TOWARDS HEALTH ASSESSMENT: FAILURE ANALYSIS AND RECOMMENDATION OF CONDITION MONITORING TECHNIQUES FOR LARGE DISCONNECTOR POPULATIONS

***Anna Lilly Brodersson*[*], *Jan Henning Jürgensen*[†], *Patrik Hilber*[†]**

[*] *Vattenfall Eldistribution AB, Sweden, annalilly.brodersson@vattenfall.com*
[†] *KTH Royal Institute of Technology, Sweden, jhjur@kth.se*

Abstract

Condition monitoring of power system equipment is an important part of asset management. Hence, health indices were developed to describe the equipment condition in a linguistic form with the obtained data. The development of health indices requires knowledge about the equipment population under investigation to consider all important factors. Therefore, this paper investigates the failure data of a large disconnector population to identify population characteristics such as failure modes and failure locations. The analysis showed that the functions maneuverability and current carrying are essential to monitor. Moreover, this paper discusses condition monitoring techniques for disconnector and their applicability in large populations. The paper concludes that even without cost-intensive investments in condition measurements or higher preventive maintenance costs, a condition evaluation can be performed.

1 INTRODUCTION

Asset management requires knowledge about the current state of the equipment in operation. [1] discusses the need for monitoring of switching equipment and argues that monitoring applications must be evaluated in detail to find the balance between the improvement of reliability and the costs of installation. The measured data of condition monitoring techniques can be combined and evaluated with assessment techniques such as a health index [2]. However, to conduct health assessment of assets, it is necessary to identify and investigate historical failure data of a utility's population which depend on the environment, type, and operation. A comprehensive review about surveys, statistical analyses, and condition monitoring of disconnectors and circuit breakers is conducted in [3]. [3] presented that only one major study has been conducted on disconnector failure statistics which is [4, 5]. The failure data in [4, 5] was gathered over a range of 25 countries on high voltage level. However, the study in this paper focuses on medium and high voltage and divides the disconnectors in remote-controlled and manually operated disconnectors to identify possible differences. A manually operated disconnector is here defined as where the open and closing of the disconnector has to be performed on site. Firstly, this paper investigates work order data from a population of disconnectors which was gathered over the period 2008 to February 2015 in Sweden to identify failures causes and reasons that led to maintenance decisions in the past. The aim towards more exact maintenance, determination of equipment health, and the lack of transparency in maintenance decisions, illustrates the need for condition based maintenance and monitoring. Therefore, the second part of the paper discusses condition measurement techniques for disconnectors based on the criteria: online monitoring possibility, additional sensor required, and under which operating condition the measurement can be obtained. Condition monitoring techniques such as number of operations, the evaluation of the electrical condition, and mechanical condition monitoring are discussed and recommendations made.

2 ANALYSIS OF FAILURES

This study focuses on one region in Sweden on distribution and region system level with a voltage range from 6 kV to 220 kV. The data was collected through 2191 work orders which included 655 unscheduled maintenance work orders and a total of 1626 disconnectors, of which 587 are remote-controlled. The work orders related to the disconnectors included information such as voltage level, remote control availability, geographical location, place of installation, and the work order description. The failures were categorized into minor and major failures according to the definition of [6] which has also been used in [4, 5]. Examples of these major failures are: the disconnector does not open or close on command because of the mechanical parts, maneuvers without command, cannot carry current or is locked in a position due to electrical functions. In contrast, minor failures could be: minor changes in functions or repair of equipment which does not lead to a major fault. The failure modes of the disconnector are categorized into:

1. **Current Carrying**: The ability to carry current

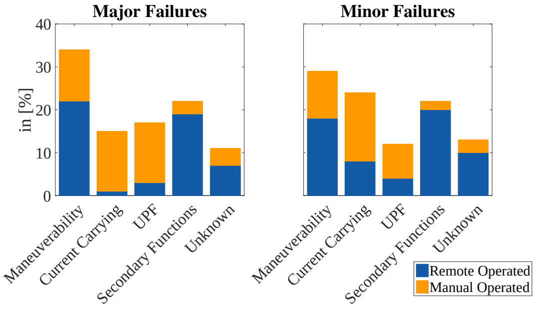

Fig. 1: Failure mode analysis of major and minor disconnector failures

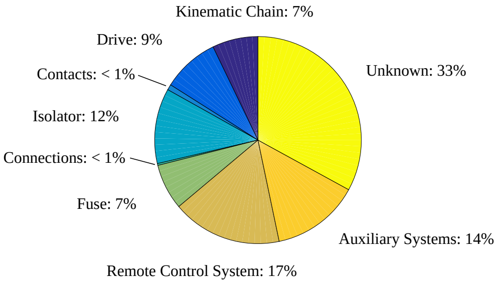

Fig. 2: Failure location analysis of major disconnector failures

2. **Maneuverability**: The ability to open and close on command
3. **Unidentified Primary Function (UPF)**: Either function 1, 2 or insulation of the primary equipment but not identifiable from the work order
4. **Secondary Functions**: The ability to support the main disconnector functions with the control and auxiliary equipment
5. **Unknown**

Fig.1 illustrates the failure modes for major and minor disconnector failures. The failure mode maneuverability has the highest contribution to major failures with 34%. Similarly, maneuverability has also the highest contribution of minor failures with 29% but secondary functions have a similar share with 22%. The reason for the high share of secondary functions within minor failures lies mainly in the definition. For example, changing a weak battery was defined as minor fault which occurred frequently, especially for remote-controlled disconnectors. It is also noticeable that remote-controlled disconnectors have a higher share of maneuverability faults.

Analysing the total faults, the study shows that the total amount of major failures doubles for remote controlled disconnectors compared to manual operated disconnectors. The difference is caused by the additional control equipment. This underlines the discussion in [7] that with an increasing number of secondary equipment, the number of faults will also increase which can have a considerable impact on the overall equipment and system reliability. The failure mode unidentified primary function has a share of 20% of all major failures.

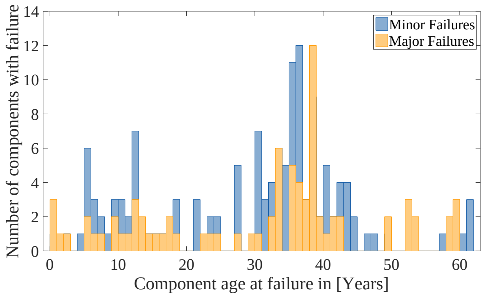

Fig. 3: Age to failure distribution of 81 major failures and 139 minor failures

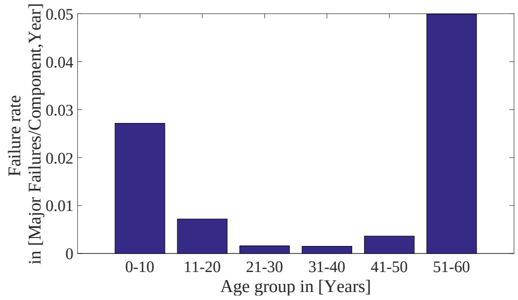

Fig. 4: Failure rate of disconnectors divided into different age groups

In Fig.2, the failure data of major failures was analysed and grouped depending on the failure location. The unknown failures have the highest share. However, the remote control system is the main contributor with 17%, followed by the isolator with 12%, and the auxiliary system with 14%. The parts drive, fuse, and kinematic chain have nearly the same share around 8%. However, only 8.6% of all major failures resulted into system outages.

The frequency of minor and major failures depending on the disconnector age is depicted in Fig.3. Information related to the equipment age was only available in 35% of the work order information. Major failures are evenly distributed until 30 years of equipment age. However, most major failures occur between 30 and 40 years. Similar results were shown in [8], were most of the disconnector failures occurred around an equipment lifetime of 30 years. In Fig.3, the equipment with minor failures has not been removed from the sample whereas the equipment with major failures was removed. However, the age distribution of the population must be considered as well. Thus, the age to failure distribution of major failures is divided by the age distribution of the total population for different age groups. The results are depicted in Fig.4 and show the bathtub curve. The failure causes are depicted in Fig. 5 and it can be seen that ageing was the main reason with 27% of all failure causes. Fig. 6 depicts the failure rate $\lambda(t)$ of the population

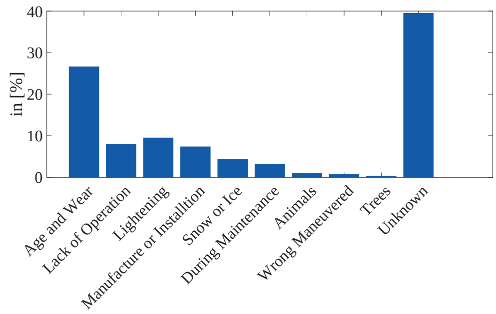

Fig. 5: Failure causes of major disconnector failures

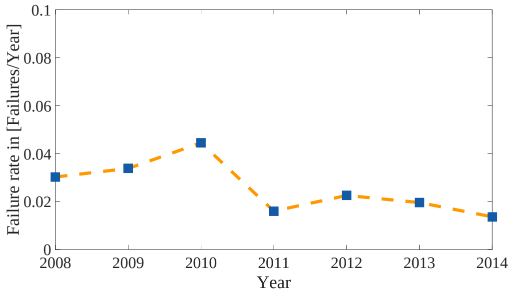

Fig. 6: Failure rate of disconnector population between 2008 and 2014

between 2008 and 2014. The failure rate was calculated by

$$\lambda(t) \approx \frac{n_i}{N_i * \Delta t} \tag{1}$$

With n_i the number of failed equipment in $\Delta t = 1$ year and N_i the amount of equipment in service. Most of the major failures were repaired or replaced and therefore the assumption was made that the disconnector population is constant.

Furthermore, the study showed that 70% of the maintenance work were preventive maintenance tasks. The decisions for corrective maintenance were depended on the technician who inspected the disconnectors. Therefore, the corrective maintenance decisions are determined by the experience and knowledge of the technician. The study showed that 43% of the faults were identified during scheduled substation inspections, 43% while non-scheduled substation maintenance, 13% were identified by the control room operator, and 1% through third party.

3 CONDITION MONITORING TECHNIQUES

Only 8.6% of major failures led to confirmed system outages. This shows that the disconnector failures have a small impact on the overall system reliability in this region. However, the time which is required to repair a disconnector contributes to the system index System Average Interruption Duration Index (SAIDI) when failures in other equipment occur. Therefore, the condition estimation cannot be neglected for disconnectors. Disconnector maintenance is planned and conducted with other maintenance actions because it is practically and economically infeasible to take only a disconnector out of service to conduct maintenance. This limits the possibilities for condition measurements and has to be considered.

Table 1 presents condition indicators for disconnectors which are sorted depending on the failure mode. Furthermore, these indicators are evaluated depending on the criteria: if online monitoring is possible, an additional sensor is required, as well as which state and action is needed to conduct the condition measurement. The failure mode current carrying is the most important because if the disconnector cannot carry the current it could cause direct system outages. The most accurate measurement for the contacts of the disconnector is measuring the resistance. However, to measure the resistance of the contacts, the disconnector needs to be out of operation. Hence, an alternative is the measurement of the temperature of the contacts with a new type of infrared sensor [9]. The authors in [9] showed that with additional ambient temperature and current measurement, the coefficient of the current can serve as a measure of the condition of the contacts. This method becomes cost intensive in large disconnector populations due to the installation of nine temperature sensors, three on each phase of the disconnector and the connection to a wireless communication with is mostly only available in substations. An option to a fixed infrared sensor installation is conventional thermography. This method is less expensive but requires higher documentation and evaluation effort.

The second most important function is maneuverability which has the highest contribution to failure modes as presented before. Gathering information about the motor which operates the opening and closing is the most accurate condition indicator. Here, the motor current as well as the time required for opening and closing can be measured and condition trends of the motor and kinematic chain can be identified. However, these condition indicators require the installation of extra sensors plus the online monitoring availability can be a significant cost factor. In addition, the disconnector needs to be operated which is often not possible under normal operation. Moreover, the temperature within the maneuver box can indicate a possible fault of the auxiliary system which operates the disconnector. Even if this failure location has a share of 14%, it requires an additional sensor to measure it. Condition information which are less cost intensive are maneuver information such as last maneuver date, maneuvers since last inspection, and total number of maneuvers. These can be collected through the control system or work order information. Another possible less cost-intensive method is measuring the maneuver torque with a newton meter during scheduled inspections. This applies especially for manual by hand operated disconnectors. Measurements can be taken during the inspection and condition trends can be evaluated over time.

Other parts such as fuses or isolators can mainly be assessed in a visual manner. Here, the stability of the mechanical con-

Table 1: Condition indicators for disconnectors with respect to online monitoring possibility, additional sensors required, and what action of the disconnector is needed to measure

Condition Indicator	**Measurement Collection**		**State and Operation needed to measure**		
	Online	**Additional sensor**	**Maneuver required**	**Under Load**	**Energized**
Current Carrying					
Crossover resistance	0	1	0	0	0
Temperature primary circuit	1	1	0	1	1
Maneuverability					
Temperature maneuver box	1	1	-	-	-
Motor current open	1	1	1	0	1
Motor current closing	1	1	1	0	1
Motor operating time (closing)	1	1	1	0	1
Motor operating time (opening)	1	1	1	0	1
Motor Voltage supply	1*	0*	0*	1*	
Last maneuver date	1*	0*	1	-	-
Maneuvers since last inspection	1*	0*	1	-	-
Total number of maneuvers	1*	0*	1	-	-
Maneuver torque	0	1	1	0	1
Contact pressure	0	1	1	0	0
Gas pressure (drive)	1	0	0	1	-
Others					
Stability in construction - Visual	0	-	-	-	-
Cracks in porcelain	0	1	0	**	
Corrosion - Visual	0	-	-	-	-
Isolator Condition - Visual	0	-	-	-	-
Secondary Function					
Control Signal Voltage	1*	0*	0*	0*	-
Position transducer signals	1	0	0	0	-

* Only remote controlled disconnectors

** Depending on the method

(Yes = 1 / No = 0)

struction, corrosion, cracks in porcelain, and the condition of the isolator can be assessed.

In general, the current carrying ability is the most important feature of the disconnector and hence also the most common condition measurement at Vattenfall at the moment. However, the failure analysis in this paper and [4, 5] showed that major failures of maneuverability contribute the most. Therefore, the ability of the function maneuverability can be evaluated with counters or measuring the maneuver torque during inspections. In addition, the time since the last operation of a disconnector can be a valuable indicator because disconnectors are not operated frequently. If these information are documented and evaluated, trends can become visible and a condition estimation in form of a health index can be performed. Furthermore, the current carrying function can be measured with thermography cameras during inspection which would require a higher documentation effort but is a rather inexpensive method compared to fixed infrared sensor installations because it can be performed for a complete substation at once.

4 CONCLUSION

The failure analysis presented that the failure mode maneuverability has a higher share than current carrying. Even if maneuverability does not directly lead to system outages, whereas current carrying ability can lead to direct system outages, maneuverability can have a negative impact on SAIDI which determines the outage costs. Therefore, the condition indicators for maneuverability should be considered while evaluating large disconnector populations. Furthermore, it was illustrated that even without cost-intensive installations of condition monitoring equipment, the condition can be evaluated when preventive maintenance actions are conducted. In general, gathering failure as well as maintenance data and analysing it, is necessary to understand the characteristics of a population to develop a health index.

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