Comparison of Frequency Converter Outages: A Case Study on the Swedish TPS System

Y. A. Mahmood, A. Ahmadi, R. Karim, U. Kumar, A. K. Verma, and N. Fransson

Abstract—The purpose of this paper is to survey the unavailability of the two main types of converters used in the Swedish traction power supply (TPS) system, i.e. the rotary and the static converter. The number of outages and the outage rate has been used to analyze and compare the unavailability of rotary and static converters. The mean cumulative function (MCF) has been used to analyze the number of outages and the unavailability trends, while the forced outage rate (FOR) concept has been used to analyze the outage rates. The study shows that the outages due to converter failure occur at a constant rate by calendar time at most of the converter stations, while very few stations have an increasing or a decreasing rate. It has also been found that the static converters have a higher number of outages and a higher outage rate by calendar time compared to the rotary converter types. The results of the study show that combining the number of outages and the forced outage rate gives a better view of the converters' performance, and provides support for the maintenance decision. In fact, using one of them alone does not reflect reality. Comparing these two indexes is also helpful in identifying the areas where extra resources are needed to improve maintenance planning and where improvements can reduce the outage in the TPS system.

Keywords—Frequency Converter, Forced Outage Rate, Mean Cumulative Function, Traction Power Supply, Electrified Railway Systems.

I. Introduction and Background

THE electrified railway has played an important role in modern transportation and social development because of its huge capacity, high efficiency, and low pollution. Today's electrified railway sector is expecting higher demands for enhanced quality of service, which will in turn impose greater demands on railway infrastructure managers. The traction power supply (TPS) system is the system which provides the electrified railway with electrical traction power. Fig. 1 shows the TPS system and its associated components and equipment in Sweden.

Obviously, any fault in the TPS system will cause operational problems for trains, which will ultimately lead to traffic delays or train cancellations. This is expensive in terms of time and money for both the train operators and the infrastructure manager, and the people who suffer most in the end are the train passengers and the taxpayers.

An analysis of the annual delay caused by the TPS system shows that the number of delay hours due to outages of frequency converters in the Swedish TPS system exceeded 60 hours in 2010 (see Fig. 2). This portion of the operational interruptions might have significant economic consequences and needs more attention. In this connection, both manufacturers and infrastructure managers can pool all their expertise and support for further improvement of the reliability and availability of electrified railway systems and TPS.

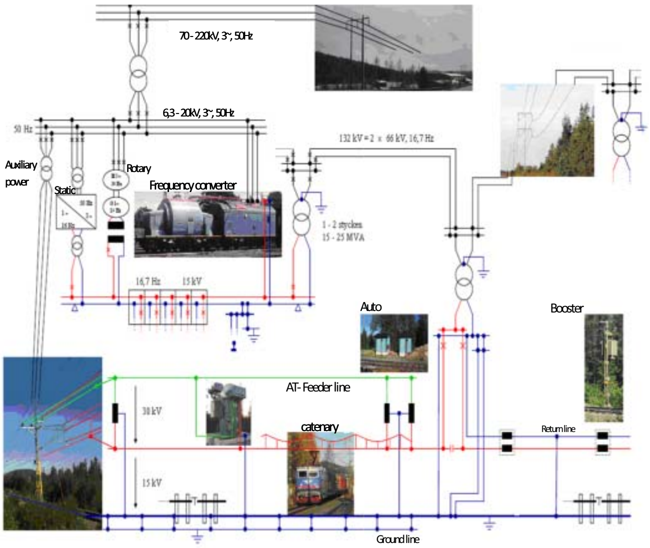

Fig. 1 Traction power supply system in Sweden

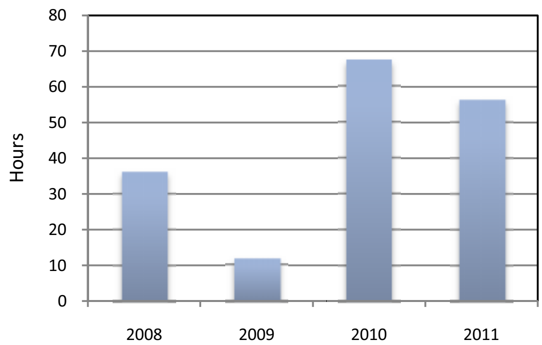

Fig. 2 Accumulated annual delay originating from outages in frequency converters

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All of the TPS components, with their varying conditions, will influence the quality and operability of the whole power supply system. Frequency converters constitute the main part of the TPS system and provide adequate traction power for the electric vehicle.

There are two main types of converters, i.e. the static and the rotary converter, which are used to convert electrical energy from the 3-phase, 50 Hz public grid to the 1-phase, 16.7 Hz traction grid which is used in Sweden and Norway. In order to make decisions for new investments and to perform improvements in the TPS system, it is vital to understand the behaviour and characteristics of both types of converters.

The literature review performed within this study has revealed that there are very few publications which compare frequency converters and that these publications do not represent today´s situation (i.e. they are too old). One example is a study by Pfeiffer et al. (1997) [1], who presented the design of the rotary frequency converter and compared it with that of the solid-state (static) one. They discussed the converters used in traction power supply, and their comparison was confined to some reasons why the static converter could not be used instead of the rotary converter, i.e. harmonics and the accessories required, e.g. filters, complexity stations, special transformers, etc. Lei Shi et al. (2011) [2] presented a comparison between the rotary and the static converter with regard to aspects such as reliability, power density, overload capacity, efficiency, cost, and flexibility of conversion, and they focused on converters used in airplanes.

The purpose of the present paper is to make a survey of outages in converters and compare the unavailability of rotary and static converters through the outage rate and the number of outages. The mean cumulative function (MCF) is used to analyze the number of outages and the trends of the outages.

The rest of the paper is organized as follows: Section II describes the frequency converters in the TPS system. Section III describes the FOR data. Section IV discusses the MCF. Section V describes the data collection process, while Section VI presents the data analysis and analytical methodology used in this study. In Section VII, the results of the study are discussed and conclusions are presented.

II. Frequency Converters in Traction Power Supply

The electrical power for railway traction is in many countries of the world provided by single-phase and low-frequency systems. Supplying this single-phase and low-frequency energy is accomplished by different means, and frequency converters are applied to transfer energy from the three-phase public grid to the single-phase traction grid. The rotary frequency converter is the converter traditionally used and it has been in operation in Sweden since 1915. However, over the past 36 years (in Sweden), static frequency converters have been put into service, sometimes in addition to, and sometimes as a replacement for rotary converters. Static frequency converter technology has emerged in recent years as an alternative to or a replacement for rotary equipment and shows a significant improvement in energy efficiency. Still the rotary converter appears to exhibit sufficient performance to justify its continued operation. The choice between the rotary and the static converter in a reinforcement of the TPS system is not an obvious choice and depends very much on the initial investment cost and on the local power demand, which differs between countries and TPS systems.

Sweden has a large number of rotary frequency converters feeding the traction network, operating side-by-side with static converters to cover around 9,543 km of electrified railway network in the Swedish railway system (2004) [3]. In this section, we discuss these two types of converters and their stations, types, and converted power (see Table I).

A. *Rotary Frequency Converter*

The rotary frequency converter consists of two main components, the motor and the generator, and is therefore also called the motor-generator (MG) set. The conversion process starts with 3-phase, 50Hz AC input power to a motor. The motor converts electrical energy to mechanical energy via the shaft, which turns a generator. The generator then converts the mechanical energy back to electrical energy with one phase and a frequency of 16.7Hz, and this power is finally supplied to the load. Rotary frequency converters can be divided into many different types according to the driving motor: the induction-synchronous, the doubly fed induction-synchronous, and the synchronous-synchronous [2]. The type of rotary converter used in Sweden is the synchronous-synchronous motor generator set made by ASEA AB. As Table I shows, there are three versions of this type of converter, the Q24, Q38 and Q48, with a rated power reach of 3.2, 5.8 and 10 MVA, respectively. The power capacity provided by the whole population of this type for the TPS system amounts to 496 MVA. There are 76 converters of this type in the Swedish TPS system and they are located in 29 converter stations, each of which includes 2, 3 or 4 converters.

The advantages offered by this type of converter are line isolation, harmonic cancellation, power factor correction, and voltage conversion with balanced, smooth and controlled power output. This converter generates a sine wave in exactly the same way as the utility does. In addition, the converter exerts a very friendly load on the public grid and creates reactive power to support the voltage just like a normal synchronous machine. The harmonics and modulations of the voltage, current, frequency or loads in AC networks can be filtered by the rotary frequency converter, which serves as a natural filter, thus rendering an extra filter unnecessary [1, 2, 4].

B. *Static Frequency Converter*

The static or so-called solid-state frequency converter is an electronic device and has no moving parts. The main components of the most common type are the rectifier and the inverter. The rectifier converts 3-phase, 50Hz AC input power to DC, and then the inverter converts this electrical DC power to 1-phase, 16.7Hz AC power for the traction grid. The development of the solid-state frequency converter is mainly constrained by the hardware of the power electronic devices and the microcontroller chips. The hardware has made great progress in the past thirty years, and therefore the solid-state frequency converter is also a research field of great current interest [2]. The most common type of static converter in Sweden is the PWM type, but there are 16 units of the cycloconverter type, out of a total number of 58 units. These units are distributed over 21 converter stations. The total amount of power capacity provided by this type of converter reaches 798 MVA, which means that they supply around 1.4 times more power than the rotary type.

Since they do not have any moving parts, there is no inertia energy storage capacity, although there are some distributed inductors and capacitors which can store that energy. Accordingly, the filtering capacity of the static frequency converter is limited. Due to the unavoidable power-pulsation in a single-phase grid, a resonant circuit tuned to twice the line frequency is connected in parallel to the DC-link capacitor. Modules for filtering and isolation must be installed, as a result of which the solid-state frequency converter becomes bulkier and heavier [1, 2, 4].

TABLE I
SUMMARY OF FREQUENCY CONVERTERS: NUMBERS, TYPES AND AMOUNT OF POWER CONVERTED

Type and no. of converters	No. of stat-ions	Version	No. of con-verters	Conv. power (MVA)	Total conv. power (MVA)
Rotary (76)	25	Q24	11	3.2	35.2
		Q38	45	5.8	261
		Q48	20	10	200
Mixed station (Rotary & Static)	5	Total rotary power = 496.2			
Static (58)	16	YOQO	16	13-15	234
		YRLA	3	8.2	24.6
		TGTO	12	14	168
		Mega15	14	15	210
		Mega6	4	6.7	27
		Cegelec	2	15	30
		Areva	7	15	105
Total no. of stations	46	Total static power = 798.6			

III. FORCED OUTAGE RATE (FOR)

The most common and straightforward index for describing the unavailability of a generating unit is the forced outage rate (FOR), which is based on a two-state model of a unit. The simplest model for a generating unit for continuous operation is a run-fail-repair-run cycle that states that every generator has two states, i.e. i) unit availability and ii) unit unavailability (measured as the FOR). The unit availability means the long-term probability that the converting unit will reside in an "on" state and the unit unavailability (measured as the FOR) means the long-term probability that the converting unit will reside in an "off" state [5-7]. The FOR is a long-established utility industry measurement formally defined by IEEE Std 762. The FOR is defined according to equation 1 below [7].

FOR=1-Availability

$$FOR = \frac{\sum[down\ time]}{\sum[down\ time]+\sum[up\ time]} \qquad (1)$$

The up-time represents the time when a unit is capable of providing service, regardless of whether it is actually in service and regardless of the capacity level that can be provided. The down-time, on the other hand, represents the unavailable state where a unit is not capable of operation due to failures.

IV. MEAN CUMULATIVE FUNCTION (MCF)

To compare the outage of the frequency converters in Swedish railway installations, this paper uses the mean cumulative function (MCF) [8], [9], which is a non-parametric method. The non-parametric model for a population of units is described as the population of cumulative history curves for the cumulative number of recurrences (e.g. the FOR). It is the population of all the staircase curves of every unit in the population.

The outage comparison is accomplished by calculating the MCF, using point estimation, and obtaining the so-called Nelson's estimate $\mu(t_j)$ of the MCF [10]. Having *n* units and *m* unique recurrences for each unit, i.e. $i = 1,2,\ldots,n$ and $j = 1,2,\ldots,m$, these recurrence times are ordered $t_1 < t_1 ,\ldots,< t_m$, see equation 2 for this estimate of the MCF.

$$\mu(t_j) = \sum_{k=1}^{j} \left[\sum_{i=1}^{n} \delta_i(t_k) d_i(t_k) \Big/ \sum_{i=1}^{n} \delta_i(t_k) \right] \qquad (2)$$

where $\delta_i(t_k)$ is as follows:

$$\delta_i(t_k) = \begin{cases} 1 \text{ if unit i is still functioning} \\ 0, \text{otherwise} \end{cases}$$

and $d_i(t_k)$ is the number of recurrences for unit *i* until time t_k.

The MCF is non-parametric in the sense that it does not use a parametric model for the population. This estimation involves no assumptions about the form of $\mu(t_j)$ or the process generating the histories [9]. The MCF is a simple plot, is informative and widely useful, requires minimal assumptions, is easy to make and present to others, and is easily understandable for management [8]. This method has allowed engineers to identify quickly trends, anomalous systems, unusual behaviour, maintenance performance, etc. Furthermore, the MCF makes it possible for decision-makers to identify areas in which extra resources are needed to improve the maintenance performance [11]. Graphical techniques based on the plotting of cumulative failure and on the MCF provide a non-parametric method for the analysis of field failures [12]. The MCF plot indicates the number of outages versus time, and the time can be the age starting from the time of installation or the calendar time in hours or days, or the number of cycles. One of the most useful features of MCFs and extensions to continuous variables is that MCFs provide the ability to make statistically meaningful comparisons between multiple populations. The MCF simply represents the average number of failures that can be expected at various ages of a system in the population and possesses all the properties of an n cumulative plot, such as the ability to reveal the average failure trends of the population of the system in the organization [12].

Line A and B in Fig. 3 represent the cumulative numbers of outages for two different converters used in Sweden. Accordingly, line C represents the step function of the mean cumulative number of outages, i.e. the MCF, for these two converters. Line D represents a fitted curve for the MCF of the outages for the whole population. To simplify the comparison of all the converters and to show the trends, we will use the fitted curves of the MCF in the remainder of the paper.

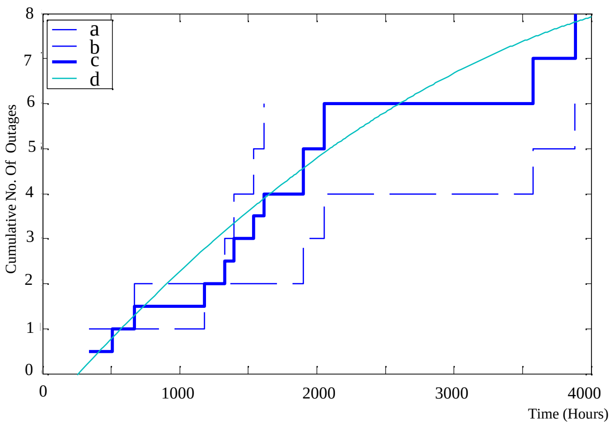

Fig. 3 Cumulative number of outages and its mean and fitting curve

V. Data Collection

In this study, the converter performance has been evaluated using comprehensive empirical data on the FOR as an unavailability index. The empirical data related to the performance of the converters used in this study were gathered using three different sources, i.e. archival records, interviews, and documents.

The archival records consisted of the operational and maintenance history of the TPS system and its converters, from January 2007 until June 2010, as stored in the "0Felia" database of the Swedish Transport Administration (Trafikverket).

"0Felia" is a fault reporting database that gathers data covering all the significant events for infrastructure systems, i.e. dates of events, descriptions of faults, failed components, descriptions of maintenance, the time spent on repair, maintenance release times, descriptions of corrective maintenance, etc... [13].

The historical data cover the 76 rotary and 58 static converters which are distributed among the 46 frequency converter stations in the Swedish railway system. The major challenges in the data collection were related to incomplete and conflicting timing. For example, sometimes the recorded time spent on repair does not represent the real repair time. In addition, some data are ambiguous and meaningless. Moreover, there are minor and major faults recorded in the database, and sometimes the minor faults do not lead to an outage. This lack of information can be considered as one of the disadvantages of this database, and in the present study all of the faults have been assumed to lead to an outage.

The interviews were performed with experienced practitioners at the Swedish Transport Administration, including both project and field technicians in the Operation and Maintenance Departments. The interviews and discussions supported the researchers in solving the challenges faced concerning the data collection, filtering and validity.

The documentation used as a source of data consisted of different descriptions, policies, and procedures pertaining to the operation, maintenance and reliability analysis of the TPS system and converters, as well as documents and standards supporting reliability analysis of TPS, such as IEEE and IEC documents, etc.

VI. Data Analysis

Fig. 4 shows the procedure of dealing with the raw data to perform the failure analysis calculations of this paper.

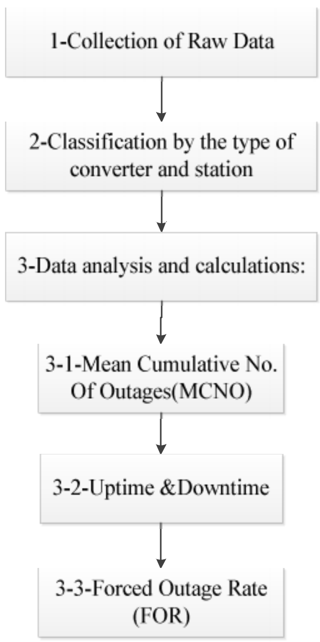

Fig. 4 Flowchart of the data analysis

For a preliminary analysis, we found the number of outages in each type of converter for the whole population of frequency converters, after which we calculated the up-time and down-time for all the converters, and then the FOR values for each converter and converter station.

In fact, the number of outages and the FOR give us a picture of the availability performance of the converters that lead to a reduction in the whole capacity of a converter station. Comparing these two indexes is also helpful in identifying the areas where extra resources are needed to improve maintenance planning and where improvements can reduce the outage in the TPS system.

However, the challenge of identifying the original causes of the outages still remains, i.e. of identifying whether the down-time is due to low reliability or low maintainability. Therefore, one also needs to consider the reliability characteristics of the converters and their failure modes, to make better suggestions for improvement, e.g. concerning maintenance planning, the modification of converters, or fault diagnosis for improvement of the maintainability.

Therefore, an analysis based on the number of outages and the FOR has been used in this paper to compare and evaluate the unavailability of the frequency converter stations in the Swedish TPS system. We can observe clearly the difference in the number of failures and the trend for each type of converter over a period of more than three years by using the mean cumulative number of outages (MCNO). Figs. 5 and 6 show the MCNO for the static and the rotary stations, respectively.

With regard to the number of outages for the static frequency converter stations, Fig. 5 shows that there is a big difference in the number of outages between all the stations, but the *Åstorp* and *Nässjö* stations have a particularly big number of outages compared to the others, and the number of failures in these stations continues to increase due to a convexity trend. As shown in Fig. 5, the *Åstorp* and *Nässjö* stations experienced an increasing rate of occurrence of outages by calendar time and suffered a much higher number of outages in comparison with the other stations.

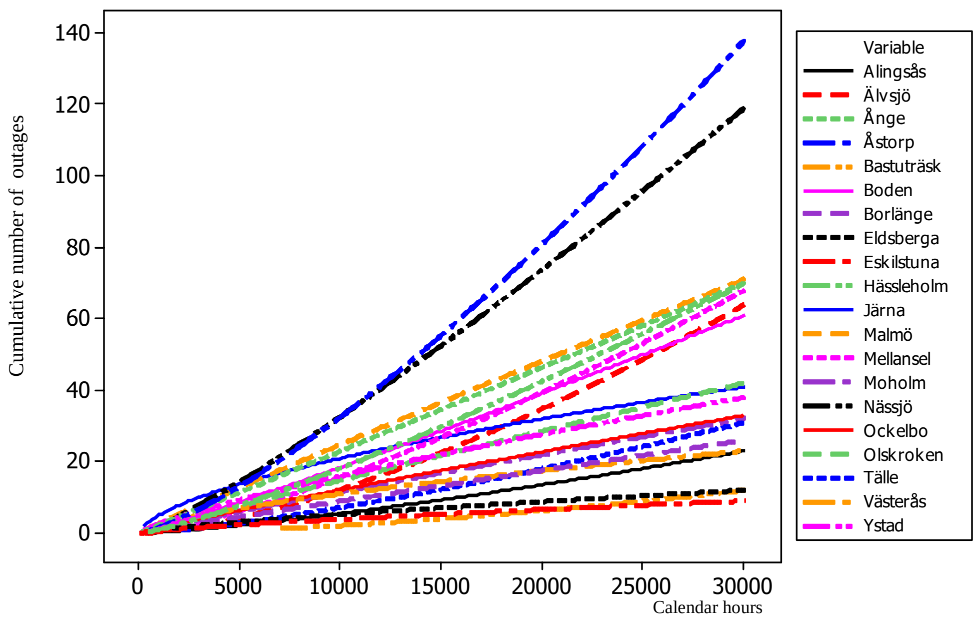

Fig. 5 Cumulative number of outages for the whole population of static stations

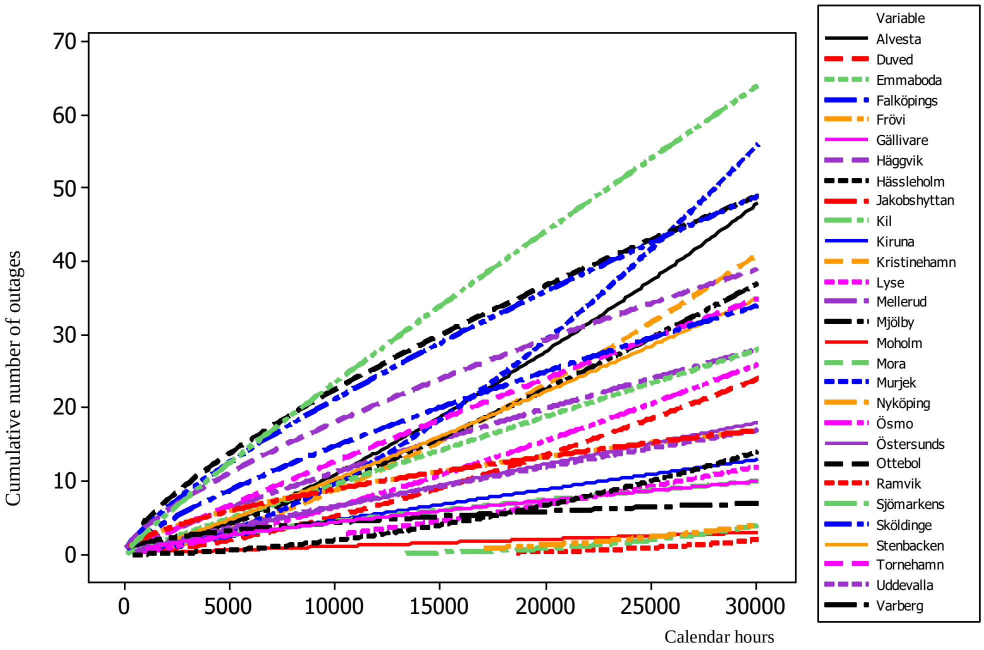

Fig. 6 Cumulative number of outages for the whole population of rotary stations

In addition, it is obvious that the *Älvsjö*, *Mellansel*, *Hässleholm*, *Malmö*, and *Ånge* stations have around 60 outages within the study period, which is a higher number than that experienced by other stations, e.g. *Olskroken*, *Ystad*, *Järna*, *Ockelbo*, *Moholm*, *Tälle*, *Borlänge*, *Västerås*, and *Alingsås*, which suffered around 20 outages. *Eldsberga*, *Bastuträsk*, and *Eskilstuna*, on the other hand, have around 10 outages within the study period.

Fig. 6 shows that the *Kil* station has the highest number of outages among all the rotary stations, and that *Kil's* outages occurred at a constant rate. It is also obvious that, while the number of outages at the *Alvesta* and *Murjek* stations was quite low in the early stages, it then increased rapidly due to an increasing rate of occurrence (see the convexity trend of the associated curves). Fig. 7 shows the MCNO for the whole population of both rotary and static converter stations. It shows clearly that there is a big difference between them in that the static stations experienced a big number of outages, i.e. around 50, within the study period, while the rotary stations suffered around 25. The MCNO of the static stations has a slight convexity trend and a high number of outages due to the worsening of stations mentioned above, see Fig. 5.

It should be noted that the MCNO alone is not sufficient as a means to compare the station outages, due to the fact that there is no information on the duration of the outages. Therefore, the FOR was also used here to show the average unavailability of the converter stations, and this provided greater clarity as to which station had a high unavailability. Hence, a combination of the FOR and the MCNO gives a better picture of the availability/unavailability of the stations.

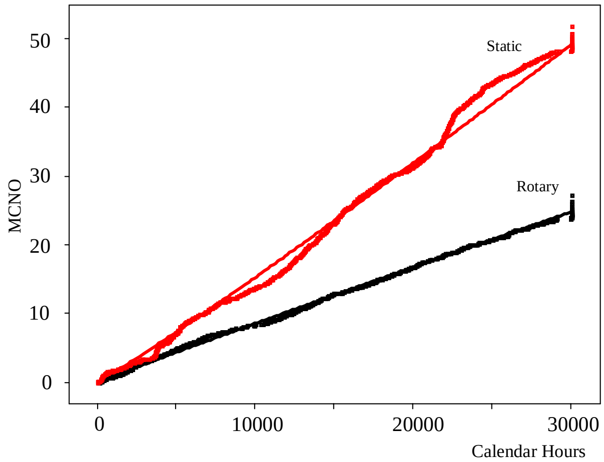

Fig. 7 The mean cumulative function for all the static and rotary stations

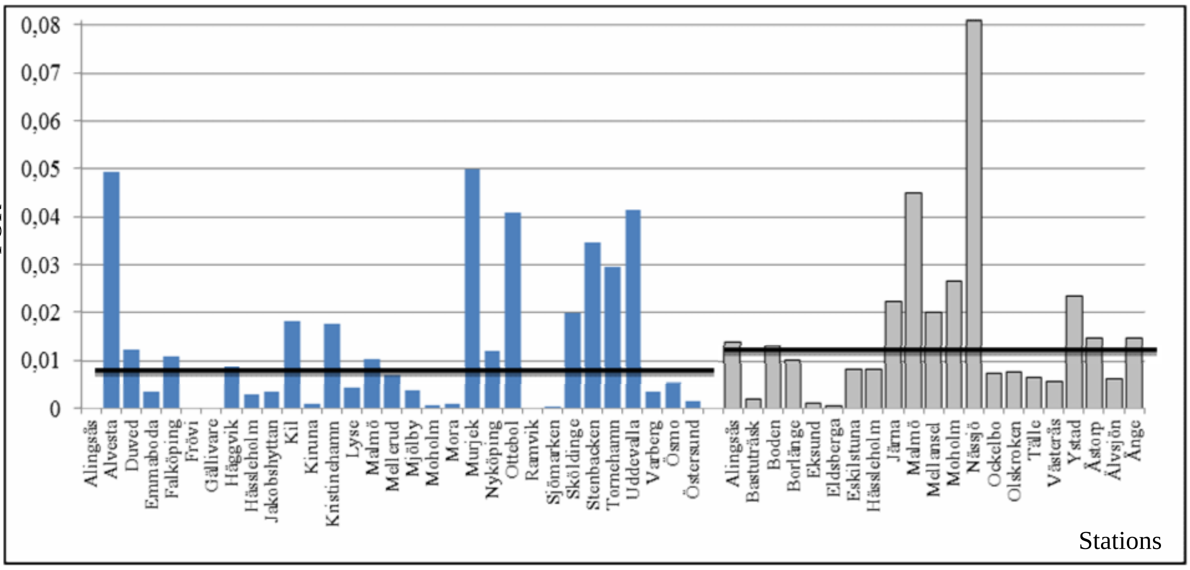

Fig. 8 Forced outage rate, Rotary converter stations, Static converter stations

Fig. 8 shows the FOR values for the converter stations covered in this study. As is evident from the figure, the average FOR value for the static stations (FOR=0.016) is greater than that for the rotary stations (FOR=0.013). However, if we remove the *Nässjö* and *Malmö* stations, the FOR value for the static stations is reduced to 0.0111, which is less than the FOR value for the rotary stations. The *Nässjö* and *Malmö* stations have the highest FOR values, i.e. 0.081 and 0.046, respectively.

The *Åstorp* (static) and *Kil* (rotary) stations have the highest number of outages, while the associated FOR values are relatively small. Moreover, it is clear that the *Nässjö, Malmö, Moholm, Järna, Ystad,* and *Mellansel* stations have a high percentage of FOR around 20% – 81%, for the static converters, but not all of them have a high number of outages. The *Moholm* station has a high FOR value, while it has a relatively small number of outages. This may indicate a difficulty in remedying the associated failure modes at those stations, e.g. due to bad accessibility, failure mode complexity, the age of the system, or perhaps even repetitive no-fault-found problems.

According to Fig. 8, *Murjek, Alvesta, Uddevalla, Ottebol, Stenbacken, and Tornehamn* have the highest number of outages among the other stations (29% - 50%). Fig. 5 shows clearly that the rate of occurrence of outages in these stations has convexity behaviour.

VII. Conclusion

The electrified railway plays a vital role in modern transportation and social development. The frequency converter is the main source of the traction power required by electric trains. The purpose of this paper is to make a survey of the outages in converters and to compare the unavailability of rotary and static converters through the outage rate and the number of outages. The mean cumulative number of outages (MCNO) and the forced outage rate (FOR) has been used to study the outages of the converters in the Swedish TPS system.

The number of outages and the FOR give a good picture of the performance of the converter stations and their maintenance teams, but one of these values alone does not reflect reality.

It has been found that the *Åstorp* and *Nässjö* stations experienced an increasing rate of occurrence of outages by calendar time, with a much higher number of outages compared with the other stations. In addition, the *Älvsjö*, *Mellansel*, *Hässleholm*, *Malmö*, and *Ånge* stations had around 60 outages within the study period, which is a higher number than that experienced by other stations, e.g. *Olskroken*, *Ystad*, *Järna*, *Ockelbo*, *Moholm*, *Tälle*, *Borlänge*, *Västerås*, and *Alingsås*, which suffered around 20 outages. *Eldsberga*, *Bastuträsk*, and *Eskilstuna*, on the other hand, experienced around 10 outages within the study period.

It has also been found that the *Kil* station has the highest number of outages among all the rotary stations, and that *Kil's* outages occurred at a constant rate. It is also obvious that, while the number of outages at the *Alvesta* and *Murjek* stations was quite low in the early stages, it then increased rapidly due to an increasing rate of occurrence (see the convexity trend of the associated curves). It is also evident that, although the number of outages at the *Hässleholm*, *Sköldinge*, and *Häggvik* stations was quite high during the period, they show a decreasing rate of occurrence.

Based on the results of the study, the average FOR value for the static converters (FOR=0.016) is greater than that for the rotary converters (FOR=0.013). However, if we remove the *Nässjö* and *Malmö* stations, the FOR value for the static converters is reduced to 0.0111, which is less than that for the rotary stations. The *Nässjö* and *Malmö* stations have the highest FOR values, i.e. 0.081 and 0.046, respectively.

Furthermore, it has been found that the *Åstorp* (static) and *Kil* (rotary) stations have the highest number of outages, while the associated FOR values are relatively small. This may indicate a good performance on the part of the maintenance groups of these stations in remedying the associated failure modes there. Moreover, it is clear that the *Nässjö*, *Malmö*, *Moholm*, *Järna*, *Ystad*, and *Mellansel* stations have a high percentage of FOR around 20% – 81%, for the static converters, but not all of them have a high number of outages. The *Moholm* station has a big FOR value, while it has a relatively small number of outages. This may indicate a difficulty in remedying the associated failure modes at those stations, e.g. due to bad accessibility, failure mode complexity, the age of the system, or perhaps even repetitive no-fault-found problems.

Finally, *Murjek*, *Alvesta*, and *Stenbacken* have a convexity trend, while *Uddevalla*, *Ottebol,* and *Tornehamn* have a concavity trend, but all of these stations have a high number of outages among the others (29% - 50%).

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