KTH Electrical Engineering

Availability Assessment of HVDC Converter Transformers Using Markov Modeling

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Abstract

High Voltage Direct Current (HVDC) is today recognized as an effective and efficient means of transmitting bulk power over long distances through overhead lines or cables. The reliability of HVDC links have always been of primary concern in planning and operating of power systems. The existence of spares and maintenance practices do affect the availability of HVDC stations. Among the components and subsystems existing at HVDC stations, the converter transformer system (CTS) has a significant impact on the total availability of the HVDC link.

In this work, the availability assessment of the HVDC CTS is undertaken by building and solving Markov-based models. Such models are effective methods 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 spare transformer units at site or other facility. This thesis work presents Markov models for single-phase and three-phase based CTS. Two failure modes are used to model the failure-restoration process of the CTS. The models are implemented in a Computer Aided Rate Modelling Simulation tool (CARMS) and solved for a set of reported failure rates. The thesis also describes the Markov modelling approach for assessing the availability of the CTS of HVDC stations under different scenarios, and illustrates the expected benefits, in term of availability of the HVDC station, of having a spare transformer unit. Plots and tables with the resulting availability of the CTS are used to illustrate the value of the analysis.

***Keywords*:** HVDC, Markov modelling, Converter Transformer, Reliability, CARMS

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Contents

1 Introduction

1.1 Background

High Voltage Direct Current (HVDC) has proven being an effective and economic solution to transport bulk power over long distances [1], [2]. The total availability of a HVDC station depends on several components, for example, AC filter, DC filter, valve hall, capacitor bank, converter transformer. The HVDC converter transformer is one of the most significant components in the HVDC converter station. The station converts Alternating Current (AC) to Direct Current (DC) in either direction. The converter transformer plays a vital role not only in term of the associated cost but also in term of the availability of the HVDC station itself. It affects the performance of the entire connected electric power system. An option to improve availability is the installation of a spare unit for solving an outage result of failures. Failures can be categorized into two typical modes which are minor and major failures. Minor failures are short duration failures. The major failures have severe consequences to the electric utility in terms of increased operation cost or customer load shaded. This failure type is a long duration failure due to its severity and must be repaired offsite. The availability of a HVDC station also depends on the availability of a spare unit. Moreover, spare transformers can be located at both stations, at supplier facilities or only at one of the stations. Nevertheless, a spare unit costs money and this has to be taken into the account when the balance between the additional cost and improve performance is considered.

The research has been performed on reliability assessment at RCAM group of Division of Electromagnetic Engineering, KTH. A Master Thesis by S. Mousavi Gargari [3] provides general idea of the analytical approach that can be applied for any reliability assessment. A Licentiate Thesis by P Fischer de Toledo [4] demonstrated many aspects of HVDC, especially the effect of HVDC to the overall system. Also, the travel report of study visit at SwePol link [5] provides figures and knowledge about HVDC technology.

This thesis has been initiated [6] by ABB Corporate Research and KTH School of Electrical Engineering. The Markov modelling approach for assessing the availability of the converter transformer has been implemented. The models are constructed in different scenarios and the results are presented. Each decision will have an impact on the HVDC station availability. Thereby, the reliability assessment may help to make better decisions.

1.2 Research objective

The objective of this research work is to apply Markov models for evaluating the availability of the HVDC converter transformer systems by using Computer-Aided Rate Modeling System (CARMS) to evaluate which schemes provide the best contribution to the overall system regardless utility cost and station capacity.

1.3 Outline

Chapter 2 introduces the definition of reliability and some associated practical definitions.

Chapter 3 describes the MARKOV modeling approach with basic examples.

Chapter 4 gives an introduction to the HVDC technology. It provides brief detail on system components, mainly on the possible converter transformer system winding connection and the failure modes.

Chapter 5 gives a detailed explanation and description about CARMS software which is used for the assessment that is presented.

Chapter 6 includes the analysis of the assessed models. In this chapter, single-phase and three-phase CTS three winding with one spare unit have been presented and implement in CARMS. The results of reliability evaluation have been introduced in this chapter.

Chapter 7 includes conclusions and discussion of future work.

2 Definitions and terminology

2.1 Definitions of Reliability and Availability

The reliability is used as a general term describing an ability of an item to perform its function measured by a set of quantitative indices. These indices are evaluated to understand the behavior of an item in providing the service. The reliability is defined through the mathematical concept of probability to explain the particular kind of performance. The reliability of an item needs to be expressed by a measure. One of the indices of reliability is the availability. The availability is the fraction of time that item is available to perform its intended purpose. It is also a probabilistic measure equals to the probability of device not being in the failed condition at a specific period. In addition, the brief conceptual definition of reliability and some associated practical definitions are given below. [7]

Definition 1: Reliability *is the ability of an item to perform a required function, under given environmental and operational conditions and for a stated period of time.* [7]

Definition 2: Availability *is the ability of an item (under combined aspects of its reliability, maintainability and maintenance support) to perform its required function at a stated instant of time or over a stated period of time.* [7]

- The availability $A(t)$ at time t = Probability (item is functioning at time t)
- The average availability $A_{av} = \dfrac{MTTF}{MTTF + MDT}$

where MTTF and MDT is Mean Time To Failure and Mean Down Time, respectively. Further explanation of MTTF and MDT will be described in section 2.3

Definition 3: **Unavailability** *is the probability that the item is not in a functioning state.* [7]

Definition 4: **Maintainability** *is the ability of an item, under stated conditions of use, to be retained, or restored to, a state in which it can perform its required functions, when maintenance is performed under stated conditions and using prescribed procedures and resources.* [7]

Definition 5: Failure rate *is the rate at which failures occur as a function of time*. [7]

Definition 6: Repair rate *is the rate that the out of service component will return in service mode during a given time interval.*

Definition 7: Replace rate *is rate that the spare component will be replaced the failed unit and bring the system back to service mode during a given time interval.*

2.2 Reliability theory

In this section, several quantitative measures for reliability of a non-repairable item are introduced and expressed as followings:

The distribution function for a continuous random variable *T* with density function *f(t)* [7] is defined by

$$F(t) = P(T \le t) = \int_0^t f(u)du \text{ for } t > 0 \tag{2.1}$$

The density function for a continuous random variable *T* [7] is defined by

$$f(t) = \frac{d}{dt}F(t) = \lim_{\Delta t \to 0} \frac{F(t+\Delta t) - F(t)}{\Delta t} \tag{2.2}$$

The reliability function is defined by

$$R(t) = 1 - F(t) = P(T > t) \text{ for } t > 0 \tag{2.3}$$

Hence *R(t)* is the probability that the item does not fail in the time interval (0, t] i.e. the probability that the item survives the time interval (0, t] and is still functioning at time *t*. The reliability function *R(t)* is also called the survivor function. [7]

The failure rate function [7] is defined by

$$z(t) = \frac{f(t)}{R(t)} \tag{2.4}$$

In contrast, the notation that describes the failure rate function in chapter 3 is *λ(t)*.

The mean time to failure (MTTF) is defined by [7]

$$MTTF = \int_0^\infty tf(t)dt = \int_0^\infty R(t)dt \tag{2.5}$$

The mathematical functions stated above are applicable to any continuous random variables. More reliability parameters and indices will be given later in this chapter.

2.3 Reliability indices

Reliability indices are significant to numerically describe the reliability of a system, thus to make the comparisons between different systems possible. The basic indices and mathematic relationships are summarized here. The system can be categorized into two types which are repairable and non-repairable system. The distinction between these systems is introduced in this section.

Non- repairable systems

There are two states for non-repairable system, i.e. functional and non-functional (failed). The system that has failed can not be neither replaced nor repaired. Considering an element that is functional at time t = 0 and fails at time t = T, then the interval time (0, T) is called the lifetime of the system. Assumed state 0 and 1 represents failed and functional state, respectively. Figure 2.2 illustrates non-repairable system's characteristic.

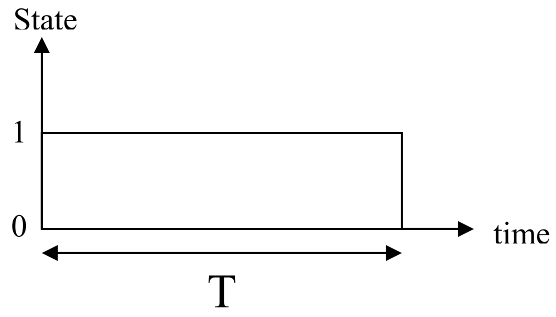


Figure 2.2: Non-repairable system's characteristic

Mean Time To Failure (MTTF) is the time that the system is in the functional state. The failure rate is determined by the reciprocal of MTTF

$$\lambda = \frac{1}{MTTF} \tag{2.6}$$

Repairable systems

For repairable system, the reparation is allowed to apply to the system when failed. Therefore, the characteristic of considered-system is most likely to be a series of state changes between functional and non-functional state as shown in Figure 2.3.

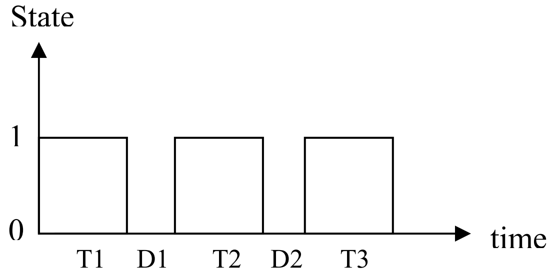


Figure 2.3: Repairable system's characteristic

The Mean Time Between Failure (MTBF) is the summation of functional time (T1+T2+T3+…) divided by functional periods and the Mean Down Time (MDT) is summation of non-functional time (D1+D2+…) divided by number of non-functional period. Both of them are related to failure rate and repair rate as follow:

$$\lambda = \frac{1}{MTBF} \tag{2.7}$$

$$\mu = \frac{1}{MDT} \tag{2.8}$$

The 'Down Time' could be short compared with the time in functional state, sometimes it is assumed, for simplicity, that MTBF approximately equals MTTF. Thus, from now on to the rest of this compendium, the failure rate is equal to the reciprocal of MTTF.

The reliability indices related to availability and unavailability are given through equation 2.9 and 2.10. [9]

$$\text{Availability (A)} = \frac{\mu}{\lambda + \mu} = \frac{MTTF}{MTTF + MDT} \tag{2.9}$$

$$\text{Unavailability (U)} = \frac{\lambda}{\lambda + \mu} = \frac{MDT}{MTTF + MDT} \tag{2.10}$$

From these two equations, one can simply found the relationship between A and U as in equation 2.11

$$A = 1 - U \tag{2.11}$$

3 MARKOV modelling

3.1 Introduction

The Markov modelling approach is a stochastic process that possesses the Markov property. For the Markov modelling approach be applicable, the behaviour of the system must be characterized by a lack of memory (memory less). This means that the future states of a system are independent of all past states except the immediately preceding one [10]. Another property is that the transition probabilities or rates, from one state to other states are assumed to be constant transition rates (stationary) at all time. This property is referred to as time-homogenous.

Markov modelling can be applied to the random behaviour of a system that varies discretely or continuously with respect to time. When the time is discrete, the approach is called Markov chain meanwhile when the time is continuous; the approach is generally known as a Markov process. The Markov chain and Markov process will be explained further in this chapter.

Markov modelling approach, in this thesis, is used to take account the distribution of component failure over time. It is possible to compute the reliability parameters as the long term probability of the system being in a given state by solving a linear differential equation system. The graphical model constructed to display all possible transition paths between states is called state space diagram.

3.2 Markov chains and Markov processes

As mentioned earlier, the Markov models that represent discrete function (time) are generally known as Markov chain. The transition between states must be stationary and the movement in discrete steps which is normally represented by probability. The same conceptual idea is applied to Markov process with the small difference that the transition occurs continuously from one state to another state which is represented by the rate of change, so called transition rate. This transition rate can be differentiated as failure rate and repair rate. The failure rate of components is normally time-dependent but during its functional time after burn in time and before wear out time, it is approximated to have constant failure rate [11]. In this thesis work, the components will be considered to have time-independent failure rates.

3.2.1 State space diagram concept

The basic concept of a state space diagram can be shown as in Figure 3.1. It illustrates the model of single component with two states, functional and failed states. The component can be failed and the terminology of restoration is to bring the components, whenever it is out off order, to functional state under certain interval of time which is called restoration time.

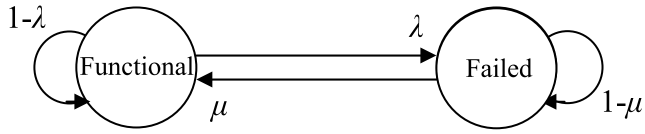


Figure 3.1: One component with two states system

In Figure 3.1, λ and μ represent failure rate and repair rate, respectively.

3.2.2 Stochastic transitional probability matrix

The state space diagram of the Markov model is transformed to the matrix so called transitional probability matrix irrespective if it is a Markov chain or a Markov process. This matrix represents the probabilities of making a transition from one state to another in a single time interval. The transitional matrix for the Markov chain or process can be represented as in Equation 3.1

$$P = \begin{bmatrix} P_{11} & P_{12} & P_{13} & \cdots & P_{1n} \\ P_{21} & P_{22} & P_{23} & \cdots & . \\ P_{31} & P_{32} & P_{33} & \cdots & . \\ . & . & . & & . \\ . & . & . & & . \\ P_{n1} & . & . & & P_{nn} \end{bmatrix} \tag{3.1}$$

In Equation 3.1, P_{ij} is the transition probability from state i to state j.
The diagonal element, P_{ii} is constructed as Equation 3.2

$$P_{ii} = 1 - \sum_{\substack{j=1 \\ j \neq i}}^{n} P_{ij} \tag{3.2}$$

On the other hand, the transitional probability matrix of Markov process is similarly like transitional probability matrix of Markov chain. The basic difference is that a discrete interval of time is not part of the problem specification. An incremental interval of time Δt is introduced, it is sufficiently small that the probability that two or more transitions occurring in the time interval can be neglected. If the failure rate of a component is λ then the probability of a failure transition in time Δt is $\lambda\Delta t$ and if the value of Δt is non-zero and finite, it is convenient to omit and express only the transition rate in the transitional probability matrix.

3.2.3 Limiting state probability evaluation

The steady-state or limiting values of state probabilities can be evaluated by multiplying a sufficient number of the transitional matrix. This multiplication is called the multiplication process [10]. This process can be time-consuming. The principle to evaluate limiting probability states that when the limiting value has been reached, the further multiplication of stochastic transitional probability matrix will not change the value of the state probability. This principle can be expressed through Equation 3.3

$$\alpha P = \alpha \tag{3.3}$$

where α is limiting probability vector
P is stochastic transition matrix

One of the equations developed from 3.3 in order to solve the system of linear equation will always be redundant and therefore it must be replaced by Equation 3.4

$$P_1 + P_2 + P_3 + \ldots + P_n = 1 \tag{3.4}$$

This equation confirms that the summation of every state's probability is equal to one.

3.2.4 Basic example of Markov modeling approach

The following example is provided to show how Markov model approach can be applied to the problems of determining long term probability.

<u>Example 3.1</u> [10]

A man's exercise habits are as follows. If he does his exercise one day, the probability that he is sure not to do them the next day is 0.7. On the other hand, if he does not do his exercise one day, the probability that he is sure not to do them the next day is 0.6. In the long run, how often does he do his exercise?

Figure 3.2 illustrates the state transition diagram of this example. In this diagram, "exercise" state (or state 1) represents a man decides to do exercise whereas "Not exercise" state (or state 2) represents a man decides *not* to do exercise. According to the construction of example, the transition probability from state 1 to state 2 is 0.7, however the total summation of probability is 1.0 thereby it can be implied that the probability that state 1 remains the same state is 0.3. The same methodology is applied in case of state 2 as well.

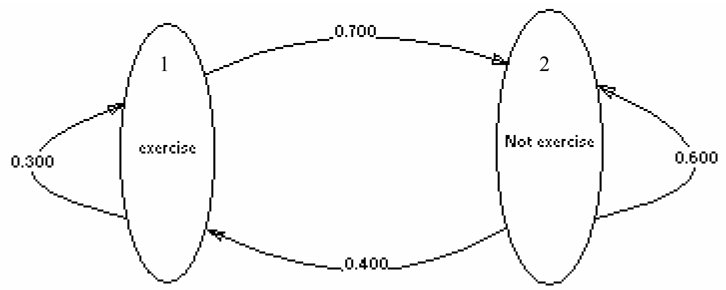


Figure 3.2: State transition diagram of man's exercise habits

Solution is divided into 3 steps

- Step1: Define state indices

  Given "exercise" as state 1 and "Not exercise" as state 2.

- Step2: Generate transitional matrix

  The transitional probability matrix is shown as following

$$P = \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix} = \begin{bmatrix} 0.3 & 0.7 \\ 0.4 & 0.6 \end{bmatrix}$$

- Step3: Apply limiting state probability principle

By applying equation 3.3, then

$$\begin{bmatrix} P_1 & P_2 \end{bmatrix} P = \begin{bmatrix} P_1 & P_2 \end{bmatrix}$$

Or

$$\begin{bmatrix} P_1 & P_2 \end{bmatrix} \begin{bmatrix} 0.3 & 0.7 \\ 0.4 & 0.6 \end{bmatrix} = \begin{bmatrix} P_1 & P_2 \end{bmatrix}$$

where P_1 and P_2 are limiting probabilities of being in states 1 and 2, respectively.

From which;

$$0.3P_1 + 0.4\,P_2 = P_1$$
$$0.7P_1 + 0.6\,P_2 = P_2$$

Rearranging gives

$$-0.7P_1 + 0.4\,P_2 = 0$$
$$0.7P_1 - 0.4\,P_2 = 0$$

Then, replace one of these two equations with Equation 3.4, to obtain

$$\begin{bmatrix} -0.7 & 0.4 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

Consequently;

$$P_1 = 0.364$$
$$P_2 = 0.636$$

From the question, one can conclude that he does his exercise 36.4%
Or this probability can be converted in a unit of hours per year as following

$$P_1 = 8760 \bullet 0.364 \quad \text{[hrs/yr]}$$
$$= 3188.64 \quad \text{[hrs/yr]}$$

3.2.5 Generalization to more complex Markov models

The Markov modeling approach is very applicable. It can be applied to many applications, especially associated with system that has more than two states (functional and failed). The following cases are simple cases to illustrate how useful it is.

Single repairable component with derated state system [10]

Since the failures from different sub-component may result in different system failure modes, a two-state model can be a rather oversimplified representation of the unit's life history. In addition to operating at full capacity and being completely failed, a unit can usually assume a number of other states where it can continue to operate but a reduced capacity. Such states are called derated states. These can occur during the outages of several auxiliaries such as water pump, or under some environmental conditions. An important advantage of state space diagram representation is that it is able to accommodate the derated states in the unit model.

The simplest model to account for derating is the one shown in Figure 3.3. This model can be the water pumps' operational model that has three modes of operation: Full operation if the pump can deliver full output. Partial operation, under some conditions that pump can deliver partial output and Failed, when it can not deliver any water at all. The state space diagram of this Markov model is depicted in Figure 3.3.

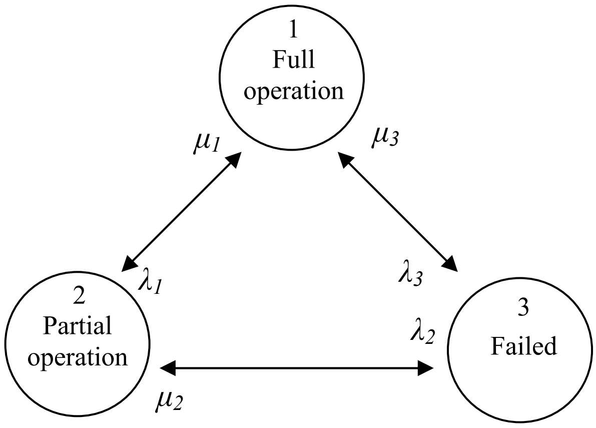


Figure 3.3: State space diagram of component with partial output state

There is one transition path that might be unreasonable i.e. the path from failed state to partial operation state (from state 3 to state 2). When the reparation is applied, it is likely to repair the failed unit back to full operation. In some applications, unit models containing a single derated state may not be sufficiently detailed. Depending on the equipment that has failed, the derated capacity can vary widely and several states may be needed to represent these possibilities. A simplified state space diagram with *n* derated states is illustrated in Figure 3.4 [12]. Transitions between the various derated states are omitted as mentioned reason.

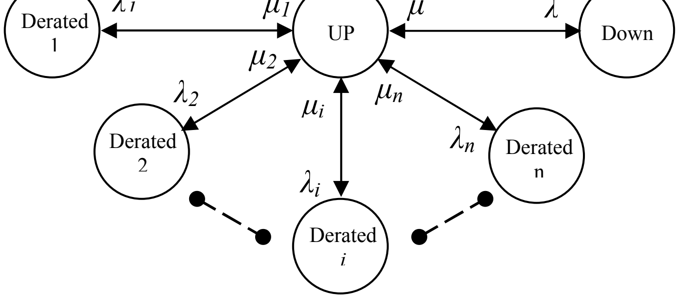


Figure 3.4: Representation of n derated states

Two repairable components system

In this case, there are two repairable components i.e. four possible states which consist of λ_1, μ_1 and λ_2, μ_2 for component 1 and 2, respectively. The state space diagram can be illustrated as in Figure 3.5

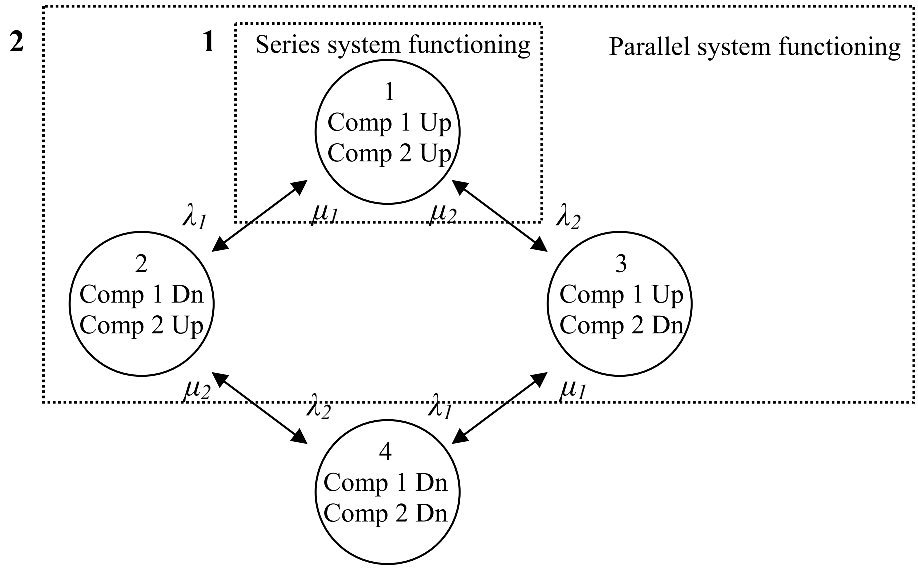


Figure 3.5: State space diagram for two components system

This figure represents the state space diagram of two components regardless whether the components are connected in series or in parallel. The type of system connection (series or parallel) has significant meaning on evaluating probability, for example if this system needs only one component to work (functional) thereby the availability that overall system works is 'box 1', in another word the probability of state 1 (P_1). If the components are connected in series the availability that overall system works is 'box 2' (P_1+P_2+P_3). This can be concluded that series system has lower operating probability compare with parallel system.

The transitional probability matrix if two components work independently to each other, is shown in equation 3.7

$$P = \begin{bmatrix} 1-(\lambda_1+\lambda_2) & \lambda_1 & \lambda_2 & 0 \\ \mu_1 & 1-(\mu_1+\lambda_2) & 0 & \lambda_2 \\ \mu_2 & 0 & 1-(\mu_2+\lambda_1) & \lambda_1 \\ 0 & \mu_2 & \mu_1 & 1-(\mu_1+\mu_2) \end{bmatrix} \qquad (3.5)$$

The number of state in the diagram is 2^n for an n-component with 2-state and will raise if there is a derated state (partial operation)

Three repairable components system

In this case, there are three repairable components, each of which component can exist in two states, i.e. 2^3 = 8 possible states. Figure 3.6 depicts the state space diagram of this system.

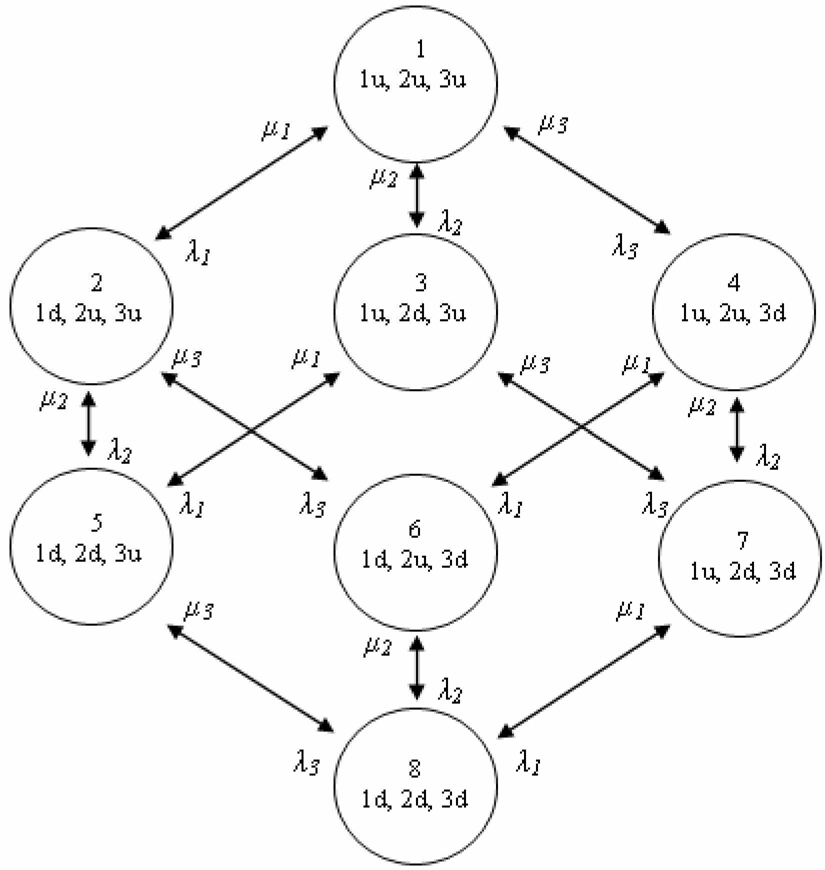


Figure 3.6: State space diagram for three components system

In Figure 3.6, assume the system is in “1u, 2u, 3u” states (or state1) which means all three components are functional. Regarding the sequence arrangement of the component, the first transition may either be to state 1d, 2u, 3u -first unit ‘down’ (fail) the others are up-, in another word state 2 or to state 1u, 2d, 3u –second unit down and the others are up- (state 3), or either to state 1u, 2u, 3d -third unit down and the others are up (state4). The transition rates are λ_1, λ_2, and λ_3 respectively. When the system is in state 1d, 2u, 3u, the next transition may be either be to state 1u, 2u, 3u (state 1) with the rate μ_1 or to state 1d, 2d, 3u (state5) with the rate λ_2 or to state 1d, 2u, 3d (state 6) with the rate λ_3. Moreover, at state 5, the next transition maybe be either be to state 2 or to state 3 or 1d, 2d, 3d (state 8) with the rate of μ_2, μ_1 and λ_3 respectively. At state 1d, 2d, 3d, this means that all three components are all failed. The component status can be concluded as shown in table 3.1

System State	Unit1	Unit2	Unit3
1: 1u, 2u, 3u	Functioning	Functioning	Functioning
2: 1d, 2u, 3u	Failed	Functioning	Functioning
3: 1u, 2d, 3u	Functioning	Failed	Functioning
4: 1u, 2u, 3d	Functioning	Functioning	Failed
5: 1d, 2d, 3u	Failed	Failed	Functioning
6: 1d, 2u, 3d	Failed	Functioning	Failed
7: 1u, 2d, 3d	Functioning	Failed	Failed
8: 1d, 2d, 3d	Failed	Failed	Failed

Table 3.1: Possible states of three components system

The evaluation of the availability is considered differently when the components are connected in different way as shown as following.

Series connection: System functioning mode → state 1
System failed mode → state 2, 3, 4, 5, 6, 7, 8

Parallel connection: System functioning mode → state 1, 2, 3, 4, 5, 6, 7
System failed mode → state 8

2-out-of 3 system: System functioning mode → state 1, 2, 3, 4
System failed mode → state 5, 6, 7, 8

The transitional probability matrix if three components work independently to each other, is shown in equation 3.6

$$P = \begin{bmatrix} 1-(\lambda_1+\lambda_2+\lambda_3) & \lambda_1 & \lambda_2 & \lambda_3 & 0 & 0 & 0 & 0 \\ \mu_1 & 1-(\mu_1+\lambda_2+\lambda_3) & 0 & 0 & \lambda_2 & \lambda_3 & 0 & 0 \\ \mu_2 & 0 & 1-(\mu_2+\lambda_1+\lambda_3) & 0 & \lambda_1 & 0 & \lambda_3 & 0 \\ \mu_3 & 0 & 0 & 1-(\mu_3+\lambda_1+\lambda_2) & 0 & \lambda_1 & \lambda_2 & 0 \\ 0 & \mu_2 & \mu_1 & 0 & 1-(\mu_1+\mu_2+\lambda_3) & 0 & 0 & \lambda_3 \\ 0 & \mu_3 & 0 & \mu_1 & 0 & 1-(\mu_3+\mu_1+\lambda_2) & 0 & \lambda_2 \\ 0 & 0 & \mu_3 & \mu_2 & 0 & 0 & 1-(\mu_3+\mu_2+\lambda_1) & \lambda_1 \\ 0 & 0 & 0 & 0 & \mu_3 & \mu_2 & \mu_1 & 1-(\mu_3+\mu_2+\mu_1) \end{bmatrix} \quad (3.6)$$

4 Overview of the HVDC Technology

4.1 Introduction

A High Voltage Direct Current (HVDC) link allows the transferring of electrical energy in the form of direct current. The high voltage transmission is interesting because higher transmission voltage improves the efficiency of transmission by reducing the transmission power loss, consequently the cost per megawatt of conductors is decreased when transmitting a given quantity of power. The HVDC system transmission consists of three main components, which are one converter station at the sending end, the transmission either overhead line or cable, and the converter station at the receiving end. The converter station at the sending end is used to convert alternating current from the grid to direct current. The converter station at the receiving end is used to convert direct current back into alternating current and send it to the transmission or distribution system.

There are two different types of HVDC technologies which are Current Source Converter (CSC) and Voltage Source Converter (VSC). They are referred to as classical HVDC and HVDC Light, respectively. The classical HVDC uses thyristor as valves whereas the Insulated Gate Bipolar Transistor (IGBT) in case of HVDC Light. This Master thesis describes the characteristics and properties related to classical HVDC only.

4.2 Motivation for the HVDC

The possible options to transmit electrical power at high voltage are either the Alternating Current (AC) or the Direct Current (DC). The following part of this section indicates some advantages of a DC link over an AC link and the main applications for which HVDC transmission are used:

- DC link can be justified for the interconnection of AC systems of different frequencies or different control philosophies [2].

- AC transmission is limited in term of maximum length due to inductive and capacitive parameter. This constrains does not exist in DC. Moreover the conductor cross section is fully used because of the absence of skin effects which is the phenomena that the tendency of an AC to distribute itself within a conductor so that the current density near the surface of the conductor is greater than at its core.

- With the appropriate control, can be used to improve the AC system stability. The power flow in the HVDC system can be easily controlled at high speed.

- An overhead DC transmission line with its towers can be designed to be less costly per unit of length than an equivalent AC line designed to transmit the same level of electric power. The DC converter stations at each end are more costly than the terminating stations of an AC solution. There is a breakeven distance which the total cost of a DC transmission is less than its AC transmission alternative. [2]

- The AC transmission solution is impractical for underwater cables longer than about 50 km distance because of the high capacitance of the cable requiring intermediate compensation. [4]

- The DC transmission solution is more environmental friendly compared with the AC solution in terms of reduction of visual impact and saves of land compensation. The AC systems need more space and the line becomes more expensive. This is because more or larger support masts are required. There are other environmental advantages with a DC transmission solution, such as lower the electric and magnetic fields.

There also are disadvantages in using the HVDC transmission solution

- Harmonic: HVDC creates harmonic voltages on DC side and harmonic currents on AC side. These harmonics must be limited to avoid unacceptable level of voltage distortion, overheat and additional losses by tuning harmonic filter [13]

- Reactive power consumption: The classical HVDC consumes reactive power, around 50% of the transmitted active power. Under transient conditions the consumption may be even higher. The addition components are required to compensate this consumption, which are shunt capacitors [13].

4.3 HVDC converter configurations

The HVDC links can be arranged in a number of configurations for effective utilization. There are three types of HVDC link which are Monopolar, Bipolar, and Homopolar [14]. In this thesis the Monopolar and Bipolar configurations, which are the most common, are presented. These transmit power from one geographical location to another. More details can be found in ref [8]. For the purpose of this work, main components in the HVDC station are the transformers and the valves. The symbols for these are shown in Figure 4.1.

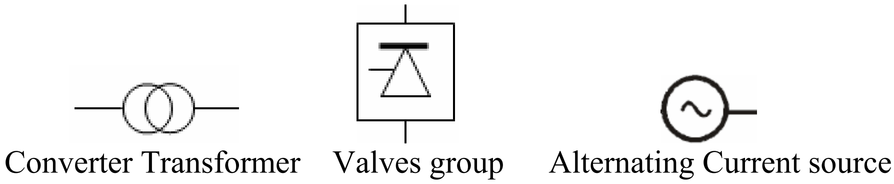


Figure 4.1: Some symbol components in HVDC system

4.3.1 Monopolar schemes

Figure 4.2 represents a monopolar configuration with ground or sea electrode return. The converter output terminals are reversed relative to one another, as indicated by the direction of the thyristors in the symbol blocks. With a ground return, the system requires just one transmission cable and earth is used as the return path. With a metallic earth return the potential is the ground, thus it does not need the full transmission voltage insulation.

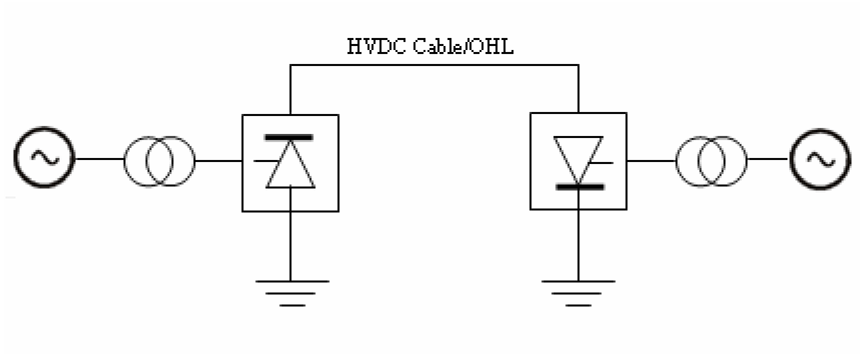


Figure 4.2: Monopolar with ground return path

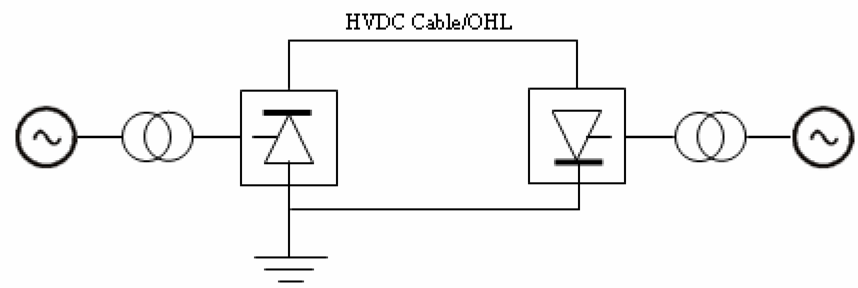


Figure 4.3: Monopolar with metallic return path

Figure 4.3 represents the same configuration with metallic return. A HVDC power transmission system utilizes a metallic return conductor for carrying return current between converters at opposite ends of the system. The return conductor is connected to earth at one end of the system and is otherwise insulated from earth so that its opposite end is floating with respect to DC.

The considerations that may lead to the adoption of metallic return are

- If the transmission line length is short enough to make it uneconomical and undesirable to build electrode lines and ground electrodes,

- If the earth resistivity is high enough to impose an unacceptable economic penalty.

For particular long distance or sea, cost considerations often lead to the adoption of a monopolar with a ground return systems. In contrast regarding to the environmental issue, the metallic return is added but this type of return increases losses and costs of the project [2].

4.3.2 Bipolar schemes

Figure 4.4 represents the bipolar configuration with ground return or sea electrode and Figure 4.5 represents the same configuration with metallic return.

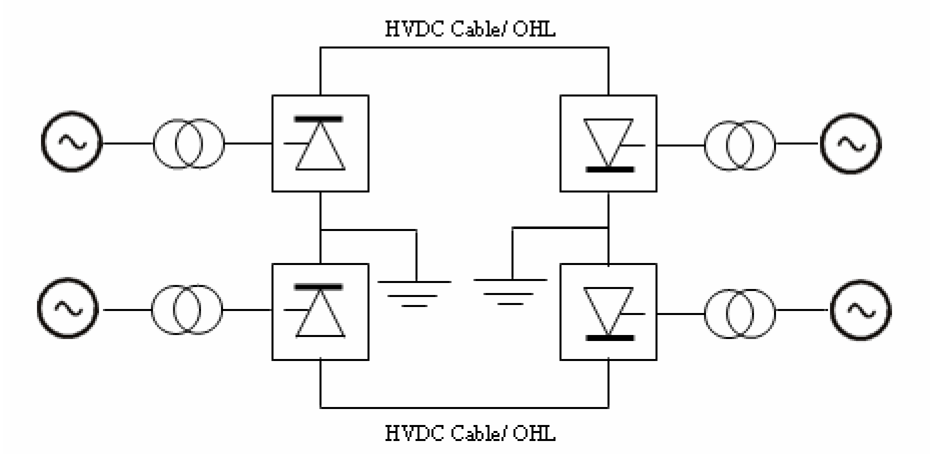


Figure 4.4: Bipolar with ground return

The bipolar system with ground return has the power flow in one direction, one pole has positive polarity to ground and the other pole as negative polarity to ground. For the power flow in the other direction the two poles reverse their polarities. When both poles are in operation, the imbalance current flows in the ground. In the event of loss of one transmission pole line, the two converter poles can also be connected in parallel by using appropriate switches for polarity reversal in at least one station pole, thus enabling both poles to operate in the monopolar ground return mode.

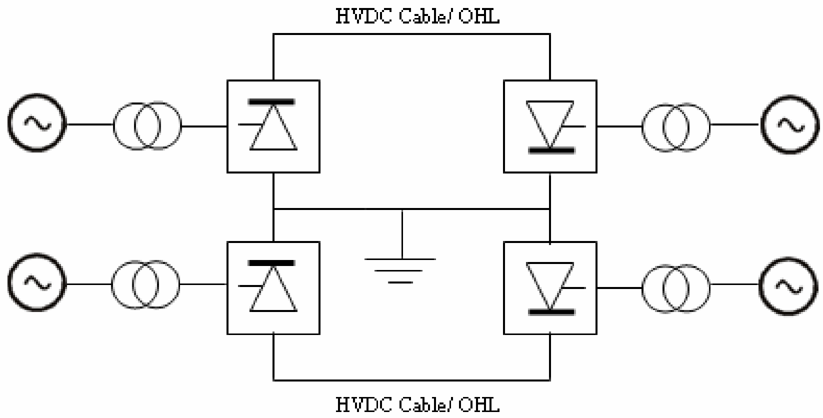


Figure 4.5: Bipolar with metallic return

When ground currents are not tolerable or when the distance between the HVDC system terminals is short or when a ground electrode is not feasible for any reason such as high earth resistivity as described in 4.2.1, the transmission line might be constructed with a third conductor to give a bipolar metallic neutral system. The third conductor carries imbalanced currents during bipolar operation. It also serves as the return path when one transmission line pole is out of service. In another word, when one substation pole becomes unavailable, the system can be operated in monopolar metallic return mode by utilizing the other substation pole.

This third conductor requires only low voltage insulation and it may also serve as a shield wire when the conductor is overhead. When it is fully insulated, it can serve as a spare conductor. If so, a separate shield wire may be required. When the third conductor is fully insulated, the system can still be operated in the bipolar mode if one conductor becomes unavailable.

The advantages of bipolar over monopolar configuration:

- Normally no earth-current flows which minimises earth losses and any earth related environmental effects [7].

- HVDC Bipolar transmission scheme provides higher flexibility with respects to the operation during the failure rise or in maintenance period. If a fault develops on one pole, the other pole can continue to operate in a monopole arrangement, using the earth as the return path.

- For a given power rating, each conductor has half the cross-sectional area of the monopolar line, thus reducing the extra cost of using a second conductor [2].

Remark: The bipolar scheme increases the flexibility and reliability but the installation and material costs of another pole compared to the monopolar must be considered.

4.3.3 six and twelve-pulse converter bridge

6-pluse bridge 12-pulse bridge

Figure 4.6: Converter bridge group

The twelve-pulse valve group is constructed by using 2 units of six-pulse valve group connected in series. The twelve-pulse valve group is normally required because it provides the conversion from AC to DC with fewer harmonics. A 12-pulse group enable to cancel the AC side 5^{th} and 7^{th} harmonic currents and DC side 6^{th} harmonic voltage, thus resulting in a significant saving in harmonic filters [6].

4.4 Main components in the HVDC station

The HVDC station consists of a number of components. Figure 4.6 and 4.7 shows a single line diagram for a monopolar HVDC station and the layout of the station, respectively. The main components and their functions will be presented later in this section.

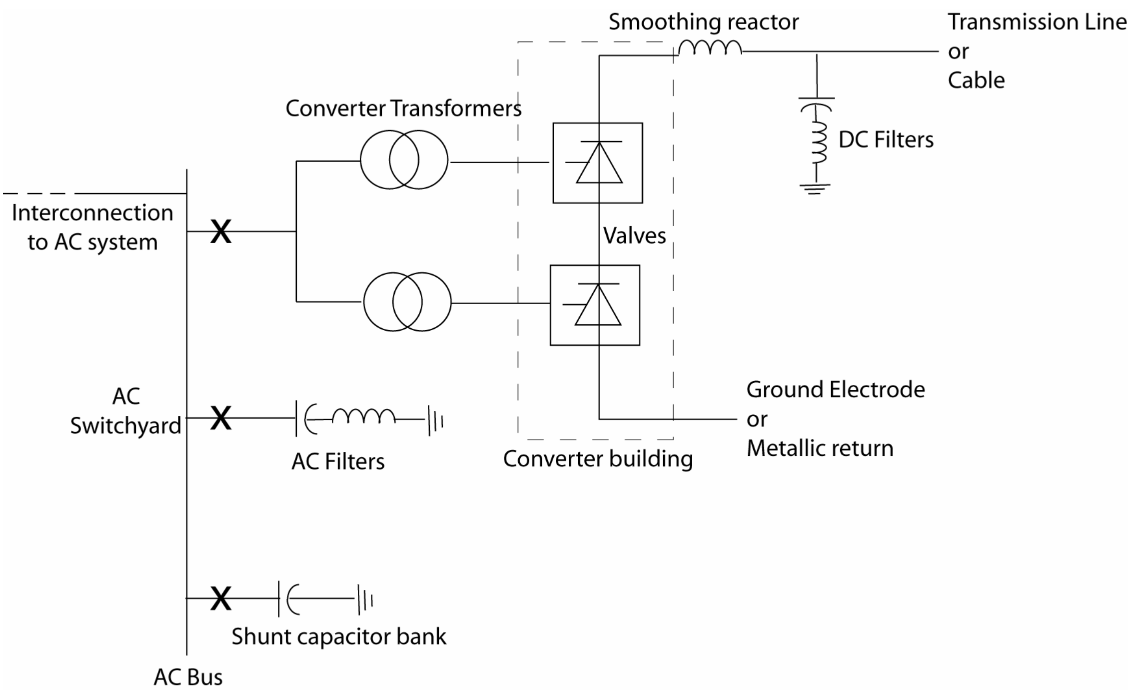


Figure 4.6: An example of a single line diagram of a HVDC station

4.4.1 Converter building (Valve hall)

The converter bridges are located in the converter building. The connection between them and converter transformers has to be made through the building's wall. The function of converter transformers is to transform the AC system voltage to which the DC system is connected. The secondary winding or DC side windings of the converter transformers are connected to the converter bridges.

For higher rated DC stations, converter transformers for 12 pulse operation are usually comprised of single phase unit which is a cost effective way to provide spare units for increased reliability [4].

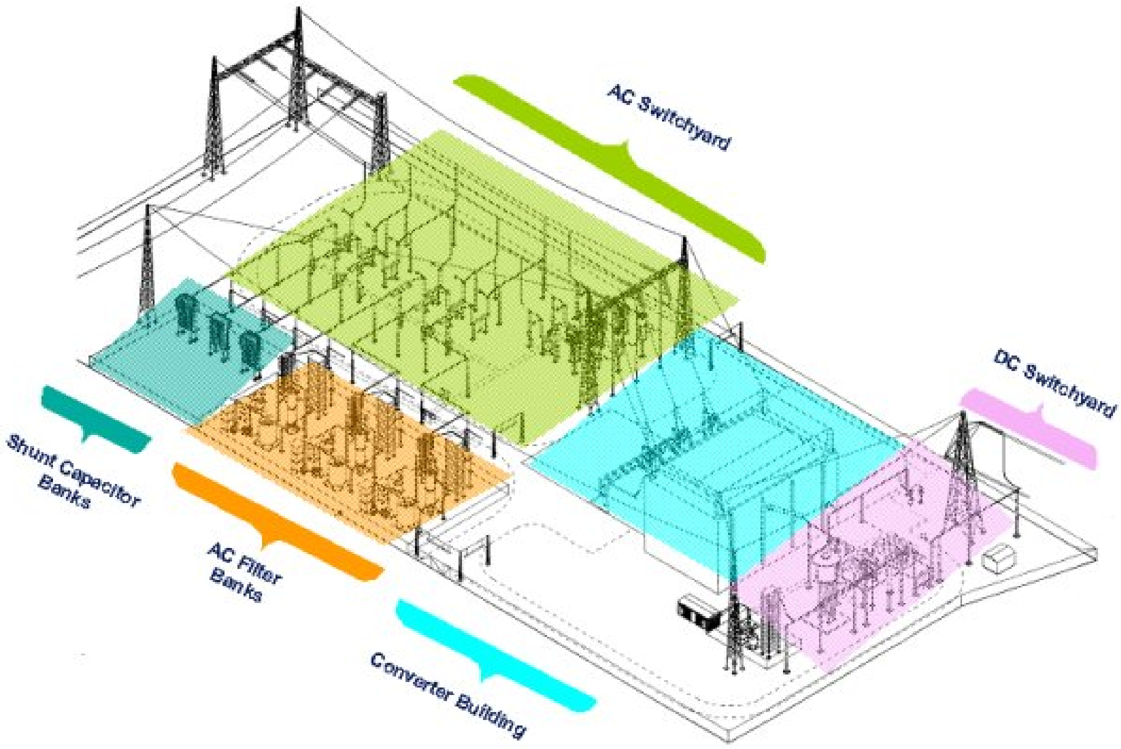


Figure 4.7: Classical monopolar HVDC station layout [7]

4.4.2 AC switchyard

The AC switchyard consists of circuit breakers and disconnectors. The main function of these two components are limiting the alternating current before going to the converter building and clearing faults in the transformer. They are normally used for clearing failure only on the AC side because at the DC side, the faults can be cleared more rapidly by fast converter control.

4.4.3 Shunt capacitor banks

Under steady-state condition of the classical HVDC, the reactive power consumed is about 45-50% of the active power transferred [1]. These capacitors and the ones associated with the AC filters help to compensate the reactive power consumed by the converters.

4.4.4 AC filter banks

The filter banks are arranged on the AC side of the HVDC station. They consist of AC filter capacitors, AC filter reactors, and AC filter resistors. They are used to absorb the harmonic currents generated by the HVDC converter i.e. typically tuned to 11^{th} and 13^{th}, and thus to reduce the impact of the harmonics on the connected AC system.

4.4.5 DC switchyard

The DC switchyard located consists of a DC filter and a smoothing reactor. The DC filter is to reduce the harmonic current on the DC side of the converter station.

The difference between AC and DC filters is AC filters can generate reactive power at fundamental frequency for compensating the demand of converter station in case of classical HVDC.

More information about HVDC components can be found in reference [1].

4.5 HVDC converter transformer

The HVDC converter transformer plays a relevant roll in HVDC converter station, not only due to the direct cost associated to them but also because its availability affects the HVDC transmission capability.[6] The decision making when design HVDC stations whether to operate with single-phase or three-phase units depends on many factors such as shipping weight, dimensional limitation, etc. Each of CTS has its own advantages. The single-phase unit has less limitation in term of transportation and it 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 wye-fed and delta-fed converter.

Almost all of HVDC power converters with thyristor valves are assembled in a converter bridge of twelve-pulse configuration. The construction of the standard 12- pulse converter transformer system (CTS), it can be obtained with either of the following arrangements [2].

4.5.1 Two-winding arrangement, single and three phase units

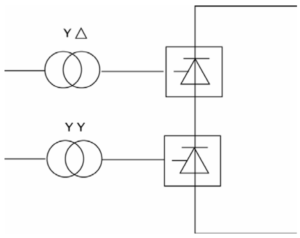


Figure 4.8: Single line diagram of two-winding arrangement

- Two three-phase-two-winding transformer units illustrated Figure 4.9
- Six single-phase-two-winding transformer units illustrated Figure 4.10

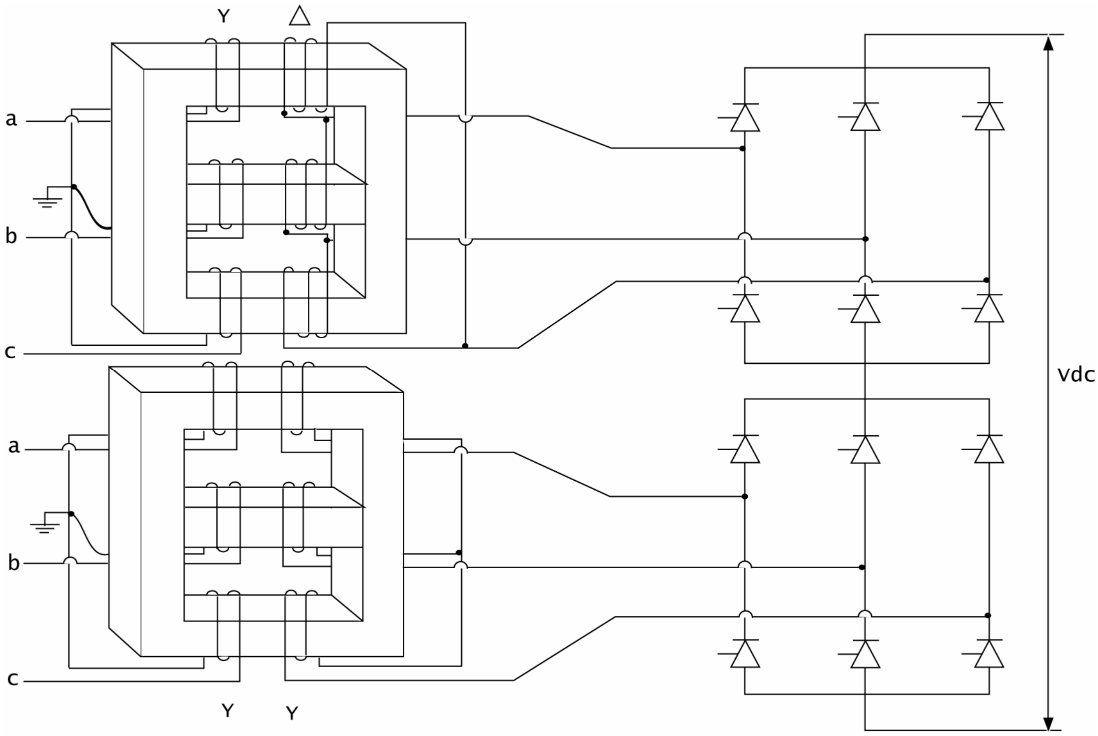


Figure 4.9: Two three-phase-two-winding transformer units CTS winding connection

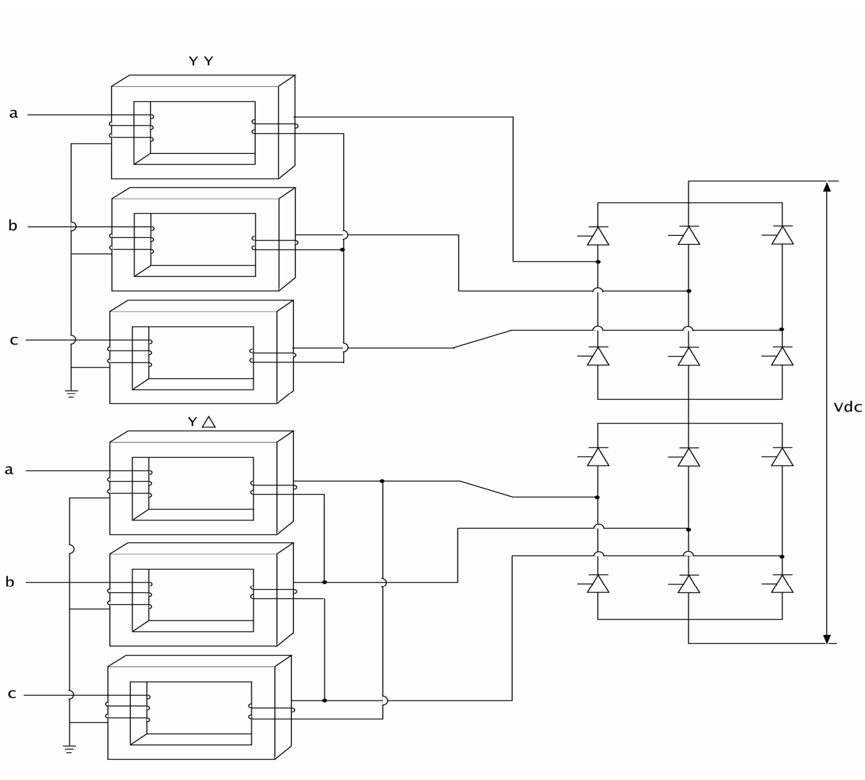


Figure 4.10: Six single-phase-two-winding transformer units CTS winding connection

Figure 4.9 illustrates two units of three-phase transformers in a Converter transformer system (CTS) with one DC side winding. This DC winding is created from Y/Y and Y/Δ transformer connected in parallel. The AC voltages applied to each six-pulse valve group that connected in series to make up the twelve pulse valve group have a phase difference of 30 degrees. In addition, since the primary winding of CTS, regardless single-phase or three-phase unit, is fed by the same voltage from the incoming AC, thereby HVDC schemes can be modified to achieve more economical solution by sharing the primary winding. This type of winding is called three-winding arrangement. Thus, the number of converter transformers that used in three-winding CTS is half compare with two-winding CTS. Figures related to three-winding arrangement are depicted in section 4.5.2.

4.5.2 Three-winding arrangement, single and three phase units

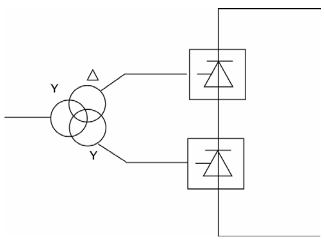


Figure 4.11: Single line diagram of three-winding arrangement

- One three-phase-three-windings unit illustrated Figure 4.12
- Three single-phase-three-winding transformer units illustrated Figure 4.13

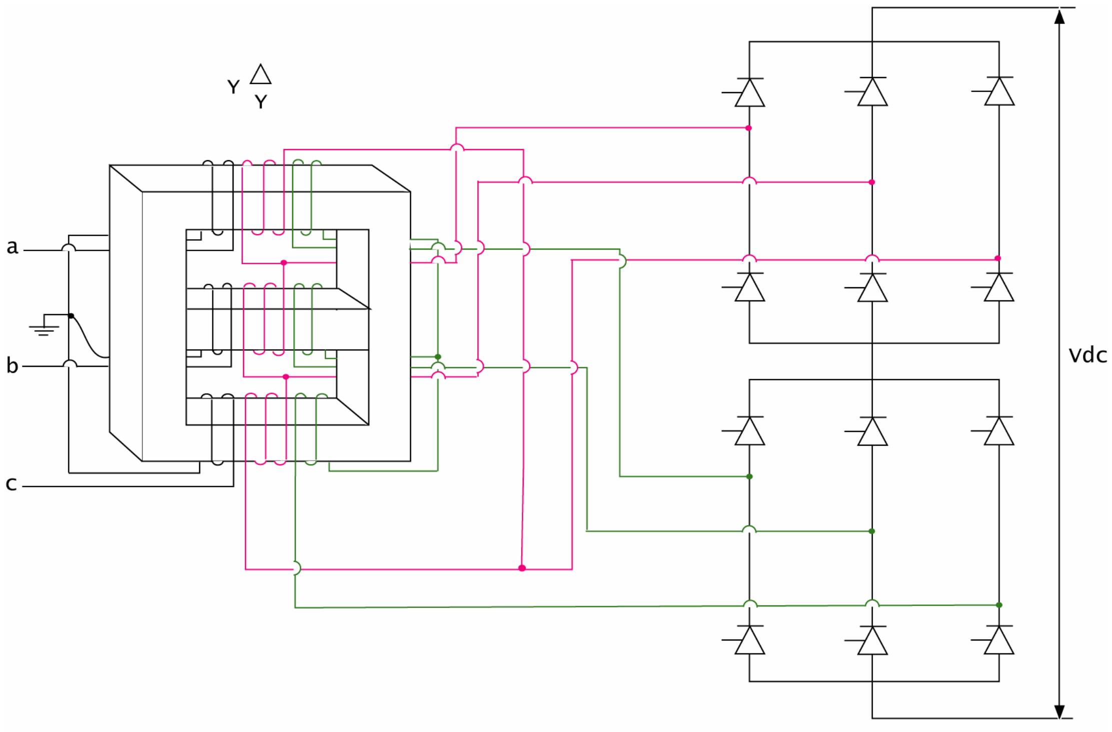


Figure 4.12: One three-phase-three-windings unit CTS winding connection

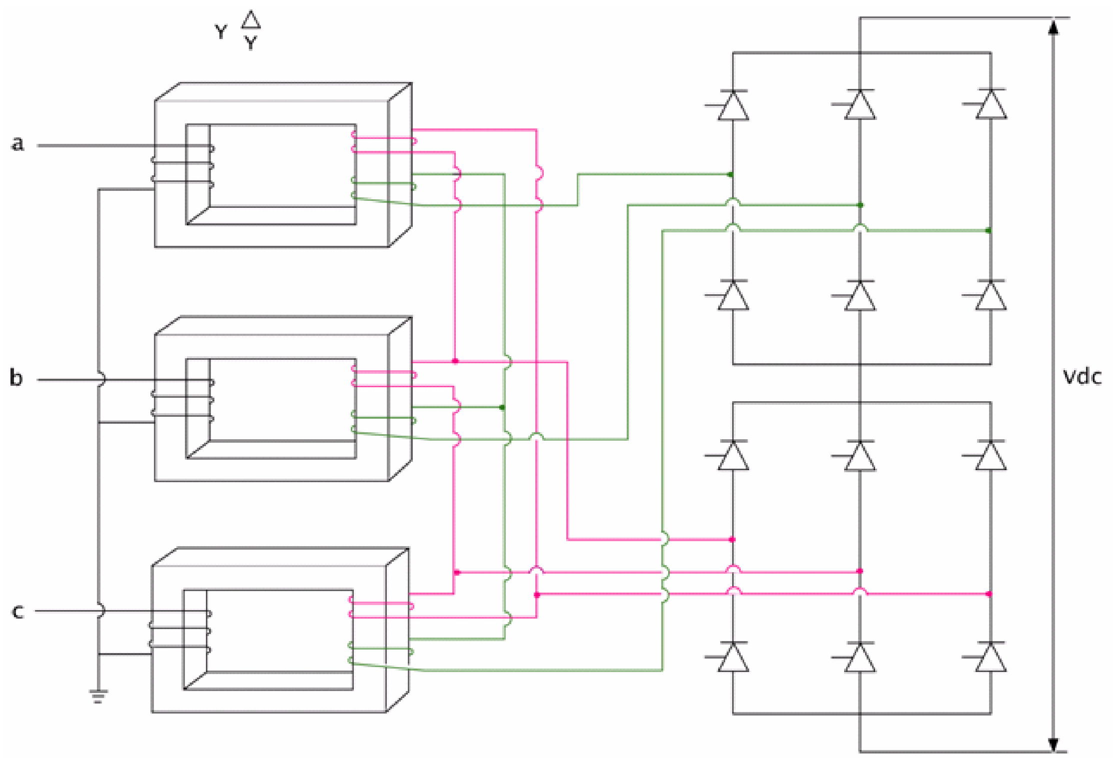


Figure 4.13: Three single-phase-three-winding transformer units CTS winding connection

4.6 Failure modes for converter transformer

4.6.1 General definition

In this thesis, the failures can be categorized into two typical modes which are minor and major (catastrophic) failure modes [16]. These two modes are handled differently. A minor failure is a short duration failure that the failed-unit can be repaired onsite without using the spare unit. A major failure is a long duration failure 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 from service for repair, and if a spare unit exists, 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 [17].

4.6.2 Definition related to HVDC converter transformer

The failures are classified in the categories of failure which are at bushing, valve winding, AC winding, Static shield, Load Tap Changer (LTC), Core & Magnetic field, and other internal connection. Since minor failures require short time of restoration process, they are assumed to occur only at bushing because the bushing installation is outside the transformer tank whereas if the other components fail, the transformer tank must be taken out of the converter for draining the oil (in case of oil-insulation) before investigating and repairing the failure. This process takes time to re-assemble and calibrate the converter transformer to synchronous with the system. It can be concluded that the repair time of major failure is longer than minor failure. In worse case, the replaced unit is not kept nearby the station, thus the time consumption for transportation the unit to the site must be added. Figure 4.14 illustrates the assumption of which components are in which type of failures.

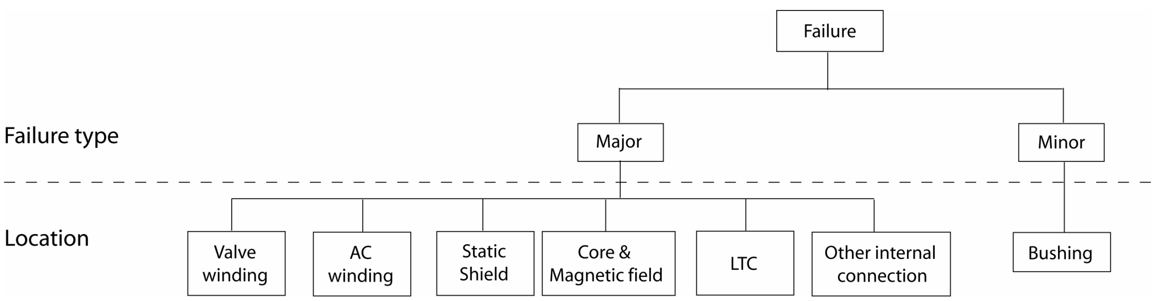


Fig 4.14: Failure mode of HVDC converter transformer for this thesis

4.6.3 Cause of failure

The most likely causes of failures can be listed as following [18]:

- Mechanical
- Dielectric
- Thermal
- Induced Current
- Operational Error
- Unknown

There are plenty of causes that generate failures on the converter transformer. For instance, the bushing failure happens because of high humidity. It may also happen by an internal flashover which creates the mechanical stress. This leads to the possible catastrophic failure or personal safety. The valve winding can be damaged by the harmonic induces eddy current heating. This failure makes valve windings overheated. The AC winding failures may happen due to a turn-to-turn short in an area of transposition created by excessive moisture. The static shield may be devastated by an earthquake. The possible cause of the breakdown on LTC is the high operating temperature which leads to a flashover and finally the mechanical damaged. The internal connections, for example the transformer cooling equipment is cracked due to vibrations from an unbalanced fan. From the study visit, some causes of failures such as conductor insulation failure and oil leakage from transformer tank are discussed as well.

4.6.4 Restoration of the failure

According to CIGRE report [18], failed-units are most likely to be taken out of service and sent to the repair centre or replaced with a spare. 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 [18]. 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.

5 Overview of the CARMS software

5.1 Introduction

The CARMS (Computer-Aided Rate Modelling and Simulation) software is an integrated, general tool, suitable for reliability, maintainability, and availability (RMA) evaluation assessments [7]. It is designed to solve a broad spectrum of RMA and other mathematically related problems, and well-suited for fault-tolerate system design. A combination of text-and graphical-based data input makes the program ideal for problems in which an engineering design is at the conceptual phase. In this phase, flexibility, ease of use, and speed are prime requirements in determining the ideal course of action and probing tradeoff scenarios. CARMS features a graphical interactive environment that allows the user to quickly change data values and graphical views of a given system. Figure 5.1 shows a flow diagram for the evaluation of a problem in CARMS.

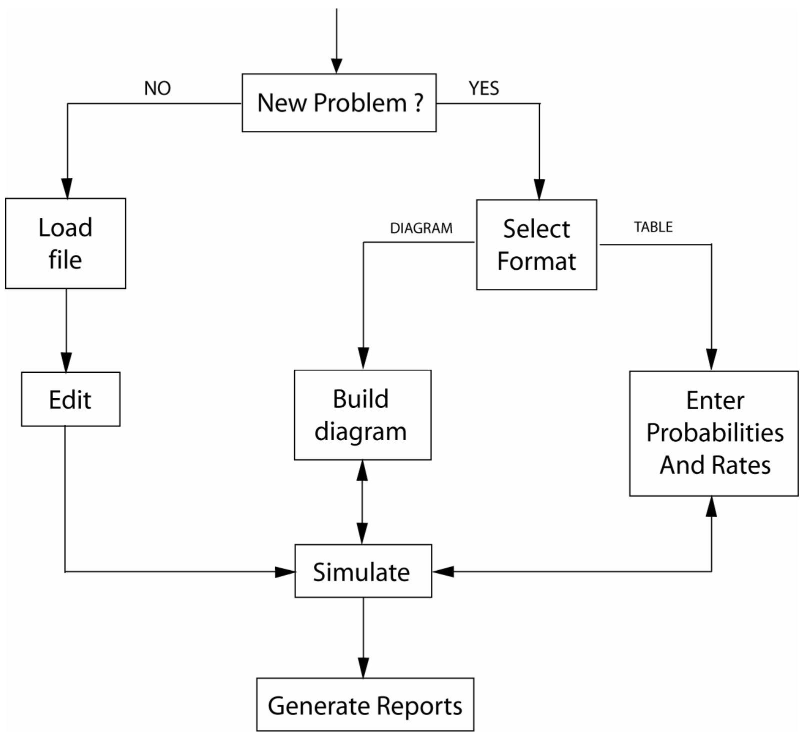


Fig 5.1: CARMS Road Map [7]

The first step in creating a new model in CARMS is to select the input format. As shown in Fig 5.1, CARMS can be started up by building either state diagram or inserting the transition value in the transition table. Both ways allow the user to give the input for the transitions from one state to other states.

The second step is to input the values in the transition matrix for the model. These transitions are probabilities for the Markov chain or rates value in case of the continuous-time for the Markov process. Also this transition matrix is associated with initial conditions to provide information how the system and state starts, consequently to determine the probability in the long term future. Since CARMS uses a graphical interface, the probabilities, rates and initial condition value can be inserted directly in the state transition diagram. Those values will also appear in the transition table.

5.2 Implementation example in CARMS

The following two examples show how models are implemented and evaluated in CARMS. Hand calculations are also provided to demonstrate how the software calculates the indices.

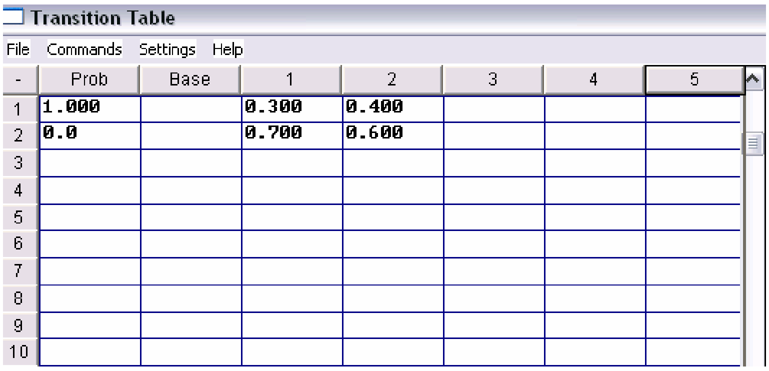
The state-diagrams are formed by clicking and dragging at the various screen positions while in the *Diagram Draw* view. After describing each of the states with the *Name* command, initial conditions are applied. Data is entered through the *Data* command in the diagram.

The transition arrows are formed by clicking at the beginning, midpoint, and endpoint of all the valid failure mode transitions. Failure rates for the transitions are then entered through the *Data* command.

After completing the state diagram, one can view the *Transition Table*. The transition probabilities/rates are filled in such a way that the column position is the state from which the transition occurs and the row position is the state to which the transition occurs. Base value in row ‘1’ and ‘2’ can be used to save time in case one wants to fill the same value to any other transition paths, also the multiplication of them.

5.2.1 Example 1: A man’s exercise habits refer to section 3.2.4.

The corresponding data is shown in Fig 5.2. State 1 represents exercise state while state 2 represents the man decides not to make an exercise.


Transition Table

File Commands Settings Help

-	Prob	Base	1	2	3	4	5
1	1.000		0.300	0.400			
2	0.0		0.700	0.600			
3							
4							
5							
6							
7							
8							
9							
10							

Figure 5.2: Table before Simulation in Formula Display Mode

Next, one invokes the *Simulation Control* view. If the initial conditions are satisfied and no conflicts are observed with the diagram, the simulation can be started by clicking the *Go* command. Figure 4.3 is the graphical results obtained from simulation, the solid line represents the probability of state 1 (decreasing value) that started from initial probability value 1 and steady-state probability value is 0.364. The dash line represents the probability of state2 (increasing value) which started from initial probability value 0 and steady-state probability value is 0.636.

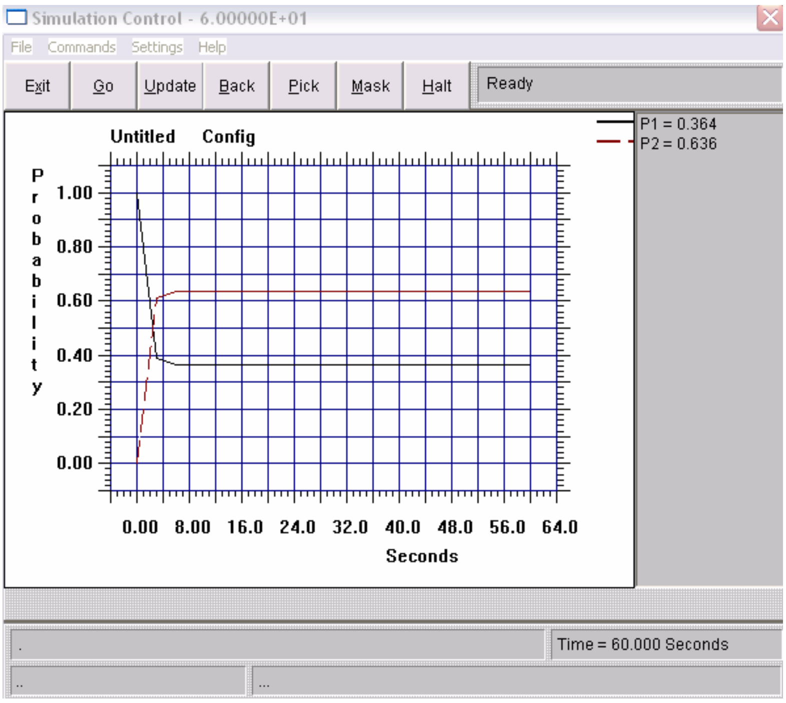
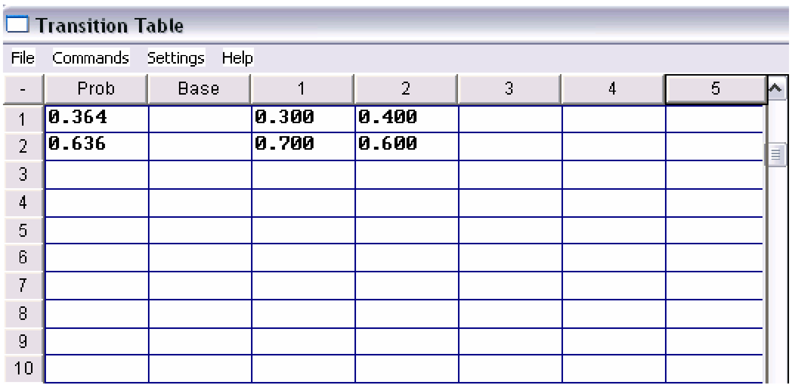


Figure 5.3: Graphical solution of Example 3.1

After finishing the simulation, we return to the Transition Table, which is updated as shown in figure 5.4.



-	Prob	Base	1	2	3	4	5
1	0.364		0.300	0.400			
2	0.636		0.700	0.600			
3							
4							
5							
6							
7							
8							
9							
10							

Figure 5.4: Table after Simulation in Value Display Mode.

At this moment, the “Prob” column and the time values are the only visible modifications to the table. By using the command *Back* or *Data Reset*, probability and time values from the previous simulation can be reloaded.

5.2.2 Example 2: Availability of a smoothing reactor system [19]

The next example demonstrates how CARMS works with a multi-state model of a smoothing reactor. It is assumed that, to make whole converter station operational two smoothing reactors must be functional.

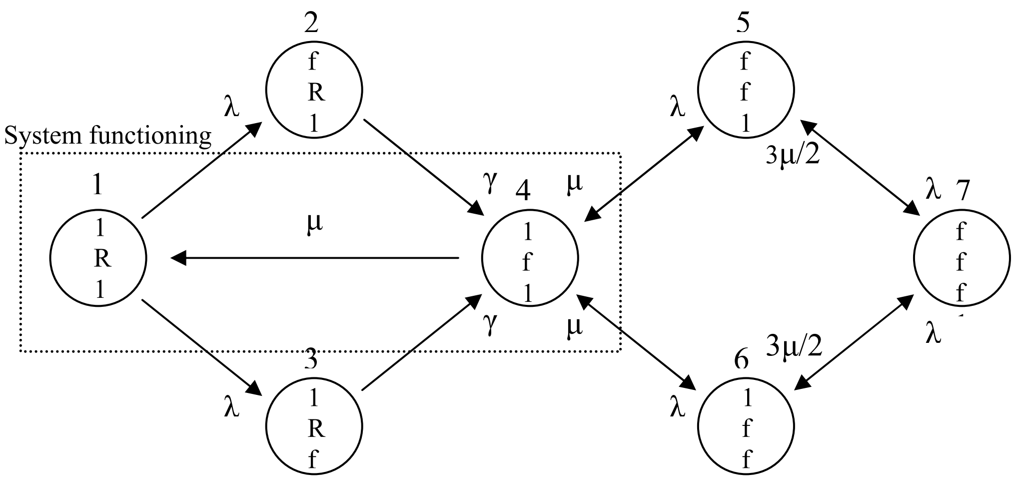


Figure 5.5: State space diagram for a converter station with 2 operational smoothing reactor and one additional spare [19].

Figure 5.5 shows the state space diagram for a HVDC reactor system [20]. There is one spare unit. At each state in this figure, R indicates the spare unit is in standby mode while f indicates failure mode. The digit and letter inside 'state' indicate the number of smoothing reactors. μ, γ, and λ represent repairing, replacing, and failure rate, respectively. Determine the availability of smoothing reactor systems if the repairing time is 1111 hours, replacing time is 90 hours and the failure rate of a single reactor unit is 0.093 f/yr.

The solution of this problem is presented in the next section where a validation of CARMS is also presented.

Hand calculation

By applying Equation 3.3, the transition probability matrix can be obtained as

$$P = \begin{bmatrix} 1-2\lambda & \lambda & \lambda & 0 & 0 & 0 & 0 \\ 0 & 1-\gamma & 0 & \gamma & 0 & 0 & 0 \\ 0 & 0 & 1-\gamma & \gamma & 0 & 0 & 0 \\ \mu & 0 & 0 & 1-\mu-2\lambda & \lambda & \lambda & 0 \\ 0 & 0 & 0 & \mu & 1-\mu-\lambda & 0 & \lambda \\ 0 & 0 & 0 & \mu & 0 & 1-\mu-\lambda & \lambda \\ 0 & 0 & 0 & 0 & 3\mu/2 & 3\mu/2 & 1-3\mu \end{bmatrix}$$

Then, apply equation 3.3, obtained

$$\begin{bmatrix} P_1 & P_2 & P_3 & P_4 & P_5 & P_6 & P_7 \end{bmatrix} \boldsymbol{P} = \begin{bmatrix} P_1 & P_2 & P_3 & P_4 & P_5 & P_6 & P_7 \end{bmatrix}$$

From which

$$\begin{aligned} & P_1(1-2\lambda) + P_4\mu = P_1 \\ & P_1\lambda + P_2(1-\gamma) = P_2 \\ & P_1\lambda + P_3(1-\gamma) = P_3 \\ & P_2\gamma + P_3\gamma + P_4(1-\mu-2\lambda) + P_5\mu + P_6\mu = P_4 \\ & P_4\lambda + P_5(1-\mu-\lambda) + P_7(1.5\mu) = P_5 \\ & P_4\lambda + P_6(1-\mu-\lambda) + P_7(1.5\mu) = P_6 \\ & P_5\lambda + P_6\lambda + P_7(1-3\mu) = P_7 \end{aligned}$$

Rearranging gives

$$
\begin{aligned}
&-2\lambda P_1 + P_4\mu = 0 \\
&\lambda P_1 - \gamma P_2 = 0 \\
&\lambda P_1 - \gamma P_3 = 0 \\
&\gamma P_2 + \gamma P_3 - (\mu + 2\lambda)P_4 + \mu P_5 + \mu P_6 = 0 \\
&\lambda P_4 - (\mu + \lambda)P_5 + (1.5\mu)P_7 = 0 \\
&\lambda P_4 - (\mu + \lambda)P_6 + (1.5\mu)P_7 = 0 \\
&\lambda P_5 + \lambda P_6 - 3\mu P_7 = 0
\end{aligned}
\tag{1}
$$

Also with the equation 3.4 gives

$$P_1 + P_2 + P_3 + P_4 + P_5 + P_6 + P_7 = 1$$

Before replacing the data into set of equation (1), one has to change all of them to the same unity by applying Equation 2.6 and 2.8, then

$$\mu = \frac{1}{1111} = 9.0009E - 04 \qquad [1/\text{hrs}]$$

$$\gamma = \frac{1}{90} = 0.0111 \qquad [1/\text{hrs}]$$

And change the failure rate to be in the unity of hours by dividing by the total number of hours per year,

$$\lambda = \frac{0.093}{8760} = 1.06164E - 05 \qquad [\text{f/hrs}]$$

Substituting μ, γ, and λ in equation set *(1)*, P_1-P_7 are calculated as following

$P_1 = 0.9746$	$P_2 = 9.3214E\text{-}4$	$P_3 = 9.3214E\text{-}4$	$P_4 = 0.02299$
$P_5 = 2.7117E\text{-}4$	$P_6 = 2.7117E\text{-}4$	$P_7 = 2.1312E\text{-}6$	

5.3 Validation of CARMS

A comparison has been made between the results from CARMS and the reliability tool, FaultTree+ in order to validate the software.

FaultTree+ is a fully interactive graphics and analysis program for performing probabilistic risk assessments using integrated fault trees, event tree and Markov model analysis. The program allows the user to construct Markov models. The Markov models may also be analysed independently of the fault tree analysis. A free demo version (v.11) can be downloaded from reference [20].

Table 4.1 shows a comparison of the results from CARMS, FaultTree+ and hand calculation for the smoothing example in section 5.2.2.

Table 4.1: State probabilites obtained from two different reliability tools and hand calculation

Probability	Hand Calculation	CARMS	FaultTree+
State 1	0.9746	0.975	0.9775
State 2	9.3214E-4	9.3E-4	9.263E-4
State 3	9.3214E-4	9.3E-4	9.263E-4
State 4	0.02299	0.023	0.02023
State 5	2.7117E-4	2.7E-4	2.659E-4
State 6	2.7117E-4	2.7E-4	2.659E-4
State 7	2.1312E-6	2.1E-6	4.686E-5

The availability of the smoothing reactor system is the summation of the probabilities of state 1 and state 4. This is because both of the states, state 1 (a state that consists of two normal smoothing reactor, plus one spare unit), and state 4 (the failed main unit has been retired and the spare switched on) has at least two smoothing reactors in operation mode.

Table 4.2: Availability and Unavailability index obtained from different reliability software

	Hand Calculation	CARMS	FaultTree+
Availability	0.99759	0.998	0.9977
Unavailability	2.41E-3	2E-3	2.31E-3

Table 4.2 shows the comparison between two different reliability tools and hand calculation. There are small differences between hand calculation and simulation results, however these small differences have no significant meaning and are small enough to be neglected.

6 Proposed MARKOV models for HVDC converter transformer system

6.1 Introduction

A converter transformer system (CTS) at a HVDC plant can be formed in a number of different ways. The CTS for a 12-pulse converter needs in principle 6 primary windings and 6 secondary windings, single-phase-two-winding or three-phase-two-winding units can be used as mentioned in chapter 4. Moreover, since the AC windings are connected to the same voltage, single-phase-three-winding or three-phase-three-winding units can be used to form a CTS. Only three-winding transformers are considered in this chapter.

For the purpose of this chapter a CTS can be modelled by one three-phase-three-winding (TPTW) unit or alternatively by a group of three single-phase-three-winding (SPTW) units. A spare transformer unit might or might not be available and this might be located at both converter stations, at one of the stations or at a third place.

This chapter focuses on the assessment of the availability of the CTS for different levels of a spare unit. The results based on TPTW or SPTW transformer system. One should keep in mind that the final decision will also be affected by aspects beyond the simulation result such as costs, transportation, etc.

6.2 The proposed models

The following models based on the arrangement in chapter 4 are presented.

Three-phase unit

- **Model 1:** Three-phase-three winding (TPTW) CTS without spare unit, one failure mode (minor or major depending on repair time)
- **Model 2:** Three-phase-three winding (TPTW) CTS with spare unit, all failures treated as major failure.
- **Model 3:** Three-phase-three winding (TPTW) CTS with spare unit, two failure modes: major and minor failure.

Single-phase unit

- **Model 4:** Single-phase-three winding (SPTW) CTS without spare unit, all failures treated as major failure.
- **Model 5:** Single-phase-three winding (SPTW) CTS with spare unit, all failures treated as major failure.

6.2.1 Model assumptions

To enable the application of Markov approach, the following assumptions are made.

- Constant failure, repair and installation rate because of exponential distribution.
- An incremental interval of time is sufficient small that the probability that two or more transitions occurring can be neglected.

The following assumptions are applied to the proposed Markov models in this thesis:

- The repair facilities are assumed to be unrestricted, i.e. as soon as the transformer fails, the repair is started irrespective of the fact that another unit may also be undergoing repair (each unit is assumed to have its dedicated repair crew)
- After the repair is completed, the unit is assumed to be as good as new.
- The down time consists of two phases which are repair time and re-installation period.
- No common mode failures i.e. the failure, which caused by the external event, that causes all functioning components to fail at the same time. [7]
- A spare unit is assumed not to fail in the standby state and switching operation is also performed perfectly.

6.2.2 Model parameters

λ_T = Total failure rate of TPTW
λ_1 = Major failure rate of TPTW
λ_2 = Minor failure rate of TPTW
λ_3 = Total failure rate of SPTW
μ_1 = Repair rate according to restoration time (refer to Table 6.6)
μ_2 = Repair rate according to minor failure (12 hours)
γ = Installation rate (refer Table 6.7)

The numerical data is given in section 6.3

6.2.3 Model 1: TPTW units without spare, one failure mode

Consider a converter transformer system formed by one unit of three-phase-three-winding transformer. Figure 6.1 shows the state diagram of TPTW without spare unit and with one failure mode.

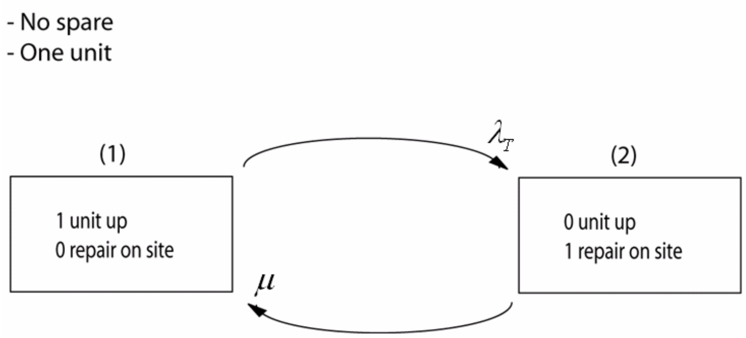


Figure 6.1: State diagram of three-phase converter transformer

In state1, the transformer is up and functional. The next transition is to state2 where the transformer is failed. The transition rate from state1 to state2 is λ_T and from state2 to state1 is μ. In order to make CTS operational, it needs one unit works.

Table 6.1: Three-phase converter transformer states' mode according to model 1

	State
CTS available	1
CTS unavailable	2

6.2.4 Model 2: TPTW units with spare, major failure mode

In case a spare unit is available, the state diagram of the TPTW CTS can be constructed as following

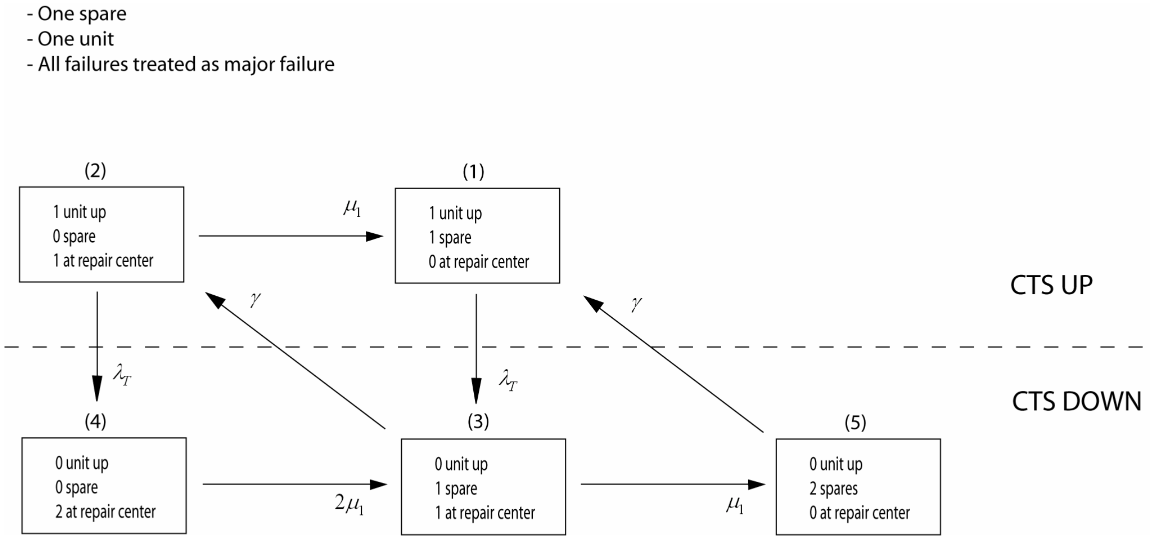


Figure 6.2: State diagram of a TPTW converter transformer system with one spare unit, major failure mode

Figure 6.2 shows the TPTW with one spare unit and all failures treated as major failure. State 1 corresponds to the state where the CTS is functional and one spare unit (a complete CTS, in this case) is available. Since a spare unit can not fail in the standby mode, the next possible transition is to state 3 where the main CTS has failed and the spare unit is available but in standby mode. The CTS is unavailable at state 3 and will remain unavailable until the spare unit replaces the failed-unit. The transition rate from state1 to state3 is λ_T. To restore the CTS into operation, a spare unit must replace the main unit. The time required to switch to spare will depend on actual field conditions. The spare unit is replaced, with the installation rate (γ). The installation rate is the inverse of the installation time. Therefore the transition rate from state 3 to state 2 is γ. At state 2, a CTS is again in operation (CTS available) because the failed-unit has been retired and the spare replaced on. The spare is now operating and can therefore fail. The failure rate of the spare is assumed to be the same as the original three-phase-three-winding transformer. At state 2 the main unit is in reparation. The possible transition paths from state 3 are therefore either to state1, which means the failed- unit is repaired at the transition rate μ_1, or to state 4 where the spare unit has failed with the transition rate λ_T. State 4 is a CTS unavailable state. The next possible state is state 3 where one unit is repaired off-site. If both units (main and spare) can be repaired simultaneously, the next state could be state 5, this is however unlikely. It is more likely that one unit is repaired (no matter which one) at $2\mu_1$ rate. Thus, one unit is put into operation with γ rate (to state 2) or repaired another failed unit (to state 5) before installing one of them back to operation mode (state1).

In order to make CTS operational, it needs at least one of these two unit works and replaced.

Table 6.2: Three-phase converter transformer states' mode according to model 2

	State
CTS available	1, 2
CTS unavailable	3, 4, 5

6.2.5 Model 3: TPTW units with spare, major and minor failure mode

In addition to model 2, generalization to a more complex system can be achieved by considering the different mode of failures: minor and major failure.

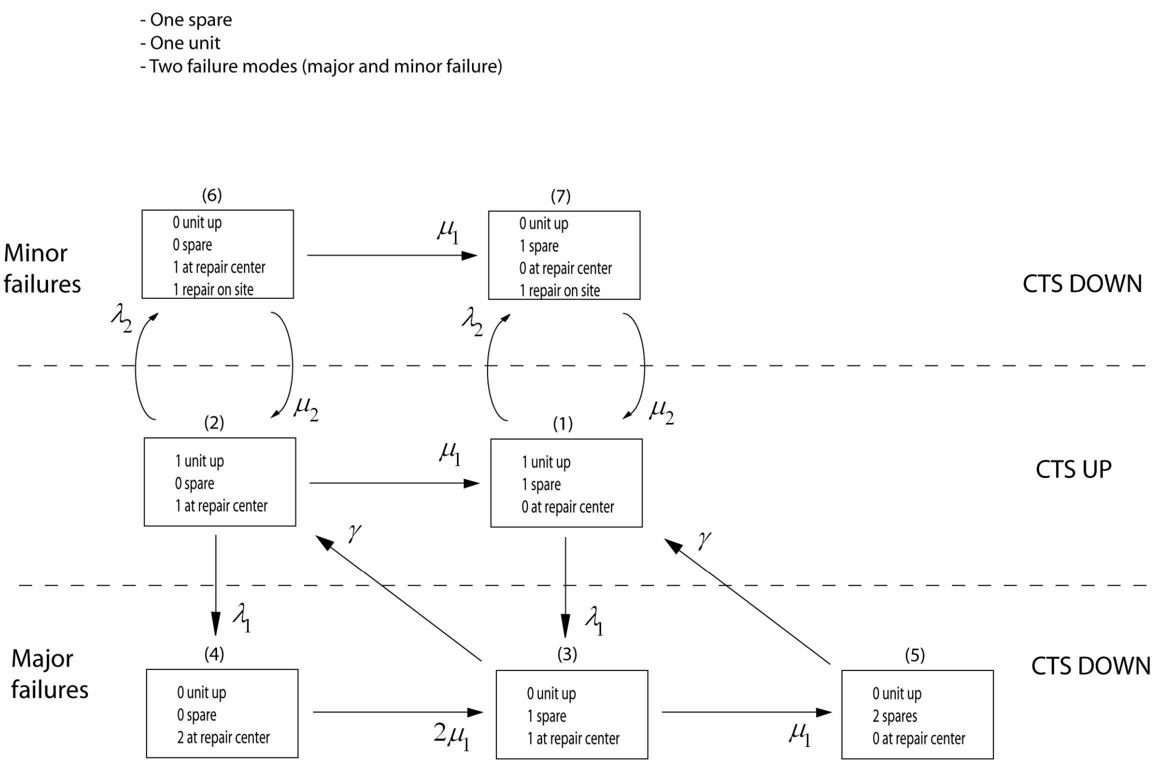


Figure 6.3: State diagram of TPTW converter transformer with spare unit, consider different failure modes

Figure 6.3, the transition path is most likely the same as the in case of Figure 6.2 with the addition of different failure mode. In this case the converter transformer possibly fails into two modes. For example, the transition path from state1, it either changes to state 7 with the transition rate λ_2 . This means that the transformer is in the minor failure mode that it can be repaired onsite and there is no necessity of using a spare or to state3 with the transition rate λ_1 which the failed unit is in major failure and needed to be replaced with the spare. The minor failure can also occur at state 2, which is the state after failed-unit is replaced by the spare unit.

Again, in order to make CTS operational, it needs at least one of these two units (main or spare) to work.

Table 6.3: Three-phase converter transformer states' mode according to model 3

	State
CTS available	1, 2
CTS unavailable	3, 4, 5, 6, 7

6.2.6 Model 4: SPTW units without spare, major failure mode

Consider a single-phase three winding CTS without spare. Fig 6.4 shows the state diagram of three identical SPTW units without spare.

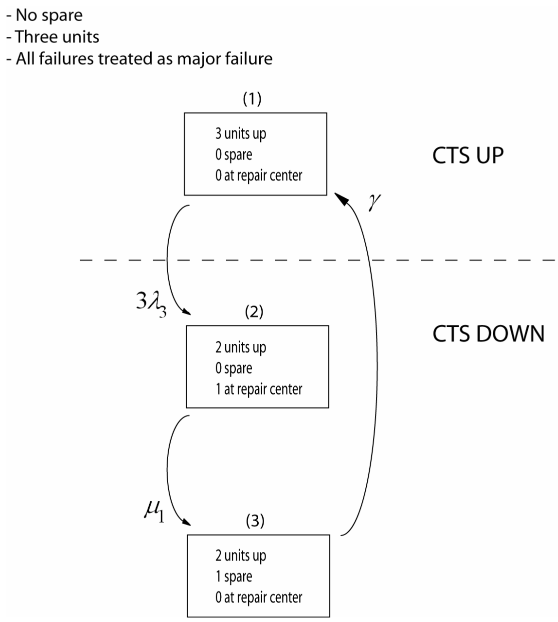


Figure 6.4: States diagram of reduced model SPTW converter transformer without spare unit

In order to make CTS available, all three units of transformer must be functional. The operation of CTS will be shut down when one of three single-phase CTS is failed. It is assumed when the operation of CTS is stopped, the others two units can not fail. These two units that still functional are not operating until the failed unit is repaired and replaced. The transition rate from state 1 to state 2 is $3\lambda_1$ according to three units from state 1 has the possibility to fail equally with the rate λ_1. From state 2 to state 3, a failed unit is repaired with the rate μ_1 and from state 3 to state 1 with the installation rate γ

Table 6.4: Single-phase converter transformer states' mode according to model 4

	State
CTS available	1
CTS unavailable	2,3

6.2.7 Model 5: SPTW units with spare, major failure mode

Figure 6.5 shows the SPTW with spare unit which due with major failure.

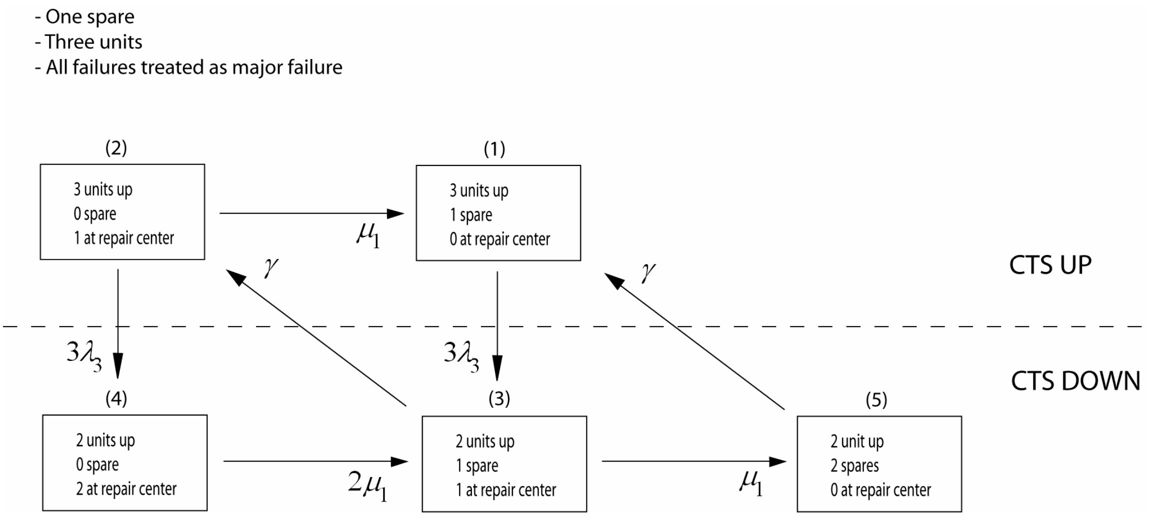


Figure 6.5: States diagram of reduced-model, SPTW converter transformer with spare unit

The model description is most likely as explained for model 2 in section 6.2.4. The only difference is the transition rate from state 1 to state 3 and state 2 to state 4 are $3\lambda_3$.

In order to have SPTW converter transformer of this model works, it needs at least 3 units works and replaced.

Table 6.5: Reduced model of single-phase converter transformer with spare states' mode according to model 5

	State
CTS available	1, 3
CTS unavailable	2, 4, 5

6.3 Input data

The following sections provide the input data to make an assessment of the proposed Markov models.

6.3.1 Restoration time

The restoration time when the failure occurs on the CTS is various. It depends on the location where the spare transformer units are kept, either at the site or other facilities. The maintenance practice also affects the total time needed for bringing the CTS back again. Table 6.6 illustrates the restoration time when CTS is unavailable. The data in table based on the engineering judgements to create different restoration scenarios.

Table 6.6: System data of converter transformer restoration time

Where the spare transformer is kept	How is the station manned	TtRst (hrs)	Installation Time (hrs)	Shipping & No action Time (hrs)	Total (hrs)
1) Onsite	24 hours a day	1	15	0	16
2) Onsite	Operators are on call 24 hrs a day	2	15	0	17
3) Onsite	Regular working hours weekdays	1	15	32	48
4) Offsite (one available at the other station)	24 hours a day	1	24	78	103
5) Offsite (at factory facilities, same country)	24 hours a day	1	24	96	121
6) Offsite (at factory facilities, oversea)	24 hours a day	1	24	792	817
7) The worst case	-	-	24	-	2160

Explanation of the table

Scenario 1 and 2: The spare transformer is kept onsite and time to reach station (TtRst) is 1 and 2 hrs, respectively. Scenario 1, one assumes the operators are at the station 24 hrs. Scenario2 assumes the operators are on calls. Thus, it takes longer time to reach HVDC station. The estimate working time to make CTS available again is 15hrs.

Scenario3: The spare transformer is also kept onsite as scenario 1 and 2. The difference is the operators work only during weekday. There is no any action until the weekday. In this case, the assumption is made, 32 hrs, before reaching weekday.

Scenario4, 5, and 6: The spare transformer is kept offsite. In these cases, the shipping time is required. For scenario4 and 5, since the spare unit is available in the same country of the location of the HVDC station, it's approximated that the shipping time is equal.

The only difference between them is when the problem is informed, for scenario 4, it will take less time to response. This is because the spare unit is kept just at another station meanwhile, scenario5 the spare unit is kept at the factory facility.

Scenario7: Assumes the unexpected events that delay the reparation process that bring CTS to be available again such as an accident during transportation of spare transformer. In this scenario, one assumes 3 months for the repair time to solve the problem.

The installation time if spare transformer is onsite and if it is offsite is different. This can be implied that, in case of the spare unit is offsite, it needs more time to remove the failed unit and re-install the spare unit instead of the failed one whereas if the spare unit is onsite, some process might be omitted, consequently takes shorter time.

Table 6.7: System data of three-phase-three-winding CTS with one spare unit

Location of spare unit	Installation time (hrs)	Installation rate (1/hrs)
Onsite	15	0.0667
Offsite	24	0.0417

In addition, if minor failures occur; it is assumed that will take 12 hours to clear the failure.

6.3.2 Failure rate

The data from CIGRE report [18] is adopted for the considered models. In case of three-phase CTS, the average failure rate and the highest failure rate are 0.0308 and 0.11, respectively. The total number of failures is equal to 121. The number of minor failure is 8 times whereas the number of major failure is 113. Therefore, the system input data of three-phase CTS is as in Table 6.8

Table 6.8: System data of three-phase converter transformer system

	Major	**Minor**
Average failure rate	**0.02876**	**0.002036**
Highest failure rate	**0.10273**	**0.007273**

Table 6.9 provides the system input data of single-phase CTS,

Average failure rate	Highest failure rate
0.0226	**0.16**

6.4 Sensitivity Analysis

The sensitivity analysis routine is also applied to the system data regards to which parameter contributes to the unavailability. The failure rate of three-phase and single-phase unit (Table 6.8 and 6.9, respectively) seems interesting to generate new failure rates with the value ±50% and 75% of their original values to see the trend of the unavailability when the failure rate value changes.

6.5 Simulation results

The considered CTS can be categorized into two different systems which are three-phase CTS with three windings and single-phase CTS with three winding. Each case can be subdivided into with and without spare unit. In addition, the different failure modes (minor and major) are applied to the three-phase CTS with a spare unit to see the effect of the failure severity on the total availability.

How to use "The results Table":
For example, refer to Table 6.10, the simulation result of three-phase three winding without spare

Failure rate (f/yr)	Repair time (hrs)	Unavailability (%)
0.0308	817	0.286

The following results are based on average value of failure rate meanwhile the results that based on the highest value of failure rate are also provided in the APPENDIX.

Basic case: The case that failure rate is equal to 100% (original value)

Table 6.10: The unavailability of TPTW at λ = 0.0308 f/yr and T_r = 2160 hrs

Model	Unavailability (%)
Model 1: TPTW without spare	**0.754%**
Model 2: TPTW with a spare, major failures	**0.011%**
Model 3: TPTW with a spare, two failure modes	**0.011%**

Table 6.11: The unavailability of SPTW at λ = 0.0226 f/yr and T_r = 2160 hrs

Model	Unavailability (%)
Model 4: SPTW without a spare	**1.662%**
Model 5: SPTW with a spare, major failures	**0.055%**

Sensitivity Analysis case:

Table 6.12 refers to model 1, simulation results of three-phase three winding without spare.

Failure rate (f/yr)	Repair time (hrs)	U (%)
0.0077	12	0.001
	16	0.001
	17	0.001
	48	0.004
	103	0.009
	121	0.01
	817	0.072
	2160	0.19
0.0154	12	0.002
	16	0.003
	17	0.003
	48	0.008
	103	0.018
	121	0.021
	817	0.143
	2160	0.378
0.0308	12	0.004
	16	0.006
	17	0.006
	48	0.017
	103	0.036
	121	0.043
	817	0.286
	2160	0.754
0.0462	12	0.006
	16	0.008
	17	0.009
	48	0.025
	103	0.054
	121	0.064
	817	0,429
	2160	1,126
0.0539	12	0.007
	16	0.01
	17	0.01
	48	0.03
	103	0.063
	121	0.074
	817	0,5
	2160	1,311

Table 6.13 refer to model 2, simulation results of three-phase three winding with spare, all failures treated as major failure.

Failure rate (f/yr)	Repair time (hrs)	U (%)
0.00719	16	0,001
	17	0,001
	48	0,001
	103	0,002
	121	0,002
	817	0,002
	2160	0,002
0.01438	16	0,002
	17	0,002
	48	0,002
	103	0,004
	121	0,004
	817	0,004
	2160	0,004
0.02876	16	0,005
	17	0,005
	48	0,005
	103	0,008
	121	0,008
	817	0,008
	2160	0,01
0.04314	16	0,007
	17	0,007
	48	0,007
	103	0,012
	121	0,012
	817	0,012
	2160	0,016
0.05033	16	0,009
	17	0,009
	48	0,009
	103	0,014
	121	0,014
	817	0,015
	2160	0,019

Table 6.14 refers to model 3 simulation results of three-phase three winding with spare, two failure modes: minor and major

Major failure rate (f/yr)	Minor failure rate (f/yr)	Repair time (hrs)	U (%)
0.00719	5.09E-04	16	0.001
		17	0.001
		48	0.001
		103	0.002
		121	0.002
		817	0.002
		2160	0.002
	1.02E-03	16	0.001
		17	0.001
		48	0.001
		103	0.002
		121	0.002
		817	0.002
		2160	0.002
	2.04E-03	16	0.002
		17	0.002
		48	0.002
		103	0.002
		121	0.002
		817	0.002
		2160	0.002
	3.05E-03	16	0.002
		17	0.002
		48	0.002
		103	0.002
		121	0.002
		817	0.002
		2160	0.003
	3.56E-03	16	0.002
		17	0.002
		48	0.002
		103	0.002
		121	0.002
		817	0.003
		2160	0.003

Continue Table 6.14,

Major failure rate (f/yr)	Minor failure rate (f/yr)	Repair time (hrs)	U (%)
0.01438	5.09E-04	16	0.003
		17	0.003
		48	0.003
		103	0.004
		121	0.004
		817	0.004
		2160	0.004
	1.02 E-03	16	0.003
		17	0.003
		48	0.003
		103	0.004
		121	0.004
		817	0.004
		2160	0.005
	2.04E-03	16	0.003
		17	0.003
		48	0.003
		103	0.004
		121	0.004
		817	0.004
		2160	0.005
	3.05E-03	16	0.003
		17	0.003
		48	0.003
		103	0.004
		121	0.004
		817	0.004
		2160	0.005
	3.56E-03	16	0.003
		17	0.003
		48	0.003
		103	0.004
		121	0.004
		817	0.004
		2160	0.005

Continue Table 6.14

Major failure rate (f/yr)	Minor failure rate (f/yr)	Repair time (hrs)	U (%)
0.02876	5.09E-04	16	0.005
		17	0.005
		48	0.005
		103	0.008
		121	0.008
		817	0.008
		2160	0.01
	1.02E-03	16	0.005
		17	0.005
		48	0.005
		103	0.008
		121	0.008
		817	0.008
		2160	0.01
	2.04E-03	16	0.005
		17	0.005
		48	0.005
		103	0.008
		121	0.008
		817	0.008
		2160	0.01
	3.05E-03	16	0.005
		17	0.005
		48	0.005
		103	0.008
		121	0.008
		817	0.009
		2160	0.01
	3.56E-03	16	0.005
		17	0.005
		48	0.005
		103	0.008
		121	0.008
		817	0.009
		2160	0.01

Continue Table 6.14

Major failure rate (f/yr)	Minor failure rate (f/yr)	Repair time (hrs)	U (%)
0.04314	5.09E-04	16	0.007
		17	0.007
		48	0.007
		103	0.012
		121	0.012
		817	0.013
		2160	0.016
	1.02E-03	16	0.008
		17	0.008
		48	0.008
		103	0.012
		121	0.012
		817	0.013
		2160	0.016
	2.04E-03	16	0.008
		17	0.008
		48	0.008
		103	0.012
		121	0.012
		817	0.013
		2160	0.016
	3.05E-03	16	0.008
		17	0.008
		48	0.008
		103	0.012
		121	0.012
		817	0.013
		2160	0.016
	3.56E-03	16	0.008
		17	0.008
		48	0.008
		103	0.012
		121	0.012
		817	0.013
		2160	0.016

Continue Table 6.14

Major failure rate (f/yr)	Minor failure rate (f/yr)	Repair time (hrs)	U (%)
0.05033	5.09E-04	16	0.009
		17	0.009
		48	0.009
		103	0.014
		121	0.014
		817	0.015
		2160	0.019
	1.02E-03	16	0.009
		17	0.009
		48	0.009
		103	0.014
		121	0.014
		817	0.015
		2160	0.019
	2.04E-03	16	0.009
		17	0.009
		48	0.009
		103	0.014
		121	0.014
		817	0.015
		2160	0.019
	3.05E-03	16	0.009
		17	0.009
		48	0.009
		103	0.014
		121	0.014
		817	0.015
		2160	0.019
	3.56E-03	16	0.009
		17	0.009
		48	0.009
		103	0.014
		121	0.014
		817	0.015
		2160	0.019

Table 6.15 refers to model 4 simulation results of single-phase three winding without spare, all failures treated as major failure

Failure rate (f/yr)	Repair time (hrs)	U (%)
0.005275	16	0.003
	17	0.003
	48	0.009
	103	0.018
	121	0.022
	817	0.135
	2160	0.306
0.01055	16	0.006
	17	0.006
	48	0.017
	103	0.037
	121	0.043
	817	0.27
	2160	0.61
0.0211	16	0.012
	17	0.012
	48	0.035
	103	0.074
	121	0.086
	817	0.54
	2160	1.213
0.03165	16	0.017
	17	0.018
	48	0.052
	103	0.110
	121	0.129
	817	0.808
	2160	1.809
0.036925	16	0.020
	17	0.021
	48	0.06
	103	0.129
	121	0.151
	817	0.942
	2160	2.104

Table 6.15 refers to model 5 simulation results of single-phase three winding with spare, all failures treated as major failure

Failure rate (f/yr)	Repair time (hrs)	U (%)
0.005275	16	0.003
	17	0.003
	48	0.003
	103	0.004
	121	0.004
	817	0.004
	2160	0.005
0.01055	16	0.005
	17	0.005
	48	0.005
	103	0.009
	121	0.009
	817	0.009
	2160	0.011
0.0211	16	0.011
	17	0.011
	48	0.011
	103	0.017
	121	0.017
	817	0.019
	2160	0.025
0.03165	16	0.016
	17	0.016
	48	0.016
	103	0.026
	121	0.026
	817	0.029
	2160	0.044
0.036925	16	0.019
	17	0.019
	48	0.019
	103	0.030
	121	0.030
	817	0.035
	2160	0.055

Fig 6.16 refers to model 1, section 6.2.3

- The percentage range of unavailability of TPTW without spare unit is in between 0.001 and 1.311

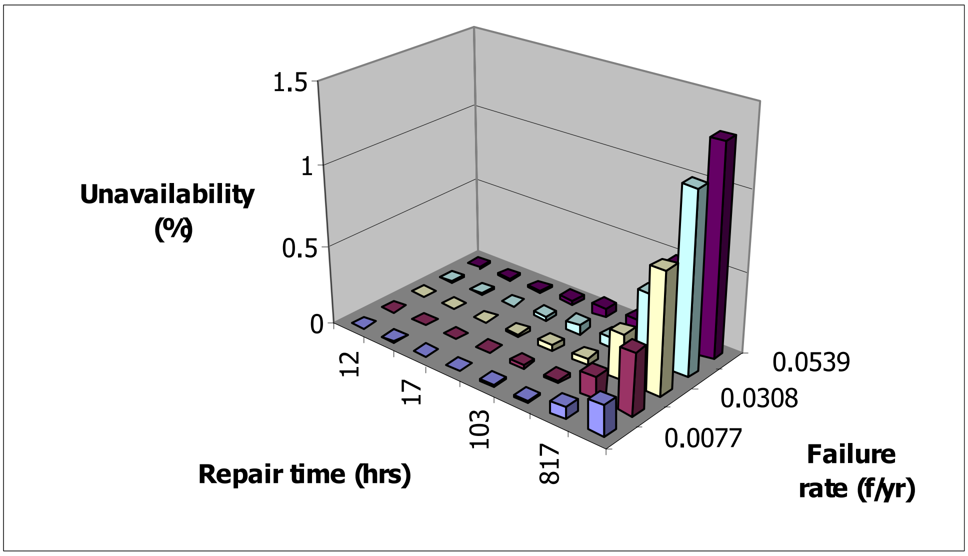


Figure 6.16: Unavailability of TPTW without spare unit, one failure mode

Fig 6.17 refers to model 2, section 6.2.4

- The percentage range of unavailability of TPTW with spare unit, all failures treated as major failure mode is in between 0.001 and 0.019

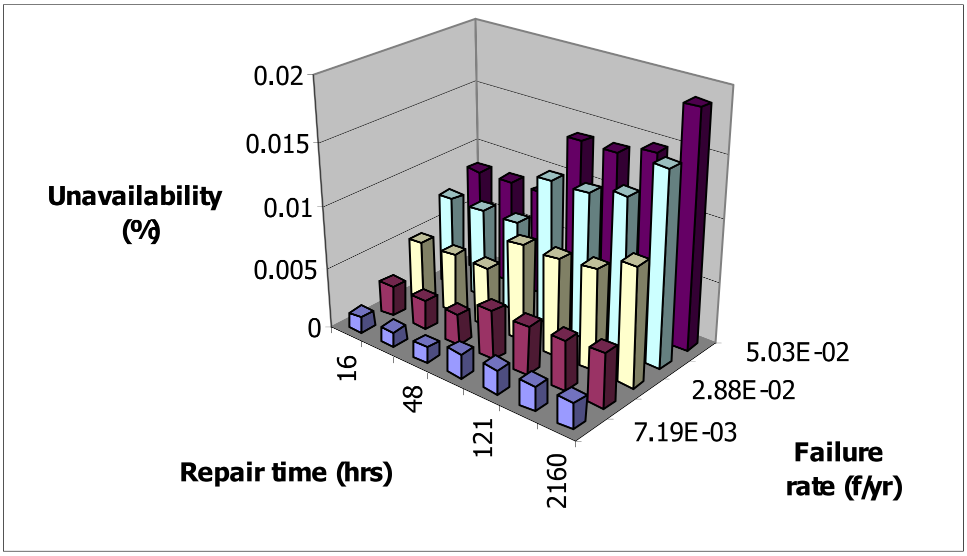


Figure 6.17: Unavailability of TPTW with spare unit, major failure mode

Fig 6.18 refers to model 3, section 6.2.5

- The percentage range of unavailability of TPTW with spare unit with two failure mode is in between 0.001 and 0.019

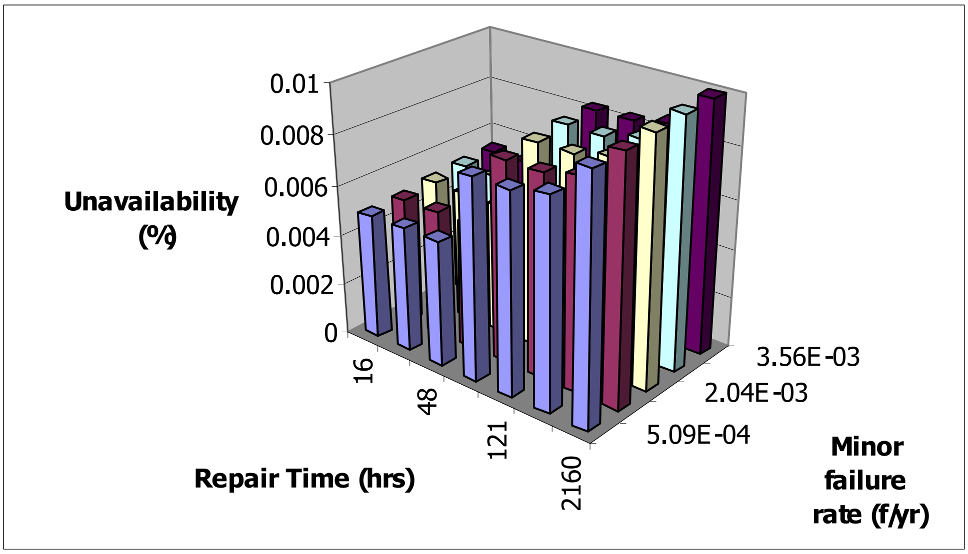


Figure 6.18: Unavailability of TPTW with spare unit, two failure modes

Fig 6.19 refers to model 4, section 6.2.6

- The percentage range of unavailability of SPTW without spare unit, all failures treated as major failure is in between 0.003 and 2.116

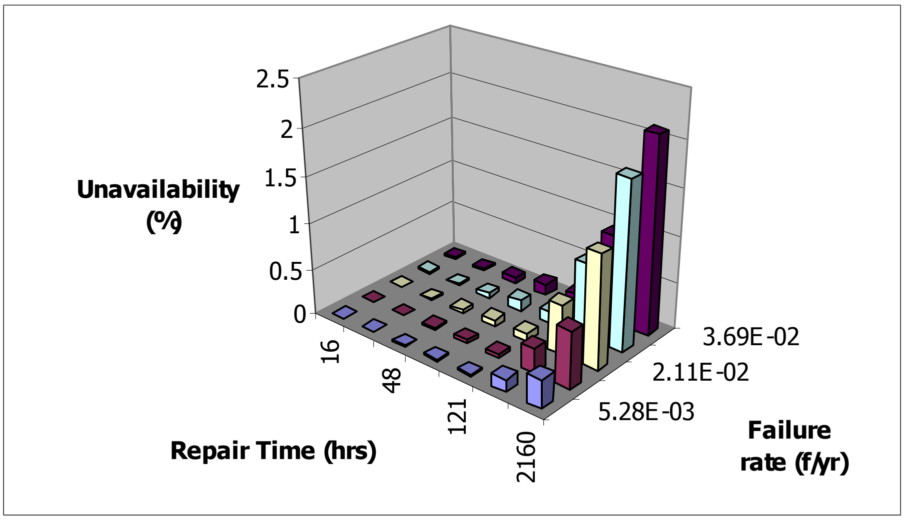


Figure 6.19: Unavailability of SPTW without spare unit, major failure mode

Fig 6.20 refers to model 5, section 6.2.7

- The percentage range of unavailability of SPTW with spare unit is in between 0.003 and 0.055

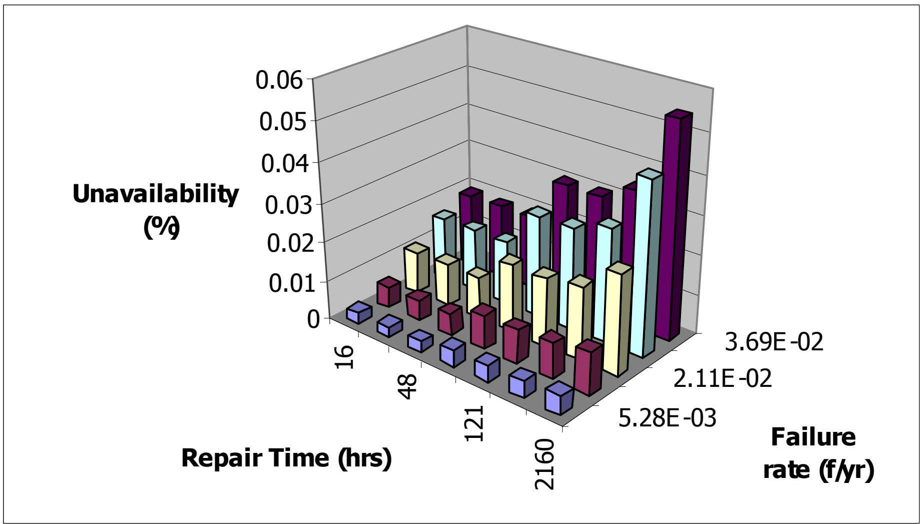


Figure 6.20: Unavailability of SPTW with spare unit, major failure mode

The trend of unavailability of CTS for both TPTW and SPTW increases when the failure rate increases. The increment of restoration time also provides the same effect to the unavailability. The failure rate seems to have more influence to the system unavailability rather than restoration time but this can not be concluded that the restoration time has less effect than failure rate. In this thesis, the restoration time is assumed only to show the difference in time that operators spend to due with the failure in the different scenarios.

6.5.1 Conclusion

The results from the assessment using CARMS tool are provided in term of the probability. The principle how to operate this tool has been presented in Chapter4 along with the basic knowledge related to Markov modelling in Chapter3. According to the simulation results, the three-phase system provides higher availability than single-phase system. It also shows the benefit of having a spare unit since the converter transformer system with a spare unit has higher availability than system without spare and less sensitive with the variability of failure rate (as shown in Table 6.16).

Table 6.16: Comparison of availability of CTS between with and without spare

	Without Spare	With Spare
Range of availability of TPTW	**98.97% - 100%**	**99.98% - 100%**
Range of availability of SPTW	**97.90% - 100%**	**99.95% - 100%**

In addition, the minor failure rate has lower effect to the availability of CTS compare with the major failure.

Table 6.17: Comparison of unavailability of TPTW between model 2 and model 3

	One failure mode	Two failure modes
Range of unavailability of TPTW	**0.001% - 0.019%**	**0.001% - 0.019**

7 Closure

7.1 Conclusion

The proposed Markov models of converter transformer systems, whether to use single-phase or three-phase units have been built in simulation tool called CARMS. The different scenarios of restoration process, different level of failure modes (one failure or two failure modes) and different level of a spare unit have been applied to the models. CARMS illustrates that the Markov modelling approach is suitable for accessing the availability of a converter transformer system when designing a HVDC link.

The results shown in Chapter 6 indicate that different configurations of CTS generate the different availability values. Other factors such as the maintenance practice also affect to the overall availability of the systems. The availability of a spare unit also influences to the results. It can be concluded that the sooner a spare unit is switched on, the higher value of the availability. This emphasizes the benefit of having a spare unit.

The major drawback of the approach is that the state diagrams of large systems are generally large and complicated to construct. The computational time of simulation tool depends on how much different between failure rate and repair rate i.e. the larger of difference, the longer computational time.

7.2 Future work

Since Markov modelling is applicable to determine long term probability of multi-state system, the system may be considered to have several derated states. According to the CIGRE report [18] describes that, in some situations, the converter transformer systems still in operation mode although failures have occurred. Therefore, it could be interested to have system with different operationing level rather than only functional or fail.

In this work, the proposed models assume that the up and down time of the components is exponentially distributed, i.e. the transition rates are constant. This assumption is made disregarded to the realistic condition such as environmental impact. The Semi-Markov process is a process in which the transitions from state to state are in accordance with a Markov chain but the time spent in a state before a transition occurs is random [21]. It may be used to make the models become more realistic. Therefore, time- dependent transition rates might be considered as a follow up work of this thesis.

Appendix

Table A.1 refers to model 1, simulation results of TPTW without spare.

Failure rate (f/yr)	Repair time (hrs)	U (%)
0.0275	12	0.004
	16	0.005
	17	0.005
	48	0.015
	103	0.032
	121	0.038
	817	0.235
	2160	0.53
0.055	12	0.008
	16	0.01
	17	0,011
	48	0,03
	103	0,064
	121	0,075
	817	0,469
	2160	1.055
0.11	12	0,015
	16	0,02
	17	0,021
	48	0,06
	103	0,128
	121	0,15
	817	0,933
	2160	2.09
0.165	12	0,023
	16	0,030
	17	0,032
	48	0,09
	103	0,192
	121	0,225
	817	1,393
	2160	3.104
0.1925	12	0,026
	16	0,035
	17	0,037
	48	0,105
	103	0,223
	121	0,262
	817	1,621
	2160	3.602

Table A.2 refer to model 2, simulation results of TPTW with spare, all failures treated as major failure.

Failure rate (f/yr)	Repair time (hrs)	U (%)
0,02568	16	0.112
	17	0,112
	48	0,112
	103	0,112
	121	0,112
	817	0,112
	2160	0,112
0,05137	16	0.112
	17	0,112
	48	0,112
	103	0,112
	121	0,112
	817	0,112
	2160	0,112
0,10273	16	0.112
	17	0,112
	48	0,112
	103	0,112
	121	0,112
	817	0,112
	2160	0,112
0,1541	16	0.112
	17	0,112
	48	0,112
	103	0,112
	121	0,112
	817	0,112
	2160	0,112
0,17978	16	0.112
	17	0,112
	48	0,112
	103	0,112
	121	0,112
	817	0,112
	2160	0,112

Table A.3 refers to model 3 simulation results of TPTW with spare, two failure modes: minor and major

Major failure rate (f/yr)	Minor failure rate (f/yr)	Repair time (hrs)	U (%)
0,02568	1,82E-03	16	0.005
		17	0.005
		48	0.005
		103	0.007
		121	0.007
		817	0.007
		2160	0.009
	3,64E-03	16	0.005
		17	0.005
		48	0.005
		103	0.008
		121	0.008
		817	0.008
		2160	0.009
	7,27E-03	16	0.005
		17	0.005
		48	0.005
		103	0.008
		121	0.008
		817	0.008
		2160	0.009
	1,09E-02	16	0.006
		17	0.006
		48	0.006
		103	0.009
		121	0.009
		817	0.009
		2160	0.01
	1,27E-02	16	0.006
		17	0.006
		48	0.006
		103	0.009
		121	0.009
		817	0.009
		2160	0.01

Continue Table A.3

Major failure rate (f/yr)	Minor failure rate (f/yr)	Repair time (hrs)	U (%)
0,05137	1,82E-03	16	0.009
		17	0.009
		48	0.009
		103	0.014
		121	0.014
		817	0.015
		2160	0.02
	3,64E-03	16	0.009
		17	0.009
		48	0.009
		103	0.015
		121	0.015
		817	0.015
		2160	0.02
	7,27E-03	16	0.01
		17	0.01
		48	0.01
		103	0.015
		121	0.015
		817	0.016
		2160	0.02
	1,09E-02	16	0.01
		17	0.01
		48	0.01
		103	0.016
		121	0.016
		817	0.016
		2160	0.02
	1,27E-02	16	0.01
		17	0.01
		48	0.01
		103	0.016
		121	0.016
		817	0.017
		2160	0.021

Continue Table A.3

Major failure rate (f/yr)	Minor failure rate (f/yr)	Repair time (hrs)	U (%)
0,10273	1,82E-03	16	0.018
		17	0.018
		48	0.018
		103	0.028
		121	0.028
		817	0.032
		2160	0.049
	3,64E-03	16	0.018
		17	0.018
		48	0.018
		103	0.029
		121	0.029
		817	0.032
		2160	0.049
	7,27E-03	16	0.019
		17	0.019
		48	0.019
		103	0.029
		121	0.029
		817	0.003
		2160	0.05
	1,09E-02	16	0.019
		17	0.019
		48	0.019
		103	0.03
		121	0.03
		817	0.033
		2160	0.05
	1,27E-02	16	0.019
		17	0.019
		48	0.019
		103	0.03
		121	0.03
		817	0.034
		2160	0.051

Continue Table A.3

Major failure rate (f/yr)	Minor failure rate (f/yr)	Repair time (hrs)	U (%)
0,1541	1,82E-03	16	0.027
		17	0.027
		48	0.027
		103	0.042
		121	0.043
		817	0.051
		2160	0.089
	3,64E-03	16	0.027
		17	0.027
		48	0.027
		103	0.043
		121	0.043
		817	0.051
		2160	0.09
	7,27E-03	16	0.028
		17	0.028
		48	0.028
		103	0.043
		121	0.044
		817	0.052
		2160	0.09
	1,09E-02	16	0.028
		17	0.028
		48	0.028
		103	0.044
		121	0.044
		817	0.052
		2160	0.09
	1,27E-02	16	0.029
		17	0.029
		48	0.029
		103	0.044
		121	0.045
		817	0.053
		2160	0.09

Continue Table A.3

Major failure rate (f/yr)	Minor failure rate (f/yr)	Repair time (hrs)	U (%)
0,17978	1,82E-03	16	0.031
		17	0.031
		48	0.031
		103	0.05
		121	0.05
		817	0.061
		2160	0.112
	3,64E-03	16	0.031
		17	0.031
		48	0.031
		103	0.05
		121	0.05
		817	0.061
		2160	0.011
	7,27E-03	16	0.032
		17	0.032
		48	0.032
		103	0.05
		121	0.051
		817	0.062
		2160	0.113
	1,09E-02	16	0.033
		17	0.033
		48	0.033
		103	0.051
		121	0.051
		817	0.062
		2160	0.114
	1,27E-02	16	0.033
		17	0.033
		48	0.033
		103	0.052
		121	0.052
		817	0.063
		2160	0.114

Table A.4 refers to model 4 simulation results of SPTW without spare, all failures treated as major failure

Failure rate (f/yr)	Repair time (hrs)	U (%)
0,03735	16	0.02
	17	0.022
	48	0.061
	103	0.13
	121	0.153
	817	0.95
	2160	2.128
0,0747	16	0.041
	17	0.043
	48	0.122
	103	0.26
	121	0.305
	817	1.882
	2160	4.171
0,11494	16	0.082
	17	0.087
	48	0.244
	103	0.52
	121	0.609
	817	2.867
	2160	6.284
0,2241	16	0.123
	17	0.13
	48	0.366
	103	0.778
	121	0.909
	817	5.443
	2160	11.59
0,26145	16	0.143
	17	0.152
	48	0.427
	103	0.907
	121	1.062
	817	6.293
	2160	13.28

Table A.5 refers to model 5 simulation results of SPTW with spare, all failures treated as major failure

Failure rate (f/yr)	Repair time (hrs)	U (%)
0,03735	16	0.019
	17	0.019
	48	0.019
	103	0.031
	121	0.031
	817	0.035
	2160	0.056
0,0747	16	0.038
	17	0.038
	48	0.038
	103	0.062
	121	0.062
	817	0.079
	2160	0.159
0,11494	16	0.077
	17	0.077
	48	0.077
	103	0.095
	121	0.095
	817	0.137
	2160	0.319
0,2241	16	0.115
	17	0.115
	48	0.116
	103	0.186
	121	0.187
	817	0.34
	2160	0.98
0,26145	16	0.134
	17	0.134
	48	0.135
	103	0.217
	121	0.219
	817	0.425
	2160	1.273

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