify the product for final installation. These tests and procedures discussed next.

a: PROCESS QUALIFICATION

This is the procedure to test a device with defined conditions. It is bounded by international standard organizations such as IEC and is industry sector specific. The application of qualification procedures to test thyristor valves used in HVdc and FACTS converters has been reported in the IEC publication 60700-1 [99]. It states that most manufacturers have given less importance to the ageing process of thyristor valves due to their intrinsic failure rates. This is because the voltage withstanding capabilities of the valves can be maintained by replacements during accelerated testing and through field failure experiments [97], [99]. However, this fact stands only when there is no systematic degradation in the module [100].

The key parameters for thyristor failure estimation include electrical characteristics such as the valve leakage current, blocking and on-state voltages, reverse recovery charge and the anode voltage. For converters enabled with IGBT devices, the estimation of life models and ageing is based on the knowledge of the stress and degradation within the device. The physical methods used for analysing typical solder joint failures can be categorized into damage, energy, and stress-strain dependent methods [100]. Among these, energy-based methods outperform others in the assimilation of test results [103]. In an energy-based model, a device is presumed to be unworthy for operation if the deformation energy reaches a predefined critical value at a certain period of time [103], [104].

b: THEORETICAL OR ANALYTICAL CALCULATIONS

The use of mathematical and analytical methods for the lifespan estimation of semiconductor devices has been reported in [102]–[105]. The major factors that influence the life models are temperature, pressure cycles, frequency and current. A common estimation model used in analytical calculations which determines the amount of stress (and thereby lifespan) of a press-pack IGBT is given by [104]:

$$\left[100 \cdot \left(\frac{\sigma}{\sigma_0}\right)\right] = (A - B)[\ln(t)]^2 \tag{1}$$

where σ_0 and σ are the initial and remaining stress after t hours. The other key parameters influencing the model ageing mechanism are the material and temperature constants represented by A and B, respectively.

The use of accelerated testing for power semiconductor devices under different conditions to emulate real situations has become a standard industrial practice. An example is the temperature estimation of thyristor PN junctions used in HVdc converters to predict their lifespan [81], [92]. Thermal and power cycling tests for accelerated life expectancy measurement for high power IGBT modules in wind power applications have been reported in [102]–[105]. These tests replicate real-time conditions to realistically reproduce correct measurement gradients, but do not include real-time measurements. The analytical equations governing the accelerated tests are given by the Coffin-Manson relation, which is widely used for estimating the number of cycles to failure [83], [105]. This is given by

$$N_f = \left(\frac{c}{\Delta T_j}\right)^b \tag{2}$$

$$AF = \left(\frac{\Delta T_{ja}}{\Delta T_{jb}}\right)^b \tag{3}$$

where N_f is the number of cycles to failure, b and c are extrapolated constants from accelerated test results, and T_j is the junction temperature.

2) EXTRINSIC AGEING

This is an ageing process which is amplified by failures related to the application and handling of power electronic devices used in HVdc and FACTS converters. The major contributors for extrinsic ageing are the environment where the device is installed and the electric stress resulting from different operating conditions [101]. As these change the physical performance of the device, the ageing process is amplified, as depicted in Figure 8 [98]. Another contributor for this ageing mechanism is the latent defects regime of those assets that can make a considerable impact on the operating expenditure (OPEX) [106]. The two main indicators that may reveal this ageing phenomenon are the field failure and PoF—which are discussed in the forthcoming paragraphs.

a: FIELD FAILURE MEASUREMENTS

Assimilation of failure experiences from field data and analysis for estimation of reliability measurements is the key process behind field failure measurement. Two common methods for understanding the ageing process in power electronic devices are long-term surveillance and statistical comparison [81]. For example, a number of thyristor devices are selected and their characteristics measured and recorded once or twice every year in the long term surveillance method. Results are then processed to find a pattern of failure modes. In [107], specific field measurements taken from a static VAr compensator (SVC) indicated that thyristor failure resulted from the degradation of associated auxiliary assets. On the other hand, few statistics and information on VSCs are available. Recent CIGRE publications reported that the highest failure rate for any converter is found in the power electronics component [80], [108]. Additionally, the application of different thermal cyclic and loading conditions on wind power converters and their impact on the failure mechanisms has been analyzed in [109]. The two main factors affecting filed failure mechanisms are discussed next.

b: IMPACT OF HARMONICS

Harmonics resulting from the switching operation of valves and their negative impact on power system assets have been discussed in [110]. The greatest impact is faced by the converter transformer, which could result in capacity derating; increase in power losses, temperature rise, vibration and noise, and operating cost; and decrease in efficiency, insulation strength and service life [111]. CIGRE has reported the harmonic impact of different converter topologies in [112] and [113]. Compared to LCC HVdc, VSC based MMC topologies have the inherent capability of generating nearly sinusoidal waveforms at the ac side, which results in a reduction on harmonic filtering requirements [112], [113]. Furthermore, this reduces the impact on the converter transformers derating and ageing; for instance, vendors claim that normal ac transformers could be employed for MMC based stations [112].

Another aspect is the harmonic transfer through the dc side, which may generate sub-harmonic currents and, in turn, could affect the ac system assets such as turbine generators and might result in shaft failure [114]–[116]. However, these negative interactions are not that severe for VSC based converters due to the decoupling of the dc side [112]. Tsai *et al.* [115] and Yacamini [116] identified torsional oscillations due to the HVdc scheme. The variable-frequency ripple current superimposed on dc currents would excite subsynchronous vibrations in turbine shafts, and could reduce the life of the shafts [116]. It should also be noted that there is an obvious connection between the harmonics generated at the converter station and the control of the converters, which will be discussed in the next section.

c: IMPACT OF CONTROL

The control system acts as the brain of the HVdc converters or FACTS controllers. Compared to the rest of the components in an HVdc converter, the control system represents only about 7% of the total cost of the converter station (see Figure 2) [15]. A number of components can be substituted before the replacement of the entire installation is required. Many utilities have followed this route for asset management. As shown in Table 2, the failure rate and repair time of the control system of converter assets is very small compared to other components. Furthermore, significant planning is necessary during the design stage to estimate the impact of the control system on the converter stations. Operating experience has shown to be a key aspect behind the control system selection for thyristor-based HVdc and FACTS devices [10]–[15]. The case is similar for VSC stations. As an example, the Trans Bay Cable MMC project built in 2010 is undergoing an upgrade to provide black start capability through both control and valve modifications [10].

CIGRE has made a detailed analysis of different control aspects in HVdc converter stations and their impact on the reliability of the power supply compared to high voltage ac (HVac) transmission systems [112]. The robustness of the converter control ensures reliable and high quality power supply from the dc network to the ac system.

Active thermal control strategies represent an alternative which can extend the lifetime of the converter assets [117]–[119]. The main objective is to minimize the high failure rate attributed primarily to the thermal cycling in power semiconductor devices [119].

d: RELIABILITY/PHYSICS ORIENTED AGEING MECHANISM

Physics or reliability-based design is a new method for estimating the ageing process of semiconductor devices [33], [98]. Until recently, engineers have used a standardized stress-based methodology for qualification tests and life assessments of power electronic assets. However, the development of these devices has been accompanied by the widespread application of PoF-based knowledge for reliability assessment [126], [127]. Moreover, the physics-based health assessment and prognosis has allowed operators to evaluate individual power modules under real-time operational conditions. This has enabled an estimation of the remaining lifetime of the assets [126]–[128]. Another important aspect in determining the physical oriented mechanism is the failure rate estimation. This is assumed as constant in many applications although in truth it varies over the operational time. An alternative technique to obtain the failure level and time is the mean cumulative function (MCF) curve [91]. An example is shown in Figure 10, which can be considered as an integration of the bath tub curve where the different lines indicate a range of failure rates.

A summary of the most common types of failure arising in power electronic devices is provided by Table 1. This shows the different contributors to the failure, ageing, and health degradation of power electronic assets. The classification provided in this work has been inspired from wind turbine converter regimes and the associated equipment failures [124], [125]. This includes semiconductor, control, dc link, cable and connection, filter, and cooling system failures. Respective failure modes, mechanisms, behavior and critical contributors are also presented in Table 1.

It should be emphasized that the mechanisms employed to estimate the physical ageing of power electronic assets have evolved over the years, with new failure indicators and degradation mechanisms related to their specific application and environmental condition being adopted. Most of the modern power electronic assets are cross-linked with their power system counterparts and thus require to be strategically managed for their effective utilization. In this line, the main challenges and opportunities associated with such an strategic level asset management are discussed in Section V-B.

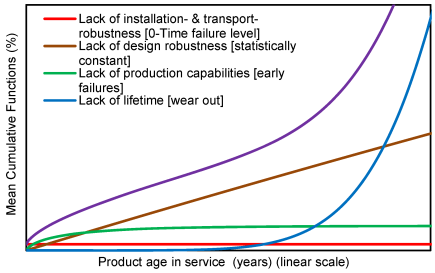

FIGURE 10. **MCF curve represented as an adaption of bathtub curve [91].**

B. ECONOMIC LIFESPAN

An asset starts depreciating its value from the time it is purchased until it reaches its retire value, which is the estimated value of the asset at the time of its disposal. The existing transmission assets need to be redefined to incorporate a depreciation cost. Furthermore, the increased complexity to construct new transmission lines and the difficulties to obtain rights of way have motivated a modification of existing transmission assets. HVdc and FACTS controllers have changed the way electric power has been transmitted and controlled [94]. Economic studies are conducted at the planning stages to estimate the most advantageous project long-term scenario. In terms of HVdc assets, this is a period of 40-50 years [11]. In general the economic life service (ELS) of a transmission line asset is determined by the period of time in which profit is made by replacing or abandoning it. This may be due to [10]–[15]:

- The deterioration or degradation rate of an asset has reached its ultimate stage, where abandoning it is cheaper than refurbishing it to extend its life-cycle. A typical example is the paradigm shift in HVdc and FACTS assets from mercury arc to thyristor-based converter units—and presently into transistor-based modules.
- Technological development, displacing older assets to add greater value. Innovation and progress in the power semiconductor technology can be related to ELS depreciation.
- Asset displacement resulting from competitive markets which focus on the substitution of devices and processes by new products, aiming to provide added value. A distinctive example of this process includes the European Supergrid developments, which have been facilitated by the increased controllability from VSC-based HVdc assets.

C. TECHNICAL LIFESPAN

Transmission networks including HVdc and FACTS assets which were installed in the 1970’s and 80’s require some kind of replacement or refurbishment [13]–[15]. The usual lifetime of power converter assets is in the range of 40-50 years, although during this time newer and better technologies may appear. Continuing operation with existing assets following refurbishments and upgrades at regular intervals can be sufficient. However, new assets may provide an increased functionality and performance [13]. Therefore, a good knowledge of the technical lifetime of converter-based assets in transmission grids is essential to develop a proper replacement

TABLE 1. Failure modes and mechanisms of power electronic assets.

Types	Failure modes	Failure mechanism	Failure Behavior	Contributors
Power Semiconductor Failure	Switch failure	Bond wire Press pack type	Bond wire heel cracking Spring relaxation and fatigue Cosmic ray failure Latch-up	T_j and ΔT_j
Control Failure	Hardware Failure Software Failure	Control card failure Sensor Failure Communication system	Solder failure Component failure False alarm, degradation of optical fibre cable Non-responsive to commands	Thermal cycling vibrations, humidity and water
DC Link Failure	Capacitor failure Chopper failure	AL electrolytic Polypropylene film Common Type Diode failure	Disconnection of terminals Electrochemical reactions Vaporization Contraction of film Breakdown of film Moisture absorption by film Dielectric loss Dielectric breakdown Voltage stress, hot resistor	V_c, T_a, I_c, vibrations and humidity Switching transients, power cycling
Cable and Connector Failure	Mechanical Cable Connector	High voltage stress on the insulation systems	Voltage stresses, power losses, misfire, leakage current in cable	Humidity, stress, DC neutral current
Filter Failure	DC filter capacitor failure	Forced outage	Flash over, noise level, fire, cracks in the inner fibreglass shells of the reactors	Ageing
Cooling system Failure	Excessive temperature	Switch failure Leaks and failures of flexible couplings	Broken cooling level sensor, Protection relay malfunction, corrosion	Auxiliary power system, ageing

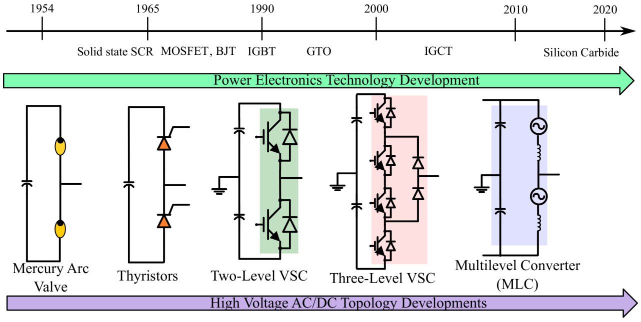

FIGURE 11. Developments in the power semiconductor technology (adapted from [135]).

strategy. Developments in IGBT devices during the recent years constitute a typical example; for instance, the voltage rating of a single IGBT module has increased to 6500 V [131]. Thus, the technical lifetime of a power semiconductor device is closely related to the developments in semiconductor technology, which has experienced drastic progression over the recent years (see Figure 11).

Failure rates and unavailability can reduce the value of assets and can become a burden for operators and asset owners. In line with this, the failure rates of the different components in a typical power electronic substations should be evaluated carefully. The critical components required for the safe and reliable operation of the station and their respective failure rate in occurrence per year (o/y) and repair time in hours per year (h/o) are presented in Table 2. The reliability data of LCC stations can be found in reference [120]. Since VSCs represent a relatively new addition to transmission networks, their corresponding failure rates and repair time are difficult to obtain in the open literature. Publications alongside with the network operators and manufacturer data have been used for this estimation and have been taken from references [121]–[123]. An insight into the lifespan alongside with failure rates of different dc substation components can be also found in [15, Table 2]. To adequately address the technical lifetime of power converter assets it is imperative to discuss the developments in semiconductor technologies over the years. This is carried out in the following sections.

1) MERCURY ARC VALVES-BASED CONVERTERS

With the availability of mercury arc valves in the early 1930's, HVdc transmission reached certain parity with ac transmission. Such a major development in semiconductor technology paved the way for the construction of the first dc link. This was a 3 MW, 45 kV link between Germany and Switzerland [132]. However, the employed high power valves were highly sensitive to vacuum conditions and the surface contamination resulting from the inherent concentration of blocking voltage into narrow regions of the device. These attributes eventually reduced their lifespan [132], [133]. By 1970's, the use of mercury arc valves in HVdc applications lost ground due to the unavailability of spare parts and the concurrent progress in thyristor valves [133]. A significant hindrance in their application was the limitation to increase the blocking voltage, which in turn restricted the selection of converter ratings for high power applications. Additionally, the need for a rapid switch-in and switch-off imposed operational limits to avoid the arch back phenomenon. This reduced the viability of these devices compared to thyristors [132]–[136]. Furthermore, the use

TABLE 2. **Major assets of typical power electronic substations: their lifetime and failure rates [15].**

Component	Lifetime (Years)	LCC Station		VSC Station	
		Failure Rate (o/y)	Repair Time (h/o)	Failure Rate (o/y)	Repair Time (h/o)
Valves	30	0.13	32	0.5	4
Transformer	45	0.015	2400	0.024	2160
Circuit breaker	35	0.0028	48	0.075	3
DC transmission line	22	0.22	8	0.6613	7
Station controls	25	20.012	3	0.0002	1.5
Cooling systems	15	0.3	12	0.27	12
Smoothing reactors	25	0.01	1400	0.28	262.5
AC filters	40	1.04	10	0.54	6
DC filters	20	0.022	6	0.001	5
Auxiliary supply	25	0.0002	12	0.0002	11
Ground electrode	40	0.0053	10	0.0042	10

of mercury-based switches has an adverse environmental impact; for instance, the amount of mercury vapors released to the atmosphere during O&M is of concern. Cautious monitoring has been employed in the valve halls to control mercury emissions. Each self-contained sealed module included 2.64 qt (2.5 L) of mercury [132]. Nowadays mercury arc-based HVdc assets have been replaced by thyristor valves except for one link [135].

2) THYRISTOR-BASED CONVERTERS

The key performance addition from thyristor-based converters was the ability to bring together control and conversion operations into one device, leading to substantial savings in space and weight [136], [137]. Even when thyristors cannot be turned off with a control pulse, their ability to achieve a low forward voltage drop led to its widespread use in HVdc installations [133]–[139]. Once thyristors started to take over the HVdc regime from mercury valves, the availability of HVdc projects increased significantly from 83 to 98% [120]–[125]. Since then, thyristor devices have been substantially deployed in transmission networks for HVdc and FACTS controllers. Their simple design, added with low maintenance costs, predictable performance and reduced area for installations are the key factors behind this fast deployment [136], [137]. For example, the typical space utilization of mercury arc-based converters is about 3.5 m^2/MW compared to 1 m^2/MW for thyristor valves [76]. Another vital aspect is the possibility to arrange thyristor valves in series, which gives the advantage of a high performance while making the modules less prone to fractional failures. This in turn enables the design optimization of an HVdc installation by having full control over ratings [138].

3) TRANSISTOR-BASED CONVERTERS

Voltage-controlled transistor-based semiconductor devices like IGBTs were developed during the late 1970's. They have found their place in the lower end of the power range for HVdc applications [133]. Their self-turn off capability, together with an independent control of active and reactive power, leads to a smaller footprint when employed in VSC stations [76], [136]. As of now, VSC-based high voltage transmission assets are in their fourth generation, with modular MMC topologies suitable for high power and high voltage applications due to their low power losses and minimal filter requirements [138], [139]. These HVdc technologies are not only used for conventional high power transmission, but are also suitable for the construction of dc grids for the integration of large-scale renewables—such as offshore wind farms [139], [140]. Until now, VSC-based transmission has paralleled thyristor-based converter assets wherever possible. With the demand for renewables to meet climate change challenges and the increasing interconnections among countries, further development of transistor-based power converter topologies is imperative.

Developments in high power semiconductors have shifted the nature of HVdc assets to a modular and cost effective transmission. One of the key improvements in this line is the transition from two-level to multilevel VSC topologies [138]. As the traditional HVdc and FACTS assets were not originally designed for modular expansions, changes introduced following installation and commissioning have been restricted to control system updates and pole upgrades [10]. It could be argued that this approach has limited the utilization of the upgraded transmission assets [138]. However, it is foreseen that future HVdc and FACTS device installations will be modular and multilevel in nature and, hence, the new topologies will have an enhanced value [138], [138], [140]. Furthermore, by adopting the modular topologies and in turn avoiding the use of additional components such as filters and transformers, the burden in maintenance and monitoring could be reduced [112]. The industry is already moving in this direction as indicated by the first MMC project in the US and the recent INELFE project linking Italy and Spain [140].

V. FUTURE WORK: RESEARCH IN POWER ELECTRONIC ASSET MANAGEMENT REQUIRES A ROADMAP

While the aforementioned procedures provide a systematic way for the selection of power converter assets considering an optimized cost, size and lifetime, their high complexity and the need for further research may restrict their application. This is highlighted in Figure 12. The review of industrial experience documented in this work, together with recent developments in power electronic assets, has allowed the identification of a range of needs and gaps faced by power

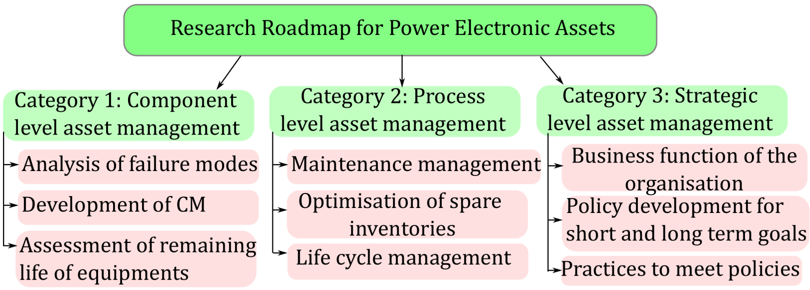

FIGURE 12. Research roadmap in terms of power electronic asset management.

transmission utilities. The primary gaps have been grouped into three categories—in line with the present industry asset management needs built on sustainability.

A. CATEGORY 1: COMPONENT LEVEL ASSET MANAGEMENT

Existing methods to gather and categorize data from ac systems are widely and efficiently applied by utilities. Dissemination of this knowledge is considerable; however, a revised asset management strategy is inevitable at device and system level due to the extensive deployment of power converter-based assets. Initial efforts in this direction have been carried out by many utilities. Practices include the utilization of CM techniques to assess the state of components; rescheduling of maintenance plans according to CM information; and a transition into RCM maintenance approaches. The major obstacles and research opportunities in the management of power electronic assets at a component level can be summarized as follows:

Challenges

1) Prevalent and increased application of power electronics in a large range of applications and different environmental exposures.
2) Outdated procedures to estimate the health and failure rates of power semiconductor equipment and a lack of understanding of critical failure modes.
3) Increased complexity in used components and in packaging.

Opportunities

1) Research in microelectronics and methodologies can be effectively used as a foundation for ongoing and future work in the field of power electronics.
2) Focus should be given to device reliability by understanding the operating regime through their lifetime.
3) Effective utilization of mission profiles and on-line CM data to understand the PoF.

B. CATEGORY 2: PROCESS LEVEL ASSET MANAGEMENT

This type of asset management deals with gaps in tools for the effective utilization and processing of assets. New assets can benefit from this as an effective life-cycle management plan can be developed using updated tools. Development of an effective framework for maintenance optimization, spares and inventory management, and economic constraints can be also integrated into the tools. To achieve this level of control over maintenance management a balance between preventive and reactive maintenance should be adopted. All these attributes can be accommodated into the platform and simulated over the life-cycle to assess the impact on asset utilization. The major opportunities and obstacles for the development of an integrated tool or software for managing power electronic assets can be summarized below:

Challenges

1) Tests that estimate the failure rates of components are resource consuming and differ from traditional constant failure rate models.
2) Improved technologies for locating faults in inaccessible areas (*e.g.* HVdc underground and submarine cables, temperature estimation in power semiconductor modules).
3) Coherence between conventional power system assets and converter-based assets in the operation and control regime—especially for power balancing.

Opportunities

1) Minimizing latent defects by robust reliability-based fault tolerant design, which may reduce failure rates and extend the lifetime.
2) Emerging modular topologies of power converters and capacitors, coupled with developments in on-line CM methods.
3) Effective utilization of dynamic time constants of grids with power electronic assets for balancing and increasing grid availability.

C. CATEGORY 3: STRATEGIC LEVEL ASSET MANAGEMENT

This category establishes gaps closely aligned with the developments of an organization at a business level with relation to training, development and implementation of asset policies and practices. These may be either technical or scientific related materials and understanding. The main drivers are cost, policies from regulators and investors, the knowledge gap associated with new technologies, and the risk associated with implementation. Approaches to be developed by the asset owner include the coordination and linkage with different utilities, collaboration with the academia and the development of in-house tools to match and validate the models from the asset provider where needed. The main challenges and opportunities associated with strategic asset development are summarized below:

Challenges

1) Resources needed for an effective application of asset management in line with the development of new components and technologies.
2) Cost-benefit analysis linked with the application of new asset management strategies and selection of the optimal method—constrained by environmental changes.
3) Approaches to cope with culture changes in support of asset management, new age assets, and future assets.

Opportunities

1) Training and communication with the academia to nurture individuals who can cope with the recent developments and new technologies in physics and engineering.
2) Development of a framework for asset management including vision and cornerstones, with training focussed in cost-benefit analysis, life-cycle cost analysis and social cost.
3) Developing data frameworks within utilities to support enterprise-wide asset management with linkage to different components.

VI. CONCLUSION

The large-scale deployment of power converter assets into transmission networks has reached a level of parity with ac system assets. Their management and maintenance has thus become an extremely difficult job for asset managers and engineers. To tackle these difficulties, this paper has characterized power electronic assets into three business trends. In particular, the different aspects that need to be considered for the development of a sustainable asset management framework for HVdc and FACTS devices have been illustrated. It has been concluded that an imminent change in the monitoring and assessment methods (ranging from traditional, reliability, or PoF-based approaches) is needed due to the inherent design of power electronic components. Moreover, the incorporation of dc substations into ac grids will pose the challenge of maintaining them in a reliable and optimal way, thus making of PoF a potential new philosophy for maintenance practice.

The failure and degradation processes of power semiconductor devices have a significant impact on their ageing and thus lifespan. Therefore, recent trends in power converter design, operation and management, bound by PoF and reliability-based approaches, can provide value for money in terms of business needs for asset owners. To provide some guidance into future work, a research roadmap for an effective management of power converter assets in line with component, process, and organization level developments has been discussed—together with the identification of challenges and opportunities that may arise.

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