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A literature survey on asset management in electrical power [transmission and distribution] system

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SUMMARY

Asset management is one of the key components in a transforming electric power industry. Electric power industry is undergoing significant changes because of technical, socio-economical and environmental developments. Also, because of restructuring and deregulation, the focus has been on transmission and distribution assets that include transmission lines, power transformers, protection devices, substation equipment and support structures. This study aims to provide a detailed exposure to asset management classification, various interesting maintenance methods and theories developed. The work encompasses the issue of data management in recent years. Because of the use of various smart metering devices, large amounts of information are being collected. The advent of data-mining techniques has changed the asset management scenario, and it has been covered in this survey paper. In the end, it also discusses various risk assessment techniques in asset management developed and used for academic research and industries. It is accompanied with survey results from pan-European Transmission System Operator (TSOs) on various aspects in asset management.

KEY WORDS: bibliography review; asset management; asset data management; mid-term horizon; maintenance planning; risk assessment

1. INTRODUCTION

In the transforming electric power industry, power system reliability is of primary concern because power industry places tremendous stress on transmission and distribution assets, which gave birth to asset management. Asset management is classified as an important activity in present day transmission and distribution system planning and operation. This is due to power market deregulation and competition among existing markets, which forces the utilities to optimize the use of their equipment, while focusing on technical, socio-economic and cost-effective aspects. Leaning towards improvement of power system reliability has encouraged electric utilities to find optimal management of installed capacity while optimizing the cost of the current components over their life span. Power system reliability researchers divide the power system activities into three main processes in which sets of decisions are taken for optimal results. These activities are usually divided into the processes [1,2]:

1. grid development (long-term)
2. asset management (mid-term)
3. system operation (short-term)

As seen from the classification, asset management is squeezed between long-term development and short-term system operation. So, the asset manager focuses on operating assets over the whole technical life cycle guaranteeing a suitable return and ensuring defined service and security standards [3].

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CIGRE Joint Task Force JTF23.18 [4] defines asset management as '*The Asset Management of Transmission and Distribution business operating in an electricity market involves the central key decision making for the network business to maximize long term profits*, *whilst delivering high service levels to customers*, *with acceptable and manageable risks.*' Complying with the needs, utilities are constantly striving to optimize the use of resources available for maintenance and new projects while ensuring system reliability is within satisfactory limits. In the electrical power industry, transmission and distribution components are capital-intensive assets, and hence, there is a requirement of utilizing them in the most efficient way.

Under asset management, maintenance of physical components and policies forms the crucial part. Literature survey shows that there have been explicit studies on maintenance of various power system components, that is, power transformers [4–8], overhead lines and cables [4,8,9], protection devices [8–10] and wind-farm components [9,11,12]. Maintenance strategies like corrective maintenance [3,9], preventive maintenance [3,9,13] and Reliability-Centered Maintenance (RCM) [13–15] have been explicitly studied. The purpose of asset management is to turn assets into a revenue stream, and hence, risk assessment in asset management forms another integral part. Brown [16] stated that asset management is the art of balancing cost, performance and risk. Because assets involve financial investment, there have been ample studies on asset management risk assessment [17,18], and more specifically, transmission and distribution systems [19–23], cables [24], substation assets [25] and renewable energy sources assets [12,26]. Reference [27] performed a risk-based asset management study in a reformed power sector taking the example of India. Accurate, timely and reliable asset information results in better decisions, and in the past, there has been quite much research on various aspects of asset management. But, till date, there has been no explicit literature study on asset management in power systems. This paper makes a maiden attempt of compiling various articles on asset management into a single literature study paper that can be used as a reference for future study.

The rest of this paper is organized as follows: Section 2 describes the classification of asset management on time and activity aspects. Section 3 presents the various domains of asset management and impact of data in asset management with related literatures. Section 4 discusses on risk assessment in asset management. This literature survey is concluded in Section 5 with discussions on the future perspective and results from surveys conducted for pan-European TSOs on various aspects in asset management.

2. ASSET MANAGEMENT: LITERATURE-BASED CLASSIFICATION

The development of smart grids, the advent of new intelligent devices and deregulation of electrical power industry since the late 1990s gave birth to 'asset management'. Asset management is also defined as the process of maximizing the return on investment of equipment over its entire life cycle, by maximizing performance and minimizing CapEx (capital expenditures) and OpEx (operational expenditures) [28]. CapEx contributes to the fixed infrastructure or new investment, and it depreciates over time, while OpEx does not contribute to the infrastructure; rather it represents the cost of keeping the system operational and include costs of technical and commercial operations, administration and so on.

Alternatively, asset management is referred to as mid-term planning when classified under the time horizons of transmission and distribution system planning and operation, others being long-term (or system/grid development) and short-term (or system operation/operational planning) [1]. CIGRE WG D1.17 gives a clear picture of how asset management relies on asset data and information extracted from this data that is to be used in future planning [29], and it is discussed later in this study when the various domains of asset management are reviewed.

A classification of asset management based on time domain [12] and activity domain [30] is shown in Figure 1. The time-domain asset management is categorized into long-term, mid-term and short-term asset management, explained below [31]:

- *Long-term asset management*: The time frame ranges from a year and beyond, and it aims at upgrading existing transmission and distribution assets. In other words, it encompasses future planning, that is, investment on new assets like phase-shifting transformers, reactive devices,

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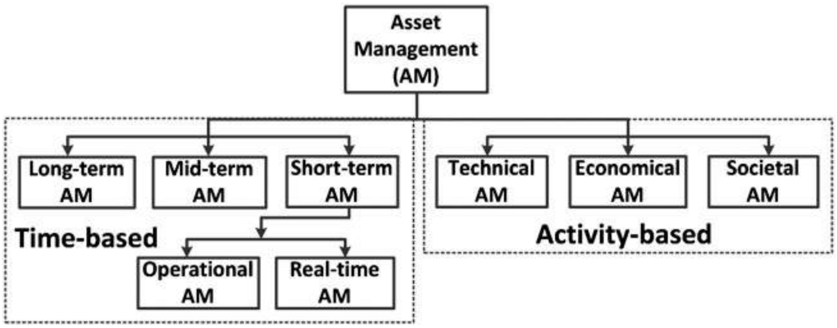

Figure 1. Classification of asset management based on literature study.

investment on capacity expansion of existing connections or upgrading substation equipment. This involves greater financial risks, and hence, proper planning can avoid the risks involved in time delays, interest rates and long-term load diversity.

- *Mid-term asset management*: The time frame of mid-term ranges from a few months to a year, and it involves optimal scheduling of equipment maintenance and allocation of available resources. The primary aim is to extend the life span of existing facilities through proper maintenance and optimally allocate the conventional and renewable energy resources and hydro/thermal units for trading energy with the market. Maintenance cost, a function of asset outages, is the most crucial or driving factor, and it can be greatly reduced when planned outages are scheduled according to availability of resources during seasonal load distributions. So, an 'optimal' maintenance plan greatly reduces the possibility of unplanned outages. It is also the task of asset managers to check that maintenance scheduling is planned based on system reliability and fuel constraints on the non-maintenance system, like the availability of water in-flows for hydro plants. Tor [12] explains the mid-term asset management as:
  - minimizing corporate financial and physical risks based on planned and forced outages of assets
  - reducing operation costs for supplying customers in a competitive era
  - optimizing the allocation of volatile and limited natural resources for utilizing corporate assets
  - extending the life span of assets through proper operational and maintenance schedules
  - prolonging investment costs for the acquisition of new assets
- *Short-term asset management*: Short-term asset management is categorized into operational asset management (daily and weekly) and real-time asset management (outage management). Operational asset management aims at minimizing risks involved with assets, both physical and financial, due to load demand and hourly prices. Real-time asset management is also called asset outage management where contingency analysis forms a vital part. It helps in assessing the effect of unexpected outages due to change in weather conditions, any sudden breakdown or load fluctuations on the asset condition and performance. With technological advancements, real-time monitoring of assets is possible because of systems like supervisory control and data acquisition, remote terminal units and geographic information system (GIS). This has contributed significantly towards better management and decision-making process in short-term.

Based on the activity aspect, Smit *et al.* [30] categorize asset management into technical, economical and societal asset managements, described below:

- *Technical asset management*: Technical asset management refers to asset-related parameters such as physical condition of assets, inventory and maintenance. Ageing of components is of primary concern that links to the physical condition of assets. Other areas in this aspect are component condition, failure probability of assets, inventory or spare parts and maintenance history and/or future planning.
- *Economical asset management*: Economical asset management evolved when technical asset management at many instances proved to be financially unstable. As the name suggests,

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economical asset management refers to financial aspect like maintenance costs and other costs related to procurement of spare parts, maintaining the inventory and doing tests and assessment.

- *Societal asset management*: Societal asset management works closely with economical asset management. It refers to how the utilization of asset affects the society and environment. Outage caused in high-priority buildings like hospital is not acceptable. Also, any disturbances in other places like schools, government offices or convention centres will impact the status of distribution companies.

3. DOMAINS OF ASSET MANAGEMENT AND ADVENT OF DATA MANAGEMENT

In this study, asset management was divided into two domains:

- *Non-physical domain*: The first one that covers aspects from technical issues like network planning to more economical themes like planning of investment and budgeting.
- *Physical domain*: The second one that covers all the physical components comprising the electrical transmission and distribution system.

In the non-physical domain, key points from Schneider *et al*. [3] can be summarized as follows:

- maintenance strategies
- determination of component condition
- asset simulation
- statistical fault analysis and statistical asset management approach (distribution)
- life assessment (transmission)

Maintenance strategy is important to analyse the dependency between maintenance and renewal actions, which gave birth to various maintenance strategies like corrective maintenance, preventive maintenance, and so on. Figure 2 shows various maintenance plans and their key functions. Corrective maintenance is the maintenance carried out after failures occur, while preventive maintenance is the maintenance carried out before failures occur. Corrective maintenance is preferred because of economic reasons and in cases where serious and immediate consequences are not generated. The downside of corrective maintenance is that if something goes wrong, then it can lead to fatal failures causing major socio-economic consequences. Also, it proved to present a very inaccurate view on future expenses. Schneider *et al*. [3] presented a contradictory view about no existence of preventive maintenance in asset management while Bertling *et al*. [14] used preventive maintenance to develop a reliability-based asset management called RCM. The Electric Power Research Institute defines RCM as a systematic consideration of system functions, the way functions can fail, and a priority-based consideration of safety and economics that identifies applicable and effective preventive

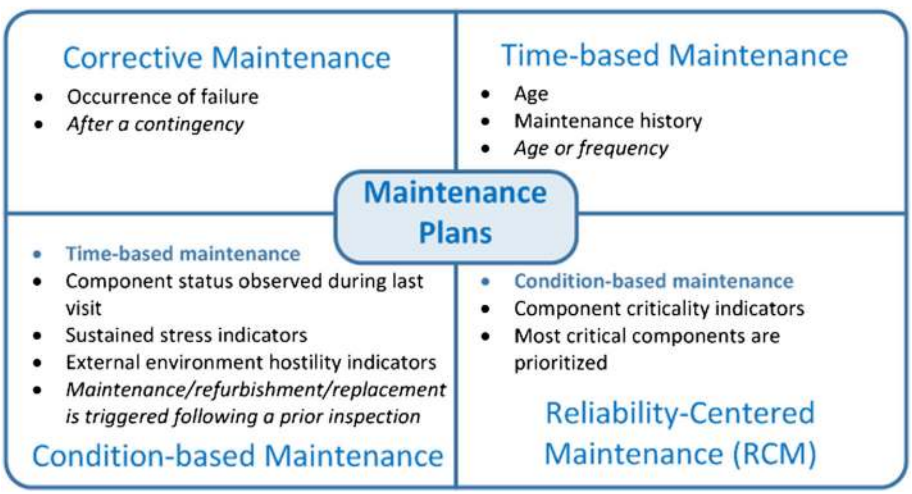

Figure 2. Maintenance plans in a nutshell.

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maintenance tasks. It is described as a structured methodology and maintenance routine that results towards an economically viable system. Literature study reveals that RCM was first implemented in the aviation industry that focused on maintenance and refurbishment needs in complex and critical assets [32]. The concept was borrowed from aviation industry to electric power industry and is widely accepted in asset management, evident from various published literatures [13,15,33–36]. Wallnerström *et al*. [37] discussed that RCM cannot be extended during rare events that have severe consequences. On the other hand, the work proposed a new framework in which the comprehensive projects are divided to allocate resources more effectively and have a detailed quantitative risk analysis.

Other two maintenance plans that are followed by asset managers are time-based maintenance (TBM) and condition-based maintenance (CBM) [38]. As the name suggests, TBM is a maintenance scheduled according to constant time intervals. One advantage of TBM is that all components are checked/maintained timely but at the same time, if the time interval is not optimized, it can lead to technical failures or economic losses caused because of unnecessary interruptions. Unlike TBM, CBM activities are executed only in the event that an emerging fault is detected. In CBM, the maintenance plan aims at exercising oversight on control parameters under normal operation. And for this reason, it requires systematic monitoring and the definition of control parameters of assets. CBM also contributes towards performance evaluation on assets while helping in detection of hidden faults or conditions that may cause a complete failure [39].

In the physical domain, electric power transmission forms the backbone of energy markets along with distribution systems. The transmission system consists of necessary assets for bringing electricity generated from power plants to the points of consumption, and thus, being able to make the energy interchanges between generation and demand. This is possible because of various assets that include power transformers, overhead lines, underground cables, protection devices and substation support structures. In general, the power transformer represents approximately 60% of the overall costs of the network and is ranked as one of the most important and expensive components in the electricity sector [40]. Study reveals about substantial research on power transformers in various literatures about health monitoring, ageing and oil-indicators [41–48]. Similarly, studies have been carried out for overhead lines [47–51], underground cables [47,48,52,53] and circuit breakers [47,48,53–57]. Suwanasri *et al*. [58] studied a zero-profit method for upgrading high-voltage equipment in a substation. The study involved power transformers, current transformers, voltage transformers, high-voltage circuit breakers, switches and surge arresters. With the integration of renewable energy sources into the main grid, wind-farms and photovoltaic plants are also part of asset management. Both have been extensively studied from asset management point of view in literatures [11,12,26,34–36,59]. A real-life case study on asset management in Singapore was conducted by Yoon and Teo [60], although it focused more on underground grids.

In the current state, one thing that binds together the physical and non-physical domains of asset management is data management. With the advent of computational tools and smart meters, a huge amount of data is collected by the utility companies that are used later for improving the performance of assets and/or maintenance policies. Data requirements for probabilistic concepts in asset management are huge and range from inspection rates and mean times to failure to probabilities of state transitions [17]. For example, the effect of maintenance on the replacement time for transformers was studied in [61]. The study used RCM and a genetic algorithm to optimally schedule maintenance activities for the transformer. In the last decade, merging of data requirements with Information Technology (IT) and Human Machine Interface is shown by the studies of Kostic [62,63]. The work studied on the application of IT in asset management. Reference [62] focuses on the aspect of integrating IT in asset management by utilizing process data (e.g. supervisory control and data acquisition, Energy Management Services (EMS)/Data Management Services (DMS)) in back-end tools such as enterprise resource planning, GIS, computerized maintenance management system and other analysis tools. Downside with the electric power industry is that utilities have used the existing models in an inefficient or wrong manner, and that paves way for data-mining process [64]. A framework of data management used in asset management is shown in Figure 3.

Use of tools have been complemented by various computational models and optimization techniques that have been developed for maintenance, refurbishment, ageing and monitoring techniques in asset management, like state diagrams [65], fuzzy techniques [35,44,66], neural networks [42], Particle Swarm Optimization (PSO) [36,48], linear programming [49,67], branch and bound techniques [68]

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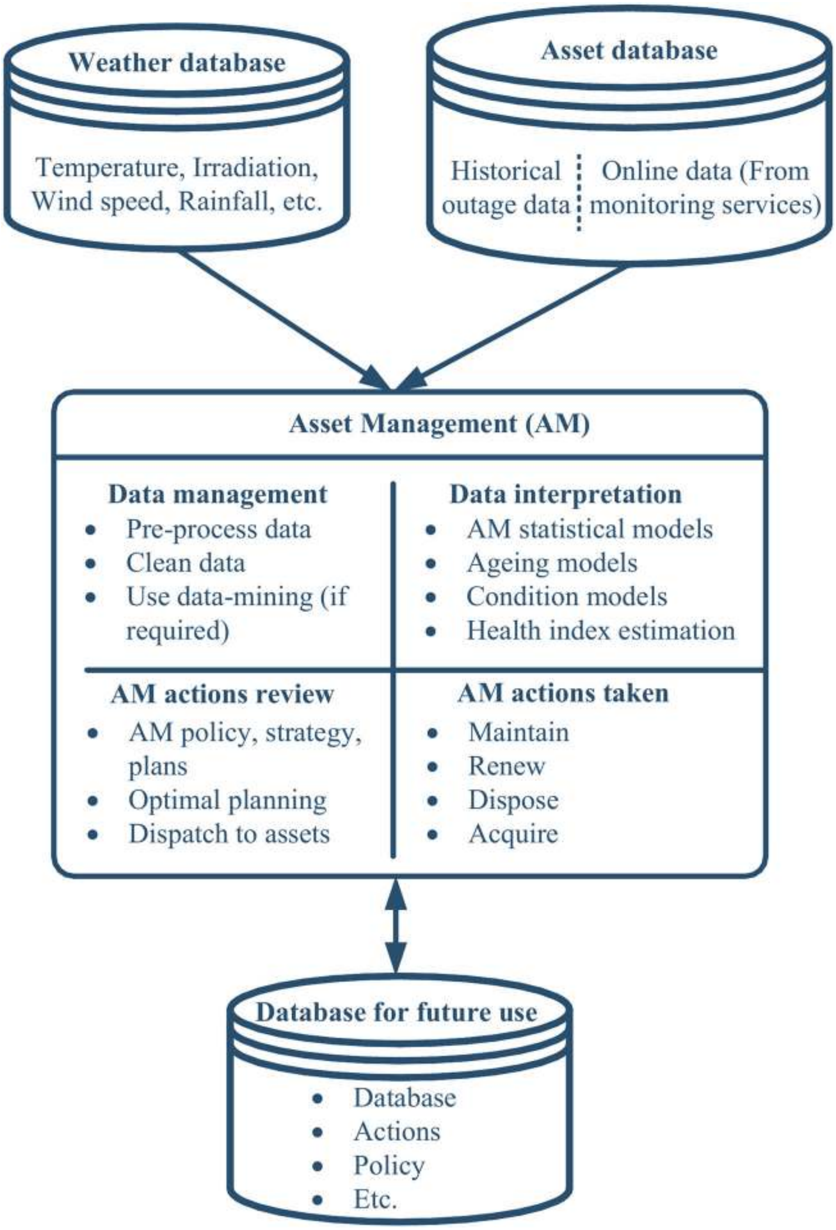

Figure 3. A framework of data management used in asset management.

and other optimization techniques [37,69,70]. Anders *et al*. [71] combined engineering and financial aspects of asset management into software tool called risk-based asset management (RI-BAM). Life-cycle data can be used to train the failure rate model based on various mathematical methods for assets. Qiu *et al*. [72] demonstrated a nonparametric regression-based failure rate model for transformers using life-cycle data. The study compared their model with the existing time-based and condition-based models [73]. Data mining is useful in this type of study where the aim is to train mathematical models and later use them for extended studies like reliability and maintenance optimization.

4. RISK ASSESSMENT IN ASSET MANAGEMENT

The electric power transmission and distribution systems constitute the greatest risk to the interruption of power supply, and hence, risk analysis constitutes an important part of asset management. This is due to the huge investments on equipment maintenance, upgrade, and so on, which has a direct impact

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on operational targets. Risk is defined as a function of probability of failure and its consequence. For asset management, CIGRE WG 23.39-07 [74] categorized risk assessment into three sectors:

1. Type I: System risk due to maintenance actions resulting in outages. It is influenced by system topology, age and condition of equipment, generation priorities, difficulties in short-term outage planning and the requirement in reducing outage times.
2. Type II: System risk due to maintenance delays resulting in asset deterioration.
3. Type III: System risk due to not taking any actions because of a failure and continuing operation.

The IEEE Power and Energy Society task force analysed the impact of maintenance on asset reliability [75], and the corresponding figure is shown in Figure 4. Literature survey suggests the development of various risk models in the past two decades. Brown [16] discussed the relation of asset management and risk analysis. Muhr [18] categorizes different kinds of risk into a cube called risk management cube. The three faces of risk management cube are risk categories (market, financial etc.), typical of trade risks (industry, utilities etc.) and structure specific risks (international or regional). It explains how any decision taken will be based not only on the technical information but also on socio-economic aspects.

A large number of methods have been developed to tackle risk associated with asset management. Value at Risk (VaR) [20], life-cycle cost (LCC) [25], Run-Refurbish-Replacement (3Rs) [27] and various probabilistic approaches [17] to name a few because citing all papers would be out of the scope of this paper. The VaR method, as defined in [20], measures the worst expected loss over a given time horizon under normal market conditions at a given confidence level. It explores the maximum loss incurred in a specific time frame with an appropriate confidence level. Similarly, LCC calculates the total operation cost of the system (which includes planning, purchase, operation and maintenance and liquidation) for the lifetime, and it aims in minimizing the total costs. LCC has been applied in asset management for, for example, photovoltaic [26] and wind-farm plants [12].

A risk management system called Intelligent Grid Management System was proposed by Endo *et al*. [76], which looks into the equipment performance in the transmission and distribution system. It looks into economics, ageing and reliability issues in transmission and distribution equipment, evaluated using a Monte-Carlo method and a nonlinear programming. Mehairjan *et al*. [24] did a statistical life

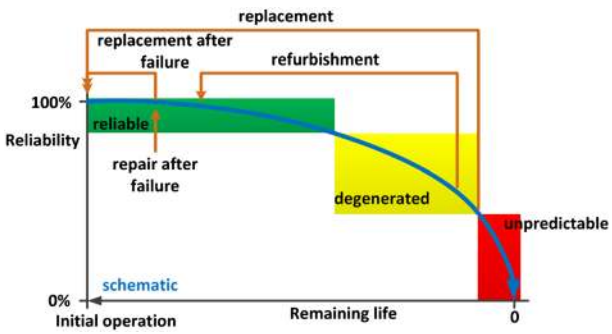

Figure 4. Ageing model for asset simulation [2].

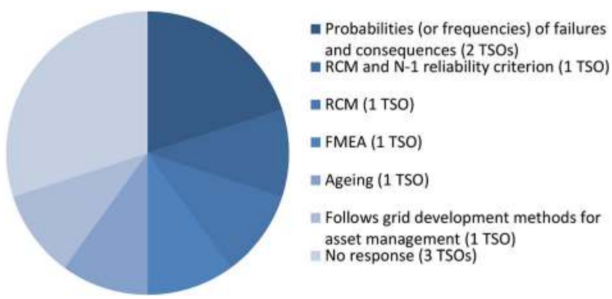

Figure 5. Answers to question on different reliability assessment methods for asset management (RCM, Reliability-Centered Maintenance; FMEA, Failure Mode and Effects Analysis).

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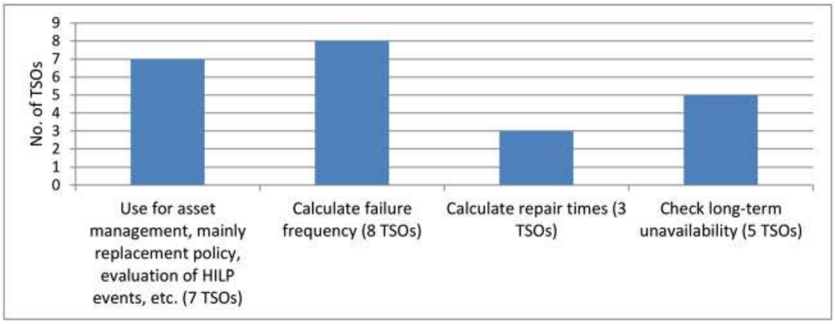

Figure 6. Answers to question on usefulness of data collection for components (HILP, high-impact low probability).

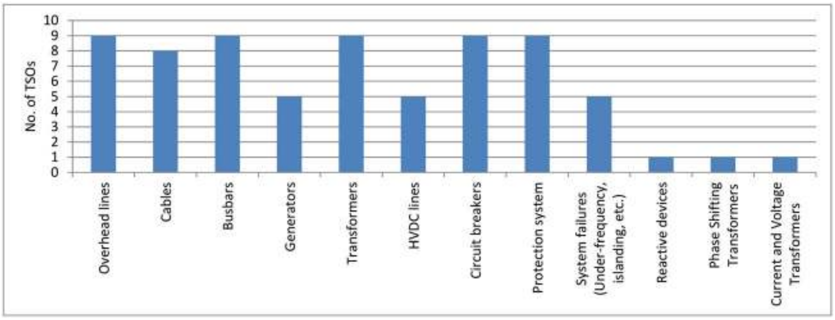

Figure 7. Answers to question on components considered under asset management.

data analysis for distribution cables, which aims at obtaining the future failure probability by considering limited or incomplete data sets of the various assets. Suwanasri *et al*. [77] performed a practical case study on risk-based maintenance for power transformer in Thailand. The study used failure statistics to determine the critical components of power transformer, and for risk-based assessment, Weibull distribution and Analytic Hierarchy Process (AHP) was used.

5. CONCLUSION

The aims of asset management are to optimize asset life cycle, improve predictive maintenance and prepare an efficient business plan for investment on new assets. This can be achieved by designing better information management systems that cannot only handle data archiving and retrieval but also help towards data analysis tools. Various outcomes of these tools are condition monitoring, maintenance management, purchase and inventory control, predictive modelling and decision-making including risk assessment software. Development of new risk tools and the clear interpretation of the results are of importance, as risk analysis is useless if the results cannot be translated into actions. As a proof, various projects on pan-European electric power system are working towards improving reliability or developing a new reliability criterion. An example is the GARPUR project [78], which aims at designing, developing, assessing and evaluating new reliability criteria to be progressively implemented over the next decades at a pan-European level and maximizing social welfare at the same time. The project studied asset management as one of the vital factors that contributes towards power system reliability [79]. The results from various TSOs on asset management ranging between different reliability assessment methods, data collection and the usefulness of data collection towards asset management are included in this study. The TSOs were also asked about the components, which are considered under asset management to have a broad aspect of current practices. The results are shown in Figures 5, 6 and 7.

The study would have been incomplete without learning about the implementation of different mathematical techniques evolved in the past two decades in real-time. Cases such as of Suwanasri

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et al. [77], Lucio *et al*. [80] and German *et al*. [81] on Brazilian and Colombian electrical energy utility respectively, quantify the importance of asset management in today's time thus fulfilling the scope of paper. This literature study on asset management in electric power transmission and distribution system is a first of its kind. In the end, the authors would like to state that a large number of articles could not be cited in this paper because citing all would be out of scope of this paper.

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