Availability Assessment of the HVDC Converter Transformer System

R. Leelaruji, J. Setréus, *Graduate Student Member, IEEE*,
G. Olguin, *Member, IEEE*, L. Bertling*, Member, IEEE*

***Abstract*-- This paper presents a reliability assessment of the HVDC converter transformer system (CTS) comparing different component models and configurations. The CTS model is based on the Markov modelling approach, which is shown to be well suited for these relatively small systems. The failure rate data in the models is based on statistical surveys by CIGRÉ.**

A number of scenarios are calculated in order to evaluate the impact of the availability of the CTS given different conditions. The result shows on the benefit in availability using a spare transformer, particularly at a close location of the HVDC station.

***Index Terms*--HVDC transmission, Markov processes, Converter Transformer, Power transmission reliability**

I. INTRODUCTION

High Voltage Direct Current (HVDC) transmission system has become a mature and well accepted technology. HVDC is today recognized as an effective and efficient means of transmitting bulk power over long distances through overhead lines. HVDC is also being increasingly applied in undersea and underground cable links and in interconnections of two asynchronous power systems.

The availability of HVDC systems has always been of primary concern in the planning and operation of power systems. The reliability requirements differ from project to project and are specified at a very early stage of the project. The system is always designed and built with a certain degree of reliability, i.e. it is possible to guarantee a particular level of availability of the HVDC system. The total availability of an HVDC system depends on the reliability of the components in the line and at the stations. Redundancy in system, existence of spares and maintenance practices will affect the availability.

Among the various components and subsystems existing at an HVDC station, the converter transformer system (CTS) has a significant impact on the total availability of the HVDC system. Depending on the design of the HVDC station and the existence of spare transformers, a single failure affecting the availability of one of the converter transformers can lead to a total outage of the link with a duration as long as three months. This sort of transformer is rarely a stock product. To improve the availability of the HVDC station, spare transformers are usually provided so that in case of a major failure, a switching-to-spare action can be taken to restore the link as soon as possible. This leads to the fact that the availability of an HVDC station also depends on the existence of spare converter transformers. Moreover, spare transformers can be located at one or both stations, at supplier facilities located in the same country or overseas. Nevertheless, spare units are costly and this has to be taken into the account when the balance between the additional cost and the improved performance is considered. Therefore, the evaluation of the expected availability of the CTS of HVDC stations is of most importance in the decision making.

In this paper, the availability assessment of the HVDC CTS is performed by constructing and solving Markov models. Such models provide an effective method to assess the expected availability of different CTS solutions. They also allow the analyst to assess the impact of different strategies for the availability of spares transformer units at site or other facilities. Markov models for single-phase and three-phase based CTS with one or two failure modes are considered. This sort of models has been presented before, for example in [1] with a three-phase CTS with one spare in, but in this paper we take the reliability assessment a bit further by including realistic failure rate data from CIGRÉ and by performing sensitivity analysis on the models. This paper is based on Master thesis [2], where several more CTS arrangement has been modelled.

II. MARKOV MODELLING

Markov models can be used in reliability assessments to model the stochastic processes of systems. Markov modelling implies the assumption of a system event process with no memory. This means that the future states for the system are independent of all past states except the immediately preceding one [3]. The stochastic process of the system also needs to be stationary or time-homogenous, meaning that the behaviour of the system must be the same at all points of time. This leads to the basic characteristic of Markov modelling that the probability of making a transition between two specific states is constant at all times in the model.

A Markov model can be applied to systems whose random behaviour varies either discretely or continuously with time. The discrete case of Markov modelling is referred to as Markov chain and the continuous as a Markov process. In this paper the Markov process has been adopted. Fig. 1 shows a

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G. Olguin was with ABB Corporate Research, Västerås, Sweden during the work with this paper, but is now with TRANSELEC S.A. Santiago, Chile.

E-mail: rujiroj.leelaruji@ee.kth.se, johan.setreus@ee.kth.se

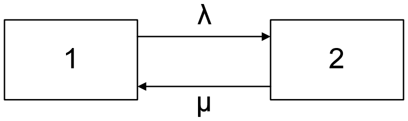

Fig. 1. State space transition diagram of a two-state Markov process.

basic example of a Markov process in a state space transition diagram. This diagram is a convenient way of illustrating the system states and transition rates between the states.

The formal definitions behind Markov modelling and relatively advanced theory of e.g. Hidden-Markov processes are beyond the scope of this paper. General system reliability theory for Markov models can be found in e.g. [3]. Furthermore, in [4] the authors present a good basis to Markov models and their ability to model repairable systems with a repair time that is not negligible and systems with spare components.

In this paper, only the equations for calculating the steady state solution of the system are presented. This solution gives the probability of being in a certain state after an infinitive time in the system. It can be shown that this steady state solution can be found by solving the equation system in (1).

$$\begin{gathered} \pi Q = 0 \\ \sum_i \pi_i = 1 \end{gathered} \tag{1}$$

Here, π is a row vector whose *i*:th element π_i is the steady state probability of being in the *i*:th state. The transition rate matrix Q for the Markov process is specified in (2). In this matrix q_{ij} is the transition rate from state *i* to state *j*. The diagonal elements in, q_{ij}, are defined in (3).

$$Q = \begin{bmatrix} q_{11} & \cdots & q_{1n} \\ \vdots & q_{ij} & \vdots \\ q_{n1} & \cdots & q_{nn} \end{bmatrix} \tag{2}$$

$$q_{ii} = -\sum_{\substack{j=1 \\ j \neq i}}^{n} q_{ij} \tag{3}$$

III. HVDC TECHNOLOGY

A. System overview

The HVDC technology is used to connect two AC systems or nodes having the same or different frequency, synchronous or not [5]. The applications of HVDC are many, but to mention a few it is used for (i) long distance bulk power transmission, (ii) asynchronous interconnection between networks, (iii) stability and voltage support within networks, (iv) integration of distributed generation, such as wind power. There are two major HVDC techniques on the market; HVDC Classic and HVDC Light. In this paper HVDC stands for HVDC Classic and is the only technique considered.

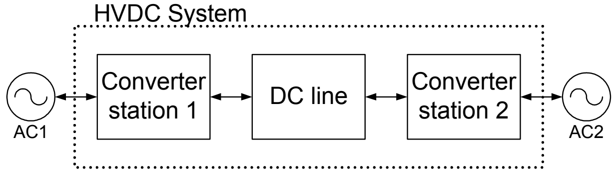

Fig. 2. Schematic picture of a typical HVDC transmission system.

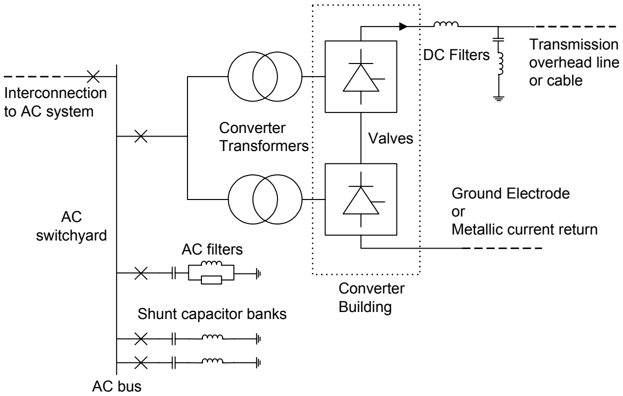

Fig. 3. Single line diagram of a typical monopolar HVDC converter station with a 12-pulse valve configuration.

Fig. 2 shows a simplified schematic picture of an HVDC system, with the basic principle of transferring electric energy from one AC system or node to another, in any direction. The system consists of three blocks; the two converter stations and the DC line. Within each converter station block there are several components involved in the conversion of AC to DC and vice versa. Fig. 3 shows a single line diagram of a typical converter station for a Monopolar HVDC system. This HVDC system configuration is commonly used for long undersea cable transmissions. The left part in the figure summarizes the components in the AC switchyard, which includes circuit breakers, filters and equipment for reactive power compensation. The next block, the converter transformers, is the component that is assessed in this paper. The name converter transformer arises from the slightly different design and requirements these types of transformer has compared to a conventional transformer. It serves as a galvanic isolator between the AC and the DC side and transforms the voltage to an appropriate and optimum level for the converter valves that converts the AC to DC. The DC is then filtered before entering the cable or line depending on application.

B. The HVDC Converter transformer system

Nearly all HVDC Classic stations in the world are designed with converter valves connected in a twelve-pulse configuration in order to reduce the dominant current harmonics. This configuration is in is turn built up with two six-pulse valve groups connected in series, as shown in Fig. 3. Each of these two is connected to the AC side via the converter transformers with a 30 degree phase difference. This is obtained by a Y/Y transformer connection to the first group and Y/Δ connected to the second one, as illustrated in Fig. 4 with two three-phase transformers. This standard twelve-pulse

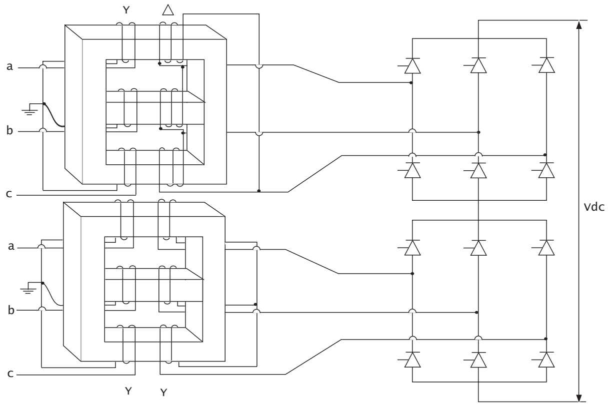

Fig. 4. Two three-phase two-winding transformers connected to the twelve-pulse converter valves, at the right, with a 30 degree phase shift.

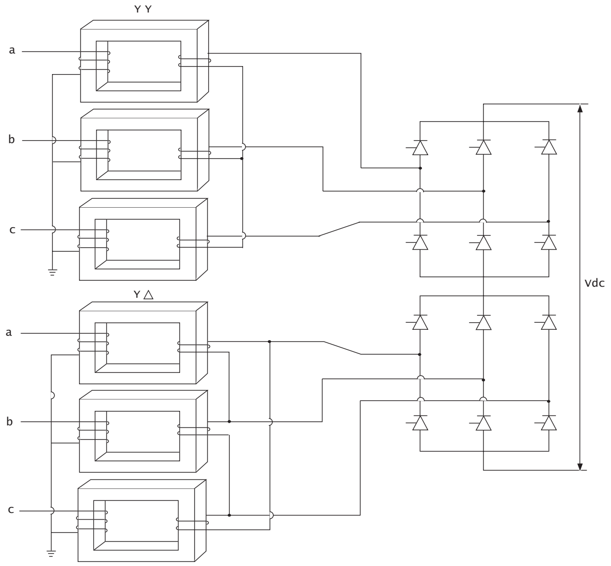

Fig. 5. Six single-phase two-winding transformers connected to the twelve-pulse converter valves, at the right, with a 30 degrees phase shift.

CTS can, however, be constructed in one of the following arrangements [6]:

- Two three-phase two-winding transformers (Fig. 4)
- Six single-phase two-winding transformers (Fig. 5)
- Three single-phase three-winding transformers(Fig. 6)
- One three-phase three-winding transformer (Fig. 7)

The decision making when designing the CTS with either single-phase or three-phase units with two- or three-winding transformers depends on many factors such as the voltage and power rating and system size. Each of the CTS arrangements has its own advantages and motivations. The single-phase unit has less limitation in term of transportation and is also attractive from the point of view of spares since the same single-phase spare transformer can be designed to be used in both the Y-fed and Δ-fed 6-pulse converter group. With the CTS with three-winding transformers only half of the units are needed, as can be seen by comparing Fig. 5 and Fig. 6. However, for large HVDC installations the high power rating will make these large transformer units impractical.

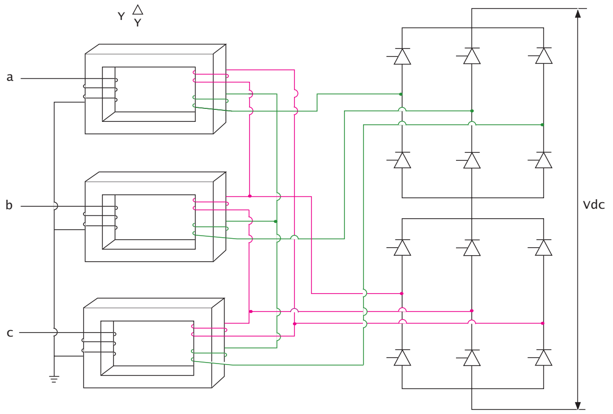

Fig. 6. Three single-phase three-winding transformers connected to the twelve-pulse converter valves, at the right, with DC side windings with30 degrees phase shift.

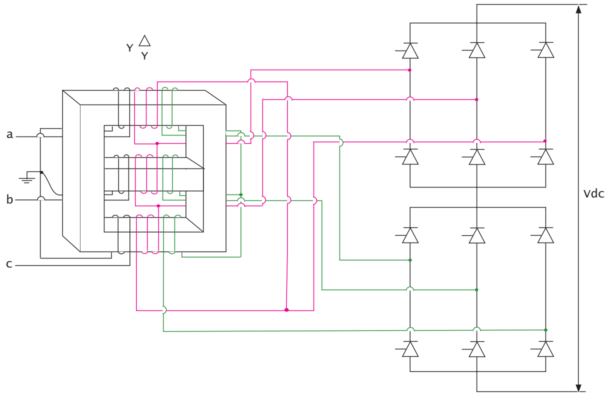

Fig. 7. One three-phase three-winding transformer connected to the twelve-pulse converter valves, at the right, with DC side windings with30 degrees phase shift.

IV. ASSESSED CONVERTER TRANSFORMER SYSTEMS

The following three CTS arrangements are modelled and evaluated in this paper:

CTS 1: Three single-phase three-winding (SPTW) transformers, as shown Fig. 6. One spare unit is available offsite. The transformer has been modelled with one failure mode and all failures are considered to be major.

CTS 2: Three single-phase three-winding (SPTW) transformers, as shown Fig. 6. One spare unit is always available onsite. If the spare unit is going to be used, an additional spare unit is ordered to the site. The transformer has been modelled with one failure mode and all failures are considered to be major.

CTS 3: One three-phase three-winding (TPTW) transformer, as shown in Fig. 7. One spare unit is available onsite. The transformer has been modelled with two failure modes: major and minor failures.

Converter transformer failures have in this paper been categorized into minor and major (catastrophic) failure modes [7]. These two modes have different characteristics. A minor failure is a short duration outage in which the failed-unit can be repaired onsite without using the spare unit. A major failure is a long duration outage and the failed-unit cannot be repaired onsite due to its severity of the damage. This type of failure requires the removal of the unit in order to repair it and if a spare unit is available it can be replaced immediately. The restoration process of the major failure, failed-units are normally sent to a central shop for which may take between one and two years depending on the nature of the failure [8].

The failures should be clearly investigated and identified the actual cause. The online monitoring may be used on suspect converter transformers to provide an early indication of transformer deterioration [9]. Many of the failures are associated to lack of appropriated test. In order to decrease the failures, the additional tests should be carried out at the manufacturers' plant before delivery. The report failure descriptions are required to support the monitoring and design review recommendations.

V. MARKOV MODELS

A. *Markov model assumptions*

The following fundamental assumptions are made for the CTS arrangements to be able to use the Markov modelling technique:

- The components are modelled with a constant failure, repair and installation rate.
- An incremental interval of time is sufficient small that the probability that two or more transitions occurring can be neglected.

The following specific assumptions have been made for the developed CTS models:

- The repair and transportation resources are assumed to be unrestricted, i.e. as soon as the transformer fails, the restoration is started irrespective of the situation in other units. Each unit is assumed to have its dedicated repair crew.
- When a repair is completed, or a new unit arrives from being transported, the unit is assumed to be as good as new.
- No common mode failures have been considered in the models.
- A spare unit or a shut down transformer is assumed to be ideal and can not fail in the standby mode.

B. *Model symbols*

λ_T = Total failure rate of TPTW [f/yr]
λ_1 = Major failure rate of TPTW [f/yr]
λ_2 = Minor failure rate of TPTW [f/yr]
λ_3 = Total failure rate of SPTW [f/yr]
μ_1 = Restoration rate after major failure [1/hrs]
μ_2 = Restoration rate after minor failure [1/hrs]
γ = Re-installation rate of transformer [1/hrs]

C. *Markov model for the CTS*

1) CTS 1:

Fig. 8 shows the state diagram of the CTS 1 arrangement. All three single-phase three-winding transformers needs to be functional in order for the CTS to be functional. The functional state for the CTS is state (1). In state (2) and (3) the system is shut down and the transformers are not energized.

All failures in this model are considered to be major, which means that if it fails it has to be brought to a central shop and is not returned. Instead a new spare unit is transported to the site with a rate of μ_1.

State (1) corresponds to the normal state, where all three transformers are up. When one of the three transformers fails, irrespectively of which, a transition to state (2) occurs, with a rate of $3\lambda_3$, and the operation of the CTS will be shut down. Immediately after the unit fails, a spare unit is ordered to be transported to the site. The transportation rate for the transformer to arrive is μ_1 , from state (2) to state (3). When the transformer arrives it is installed with a rate of γ to state (1).

2) CTS 2:

Fig. 9 shows the state diagram of the CTS 2 arrangement. This CTS arrangement is similar to CTS 1, with the exception that CTS 2 has one spare transformer available onsite. The functional states for the CTS are state (1) and (2). In state (3), (4) and (5) the system is shut down and the transformers are not energized.

All failures in this model are considered to be major, which means that if it fails it has to be brought to a central shop and is not returned. Instead a new spare unit is transported to the site with a rate of μ_1.

State (1) corresponds to the normal state, where all three transformers are up and one spare unit is available on site. When one of the three transformers fails, irrespectively of which, a transition to state (3) occurs, with a rate of $3\lambda_3$, and the operation of the CTS will be shut down. From state (3) the spare unit can either replace the failed transformer with a rate

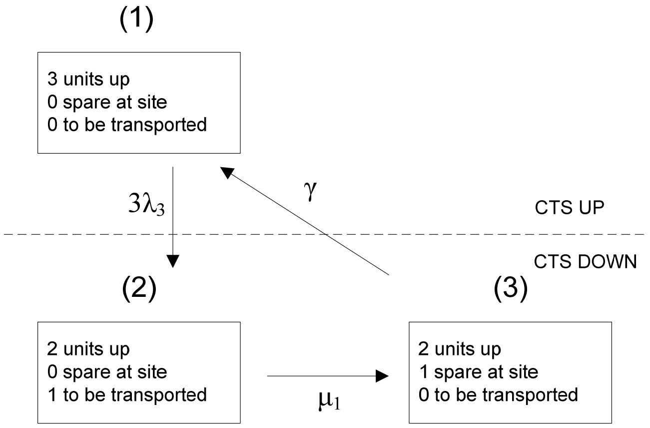

Fig. 8. State space transition diagram for CTS 1, with three single-phase converter transformers and one spare unit available for transport to the site. The transformers have been modelled with one failure mode.

of γ to state (2), or the failed unit can have been replaced and placed besides the other spare in state (5) with a rate of μ_1. In state (2) the CTS is functional and the new replacement spare unit is still being transported. It arrives with a restoration rate of μ_1 and is used as a spare in state (1). If one of the three units fails in state (2) a transition to state (4) is made. Now two units are being transported simultaneously and the transition rate for one of the units to be onsite is $2\mu_1$.

3) CTS 3:

Fig. 10 shows the state diagram of the CTS 3 arrangement. The functional states for the single transformer in the CTS are state (1) and (2). In state (3)-(7) the system is shut down and the converter transformer is not energized. The failure modes for the transformer are either minor or major. A minor failure can be restored without removing the unit. A major failure means that it has to be brought to a central shop and is not returned. Instead a new spare unit is transported to the site with a rate of μ_1. If a spare unit is available onsite, a switching-to-spare action can be made directly.

State (1) corresponds to the normal state, where the transformer in the CTS is functional and one spare unit is available and ready to be used. A major failure in the transformer means a transition to state (3) with a rate of λ_1. From state (3) the spare unit can either replace the failed transformer with a rate of γ to state (2), or the failed unit can have been replaced with a new and placed besides the other spare in state (5) with a rate of μ_1. In state (2) the new replacement unit is still being transported with a rate of μ_1. If arriving, a transition is made from state (2) to (1) and the unit can be used as a spare. If the transformer suffers a major failure in state (2) a transition to state (4) is made. Now two units are being transported simultaneously for their major failures and the transition rate for one of the units to arrive is $2\mu_1$.

In both state (1) and (2) a minor failure of the transformer is possible with a transition rate of λ_2 to state (6) or (7). The minor failure is repaired on site with a rate of μ_2. In state (6) the transformer that suffered a major failure might have been replaced with a new and a transition is in this case possible to state (7) with a rate of μ_1. In state (7) it is assumed that no switching operation is made with the on-site minor failed unit and the now available spare.

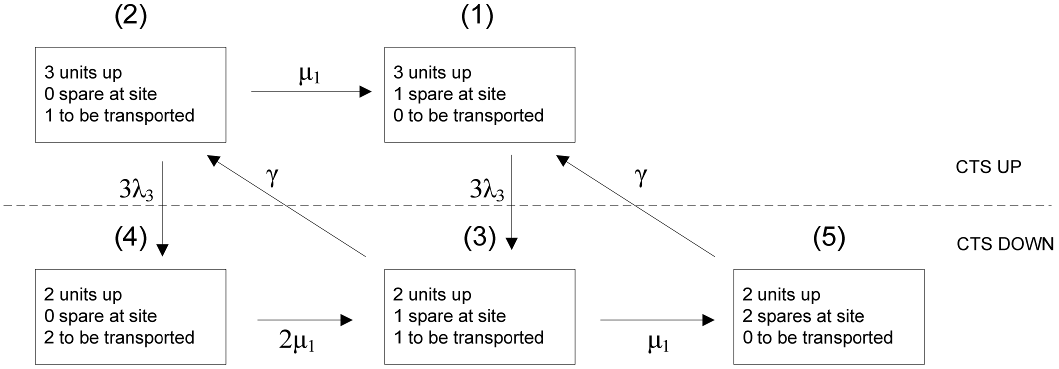

Fig. 9. State space transition diagram for CTS 2, with three single-phase converter transformers and one spare unit available at site at normal operating conditions. The transformers have been modelled with one failure mode.

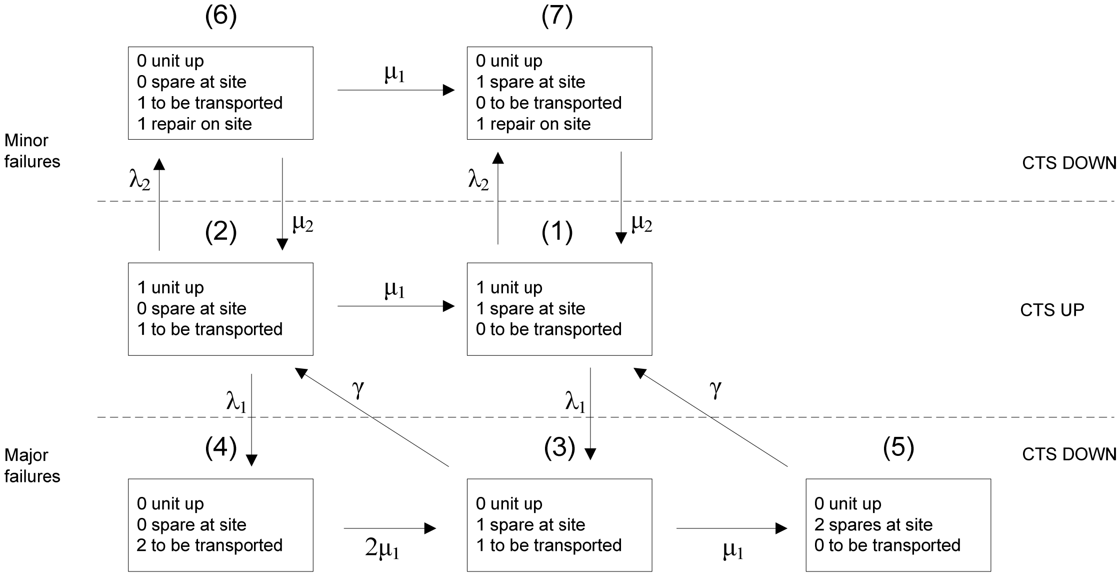

Fig. 10. State space transition diagram for CTS 3, with one three-phase converter transformer, one spare unit and two failure modes; minor and major.

D. Model input data

The failure rate data for the single- and three-phase converter transformers is based on data from [9] by CIGRÉ Joint Task Force B4.04 /A2-1. From this report, where a total of 121 three-phase HVDC converter transformer failures have been recorded, the failures have been classified into major and minor failure modes.

Table 1 presents the average failure rate for the three-phase converter transformer. The failure rate for the single-phase transformer is presented in Table 2.

The restoration and installation time for the transformers is based on assumptions from expert judgements. The restoration time includes the upstart time of the station after a unit as been replaced or repaired.

Table 3 shows the restoration time for major failures in the three-phase converter transformer. A major failure means that it has to be brought to a central shop and is not returned. Instead a new spare unit is brought to the site. Its location could be close to the site or overseas and for this reason seven different scenarios have been constructed to evaluate the impact on the availability of the CTS. No difference in restoration time for single- and three-phase transformers has been considered.

Table 4 shows the restoration time for minor failures of the transformer. Table 5 shows the assumed installation times for the switching-to-spare action.

VI. RELIABILITY ANALYSIS AND RESULTS

The CTS models have been implemented in a Computer Aided Rate Modelling and Simulation tool (CARMS) [10] and solved for a set of reported failure rates. A more detailed result from the analysis can be found in [2].

A. Basic Case

In the first analysis of the modelled CTS arrangements the failure rate of the transformers is unchanged. The restoration time is set to scenario seven; worst case scenario. This means the following input data for the CTS arrangements in the Basic Case:

- CTS 1: $\lambda_3 = 0.0211$ f/yr , $\mu_1 = 0.00046$ 1/hrs
- CTS 2: $\lambda_3 = 0.0211$ f/yr , $\mu_1 = 0.00046$ 1/hrs
- CTS 3: $\lambda_1 = 0.02876$ f/yr, $\mu_1 = 0.00046$ 1/hrs,
  $\lambda_2 = 0.00204$ f/yr, $\mu_2 = 0.08333$ 1/hrs

Table 6 shows the unavailability results for the basic case of the CTS arrangements.

TABLE 1
THE AVERAGE FAILURE RATE FOR THE THREE-PHASE CONVERTER TRANSFORMER, SEPARATED INTO MAJOR AND MINOR FAILURES. DATA COLLECTED FROM CIGRÉ JOINT TASK FORCE B4.04 /A2-1[9].

Type	Failure rate (f/yr)	Symbol
Major failure	0.02876	λ_1
Minor failure	0.00204	λ_2
Total	0.03080	λ_T

TABLE 2
THE AVERAGE FAILURE RATE FOR THE SINGLE-PHASE CONVERTER TRANSFORMER . DATA COLLECTED FROM CIGRÉ JOINT TASK FORCE B4.04 /A2-1[9].

Type	Failure rate (f/yr)	Symbol
Major	0.0211	λ_3

TABLE 3
AVERAGE RESTORATION TIME FOR MAJOR FAILURES IN TRANSFORMERS IN SEVEN DIFFERENT SELECTED SCENARIOS. WHEN A MAJOR FAILURE OCCURS A NEW UNIT HAS TO BE TRANSPORTED TO THE SITE AND THE TIME IT TAKES HIGHLY DEPENDS ON ITS CURRENT LOCATION.

Position of the additional spare unit transformer	How the station is manned	Restoration time (hrs)	Restoration rate, μ_1 (1/hrs)
1. Onsite	24 hrs/day	16	0.06250
2. Onsite	24 hrs/day (On call)	17	0.05882
3. Onsite	8 hrs/ weekdays	48	0.02083
4. Offsite - spare is available at the opposite HVDC station	24 hrs/day	103	0.00971
5. Offsite - spare at factory facilities, same country	24 hrs/day	121	0.00826
6. Offsite - spare at factory facilities, overseas	24 hrs/day	817	0.00122
7. Worst case scenario	-	2160	0.00046

TABLE 4
RESTORATION TIME FOR MINOR FAILURES IN THE TRANSFORMER.

Position	Restoration time (hrs)	Restoration rate, μ_2 (1/hrs)
The transformer is not removed during repair.	12	0.08333

TABLE 5
INSTALLATION TIME FOR THE SWITCHING-TO-SPARE ACTION OF THE SPARE TRANSFORMER.

Position of the spare unit transformer	Installation time (hrs)	Installation rate, γ (1/hrs)
Onsite	15	0.0667
Offsite	24	0.0417

TABLE 6
THE EXPECTED UNAVAILABILITY OF THE THREE CTS ARRANGEMENTS IN THE BASIC CASE (WORST CASE SCENARIO).

CTS arrangement	Expected unavailability (%)	Expected Unavailability (hrs/yr)
CTS 1: SPTW without a spare unit onsite, major failures	1.55%	136
CTS 2: SPTW with a spare onsite, major failures	0.023%	2.0
CTS 3: TPTW with a spare, two failure modes	0.011%	0.96

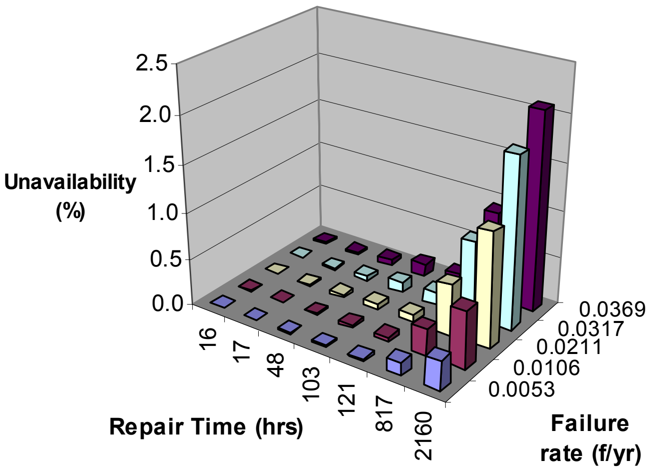

Fig. 11. Graphically representation of the expected unavailability of the CTS1 arrangement for seven different restoration times and five different failure rates.

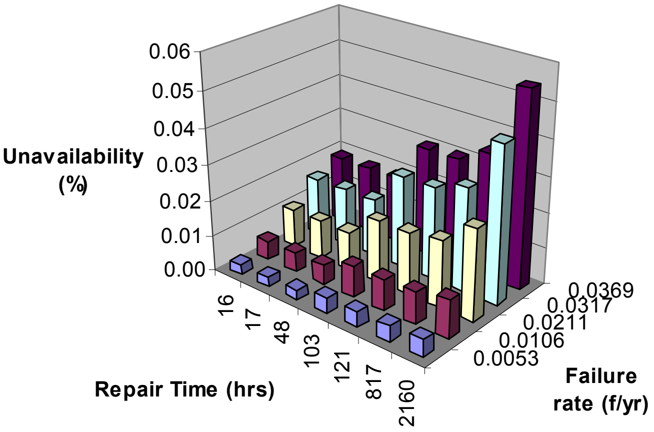

Fig. 12. Graphically representation of the expected unavailability of the CTS2 arrangement for seven different restoration times and five different failure rates.

B. *Sensitivity Analysis*

Sensitivity analyses have been made on the failure rates for the studied CTS models in order to study trends. The failure rates of the transformers have been varied with ±50% and ±75% of their original values, as presented in the basic case. For the CTS 3 arrangement, with two failure modes, the sensitivity analysis is performed on the minor failure rate.

For each failure rate, all scenarios with restoration times in the interval of 16 to 2160 hours have been studied.

The results from the sensitivity analysis are represented graphically in the following figures.

Fig. 11 show a bar diagram of the unavailability in percent for the CTS 1 arrangement. The results are in the interval between 0.003 and 2.116%.

Fig. 12 shows the same type of diagram for the CTS 2 arrangement with a spare normally available onsite. In this case the unavailability is in the interval of 0.003 to 0.055%.

Fig. 13 shows the results for the CTS 3 arrangement. The unavailability results are in this case in the interval of 0.005 to 0.010%.

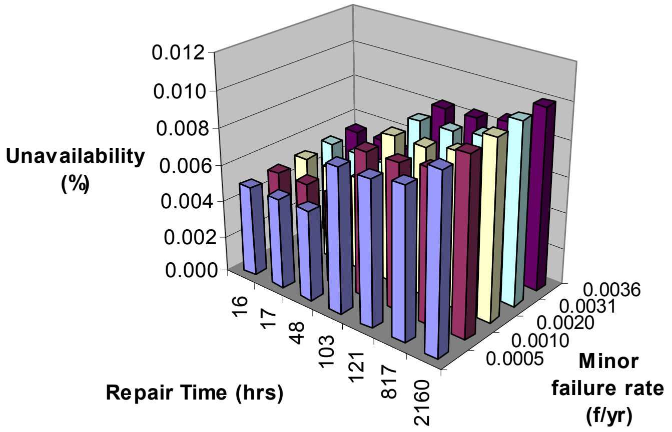

Fig. 13. Graphically representation of the expected unavailability of the CTS3 arrangement for seven different restoration times and five different minor failure rates. The major failure rate is unchanged.

VII. CONCLUSIONS

This paper has shown the benefit of using Markov models in the evaluation of different CTS configurations. Realistic failure rate data from CIGRÉ has been used for the transformers and a sensitivity analysis has been performed on the models. It has been shown that different CTS arrangements, with or without spares, and with several failure modes, can easily be modelled in a state space diagram and then be evaluated with a computer program.

Generally, the major drawback of the Markov technique is that the state diagrams and equations of larger systems become very large and thereby hard to handle practically. However, the CTS for HVDC is normally quite small and therefore suitable for Markov modelling.

According to the results, the three-phase system in CTS 3 provides a higher availability than the single-phase system in CTS 2, despite the fact of a higher individual failure rate for the transformer in CTS 3. The considerable difference in unavailability between CTS 1 and CTS 2 also show the benefit of having a spare unit available onsite for the CTS arrangement. Hence, the location of the spare transformer unit is of great importance for the overall availability of the CTS and thereby also the total HVDC system. Given an approximation of the average outage cost for the HVDC link, the average reliability worth for the CTS can be evaluated with the presented Markov models. This can be valuable in the planning phase of the CTS, especially when deciding the number of spare transformers for the HVDC system and the optimum locations of these.

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IX. BIOGRAPHIES

Rujiroj Leelaruji received the B.Sc. degree in electrical engineering from Sirindhorn International Institute of Technology (SIIT), Thailand, in 2004, and the M.Sc. degree in electric power engineering from Royal Institute of technology (KTH), Stockholm, Sweden, in 2007. He is currently a Ph.D. student within the electric power systems (EPS) research group at KTH. His research interests include dynamic behaviour of power systems, coordination of system protection, HVDC/FACTS controllers and cascading failures. The main theme of the research is to investigate the effectiveness of the interfaces to mitigate blackouts in large interconnected area that suspiciously caused by cascading failures.

Johan Setréus (GSM'06) was born in Stockholm 1980. He received his M.Sc. in electrical engineering in 2006, from KTH - the Royal Institute of Technology, Stockholm, Sweden. He has been held a Ph.D. position at KTH School of Electrical Engineering since 2006 within the research group on reliability-centered asset management (RCAM). The title of his Ph.D. project is "Reliability modeling and design for complex power systems", which will investigate possible benefits and challenges of introducing new technologies for the power system design e.g. HVDC. His research interests also include techniques and methods to combine traditional deterministic criterions in the transmission system with probabilistic methods.

Dr. Gabriel Olguin (M'01) received the B.Sc. degree from University of Santiago, Chile, in 1994, the M.B.A. degree from University of La Serena, Chile, in 1998, the M.Sc. degree in power engineering from the Federal University of Santa Catarina, Brazil, in 1999 and the Ph.D. degree from Chalmers University of Technology, Gothenburg, Sweden in 2005. He was with ABB Corporate Research, Västerås, Sweden where he undertook several studies on HVDC reliability and protection of generators. He is now with TRANSELEC S.A. Santiago Chile. His research interests are HVDC technology and reliability of power systems.

Dr. Lina Bertling (S'98-M'02) is Assistant Professor at KTH School of Electrical Engineering and, Assistant Research Director at Svenska Kraftnät (from 2007), in Stockholm Sweden. She received the Ph.D. in Electric power systems in 2002, and was a visiting postdoctoral student at the University of Toronto, associated with Kinectrics Inc. 2002/2003.

Her research interests are in; reliability assessment and modeling, and maintenance planning for electric power systems and equipments. She was the general chair of the 9th International conference on probabilistic methods applied to power systems (PMAPS) in Stockholm, in 2006. Dr. Bertling is the secretary of the IEEE Sweden Section, and the IEEE PES Subcommittee on Risk, Reliability, and Probability Applications (RRPA), and involved in several IEEE activities including organizing a tutorial on asset management for the IEEE PES GM in Tampa 2007. She is reviewer for several journals, and is engaged as an evaluator by the EU commission. She is a member of the Royal Swedish Academy of Engineering Sciences, and the Industrial Research Group during 2007-2009.