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Full Length Research Paper

Reliability assessment of 3-phase three winding converter transformer of HVDC transmission system

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High voltage direct current (HVDC) is today recognized as an effective and efficient means of transmitting bulk power over long distances through over head 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. The HVDC converter transformer plays a relevant roll in HVDC converter station, not only due to the direct cost associated to them but also causes its availability affects the HVDC transmission capability (or) capacity. In this paper the effect of converter transformer failure rate, repair time on expected capacity level of three phase three winding converter transformer with and without spares is analyzed and compared. It also effect of number of spares on expected capacity level is presented.

Key words: HVDC transmission system, converter transformer, unavailability, Morkov modeling.

INTRODUCTION

High voltage DC transmission is growing much importance in evaluating reliability analysis of composite power systems due to its advantages and applications (Bhagawan, 2001). There is need to study the reliability analysis of equipment behaviors of each component in the HVDC system (CIGRE Joint Task Force, 2004). The HVDC system has been treated as a whole unit consisting of AC equipment, converter transformer, pole equipment, filters etc. It is well known that system reliability can be modeled by a continuous time homogeneous Morkov process whenever the components of the system have constant failure and repair rates (Singh and Billinton, 1977; Descrochrs, 1985).

The availability of HVDC systems has always been of primary concern in the planning and operation of power systems. The reliability requirements differ from project to project and are specified at a very early stage of project. The system is always designed and built with a certain degree of reliability i.e it is guarantee a particular line of availability of HVDC system (Hamoud et al., 2004; Direct Current Transmission, Volume 1). The total availability of the components in the line and at the stations. Among the various components and subsystems existing at an HVDC station, the converter transformer system (CTS) has a significant impact on the total availability of the HVDC system (Setres and Bertling, 2008: Hwan-Cha, 2006). To improve the availability of the HVDC station, spare transformers are usually provided so that in case of major failure, a switching to spare action can be taken to restore the link as soon as possible.

This leads to the fact that the availability of an HVDC station also depends on the existence of spare converter transformer (Billinton and Ronald). Moreover, spare transformers can be located at one or both stations, at supplier facilities located in the same country or overseas. Nevertheless, spare units are costly and this has to be taken into the account when the balance between the additional cost and the improved performance is considered (Leelaruji, 2007; Roy and Prasad, 1970).

Therefore, the evaluation of the expected availability of the CTS of HVDC stations is of most importance in the decision making.

In this paper Markov models for 3 phase three winding converter transformer system with and without spares is analyzed and compared.

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METHODOLOGY

In this paper Markov modeling approach 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.

A Markov model can be applied to systems whose random behavior varies either discretely or continuously with time. In this paper Markov modeling has been adapted. Figure 1 shows a basic example of two state systems.

In Figure 1 there are two states up state (State 1) and down state (State 2). There are two transitions associated with each component, the first L representing the failure process and the second M representing the repair process. This model implies that the component becomes operational and in service immediately following the repair action. The duration of the failure is limited to the time it takes to install the spare unit rather than to repair of the equipment itself.

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

$$PQ = 0, \quad \sum P_i = 1 \qquad \text{……………(1)}$$

Here P_i is a row vector and

Q = transition rate matrix for the Markov process.

$$\begin{pmatrix} P_{11} & P_{12}\dots\dots\dots P_{1n} \\ P_{21} & P_{22}\dots\dots\dots P_{2n} \\ \dots\dots\dots & \dots\dots\dots \\ P_{n1} & P_{n2}\dots\dots\dots P_{nn} \end{pmatrix} \qquad \text{………(2)}$$

In this matrix P_{ij} is the transition rate from state i to state j. The diagonal element P_{ii} defined as:

$$P_{ii} = 1 - \sum P_{ij} \qquad \text{…………(3)}$$

HVDC technology

High voltage direct current transmission is used to interconnection between two AC systems. These HVDC technologies are two types HVDC classic and HVDC light. HVDC Classic converters are driven by thyristor valves and HVDC light converters are driven by IGBTS. In this paper HVDC classic are designed with converter valves connected in 12-pulse configuration, in order to reduce the harmonics. In HVDC system converter transformer is connected in series with the 12-pulse converter at both ends.

The types of converter transformers used in HVDC transmission systems are:

1. Three Single Phase Three Winding (SPTW)
2. Two Three Phase Two Winding (TPTW)
3. Six Single Phase Two Winding (SSPTW)
4. One Three Phase Three Winding (TPTW)

In this paper the effect of failure rate and number of spares on expected capacity level of three phase three winding converter transformer at different capacity values is analyzed and compared.

State space model of converter transformer without spare

State space model of three phase three winding transformer is as shown in Figure 2.

State 1 represents operating or up state, when the transformer is up. When the transformer fails, a transition to state 2 occurs, with a rate of L, and the operation of CTS will be shut down. When any unit fails immediately a spare unit is ordered to be transported to the site. The transportation rate for the transformer to arrive is M, when the transformer arrives it is installed with the rate of G.

Using STPM approach:

$$\alpha P = \alpha \qquad \text{……..…(4)}$$

Where α is a row vector.

$$[P_1\ P_2\ P_3] \begin{pmatrix} 1-L & L & 0 \\ 0 & 1-M & M \\ G & 0 & 1-G \end{pmatrix} = [P_1\ \ P_2\ \ P_3\ ] \qquad \text{..…. (5)}$$

Writing the state equations for Equation 5,

$$P_1\,[1 - L] + P_3G = P_1 \qquad \text{……….(6)}$$
$$P_1L + P_2\,[1 - M] = P_2 \qquad \text{………(7)}$$
$$P_2M + P_3\,[1 - G] = P_3 \qquad \text{……(8)}$$

We know that $P_1 + P_2 + P_3 = 1$ ……(9)

Putting Equations 6, 7 and 9 in matrix form:

$$\begin{pmatrix} -L & 0 & G \\ L & -M & 0 \\ 1 & 1 & 1 \end{pmatrix} \begin{pmatrix} P_1 \\ P_2 \\ P_3 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \qquad \text{… (10)}$$

Applying Cramer's rule to the above Equation 10; The obtained probabilities are:

$$P_1 = \frac{GM}{GM + LM + LG}$$

$$P_2 = \frac{LG}{GM + LM + LG}$$

$$P_3 = \frac{LM}{GM + LM + LG}$$

For selected values of failure rates the expected capacity level of converter transformer without spare is tabulated as shown in Table 1.

State space model of converter transformer with one spare

Consider now the situation that could exist it one spare was normally available. In this case, when a transformer fails, it can be replaced by the spare. Provided that either the spare has not already been used or the component it has replaced has been repaired and is available as a spare. This provides the state space model of three phase three winding converter transformer with one spare as shown in Figure 3.

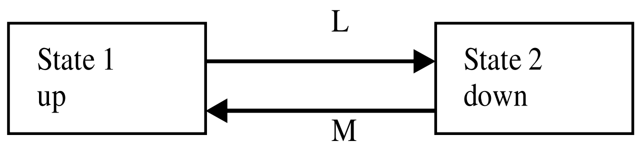

Figure 1. State space diagram of two state Markov process.

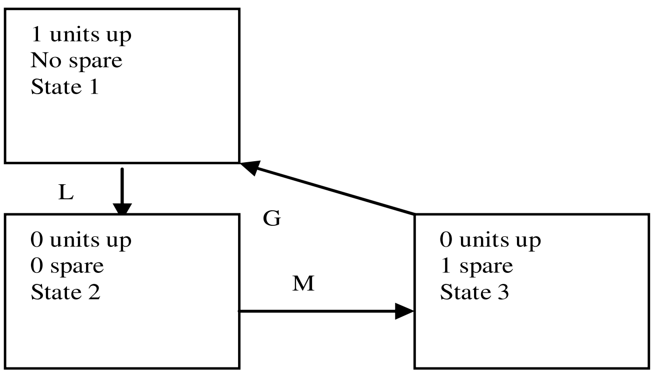

Figure 2. State space model of three phase three winding converter transformer without spare. Where L = Transformer failure rate, M = Transformer repair time, G = Transformer installation time.

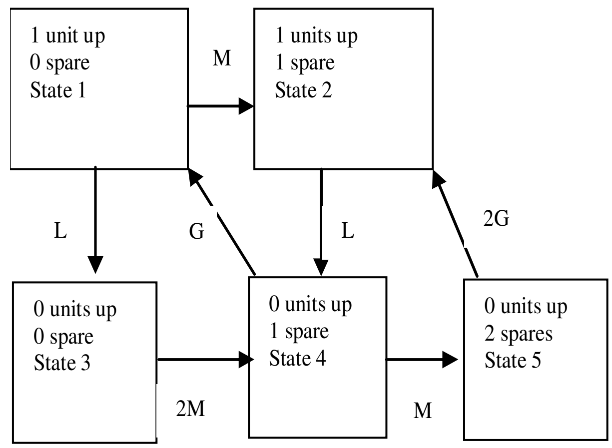

Figure 3. State space model of three phase three winding converter transformer with one spare.

In Figure 3, States 1 and 2 are up states, states 3 to 7 are down states. For selected values of failure rates (ref from CIGRE) expected capacity level of converter transformer at different capacity values is evaluated and tabulated in Table 2.

When number of spares increase number states also increases so it is difficult to find out the limiting state probabilities. Therefore, software has been developed in CPP to find the limiting state probability values of three phase three winding converter transformer with two spares. Figure 4 shows the state space diagram of three phase three winding converter transformer with two spares.

Similarly for selected failure rates expected capacity level of three phase three winding converter transformer with two spares at different capacity values are evaluated and tabulated in Table 3.

Description of tables

The failure rate data for the three phase converter transformer is based on data from CIGRE joint task force.

In Table 1 first column represents failure rates of converter transformer column 2 reliability values and columns 3, 4, 5 and 6 represents expected capacity level of three phase three winding transformer without spares at different capacity values. Similarly Tables 2 and 3 represents effect of failure rates on expected capacity level of three phase three winding transformer with one and two spares at different capacity values.

RESULT ANALYSIS

In this paper effect of failure rate and number of spares on three phase three winding converter transformer is analyzed. From the report of CIGRE maximum major failure rate is taken as 2.0 f/yr (percentage). The repair time in worst case is taken as 90 h. Installation time is taken as 48 h. The results from three tables are represented graphically in the following Figures 5 to 8.

Figures 5, 6 and 7 shows the variation in expected capacity level due to variation in failure rate at 120, 150, 180 and 300 MVA capacity values. In Figures 5, 6 and 7 curve 1 represents expected capacity level at 120 MVA. Curves 2, 3 and 4 represents expected capacity levels at 150, 180 and 300 MVA, respectively.

In Figures 6 and 7 variations in expected capacity level is less as compared to Figure 5. Figure 8 shows the effect of number of spares on expected capacity level of three phase three winding converter transformer at failure rate 0.1f/yr, repair time 90 days and installation time 48 h with and without spares.

In Figure 8 curve 1 shows variation of expected capacity level at 120 MVA at spares one, two, three and without spares. Similarly curves 2, 3 and 4 at 150,180 and 300 MVA, respectively.

Conclusion

This paper has shown the benefit of using Markov models in the evaluation of expected capacity level of three phase three winding transformer with and without spares.

Table 1. Expected capacity level of three phase three winding converter transformer without spare.

Failure rate	Reliability	Expected capacity level of three phase three winding transformer			
		120 MVA	150 MVA	180 MVA	300 MVA
0.01	0.997452	119.69	149.61	179.53	299.23
0.02	0.994916	119.38	149.23	179.0	298.47
0.05	0.987387	118.48	148.10	177.73	296.21
0.09	0.977524	117.302	146.63	175.95	293.26
0.1	0.975088	117.91	146.26	175.51	292.53
0.5	0.886729	106.4	133.0	159.61	266.01
0.8	0.8303	99.636	124.54	149.45	249.09
1.0	0.796508	95.58	119.48	143.37	238.95
1.5	0.722951	88.754	108.44	130.13	216.88
2.0	0.661831	79.42	99.24	119.13	198.549

Table 2. Expected capacity level of three phase three winding converter transformer with one spare.

Failure rate	Reliability	Expected capacity level of three phase three winding transformer			
		120 MVA	150 MVA	180 MVA	300 MVA
0.01	0.997748	119.99	149.99	179.99	299.99
0.02	0.999878	119.8	149.98	179.98	299.98
0.05	0.959777	119.96	149.96	179.96	299.98
0.09	0.99832	119.91	149.89	178.89	299.78
0.1	0.998157	119.64	149.55	179.45	299.0
0.5	0.98956	118.86	148.58	178.3	297.17
0.8	0.96453	117.57	146.96	176.36	293.9
1.0	0.70031	116.52	145.65	174.77	291.29
1.5	0.942207	113.4	141.75	170.1	283.5
2.0	0.90682	109.85	137.31	164.77	274.62

Table 3. Expected capacity level of three phase three winding converter transformer with two spares.

Failure rate	Reliability	Expected capacity level of three phase three winding transformer			
		120 MVA	150 MVA	180 MVA	300 MVA
0.01	0.9997295	119.99	149.99	179.99	299.99
0.02	0.999944784	119.99	149.99	179.99	299.99
0.05	0.99862093	119.98	149.98	179.98	299.98
0.09	0.999747	119.96	149.96	179.96	299.96
0.1	0.999718	119.96	149.96	179.96	299.96
0.5	0.998214	119.78	149.78	179.78	299.78
0.8	0.99642	119.57	149.46	179.35	298.72
1.0	0.994804	119.37	149.22	179.06	298.44
1.5	0.989075	118.68	148.36	178.3	296.72
2.0	0.980797	117.69	147.11	176.58	294.24

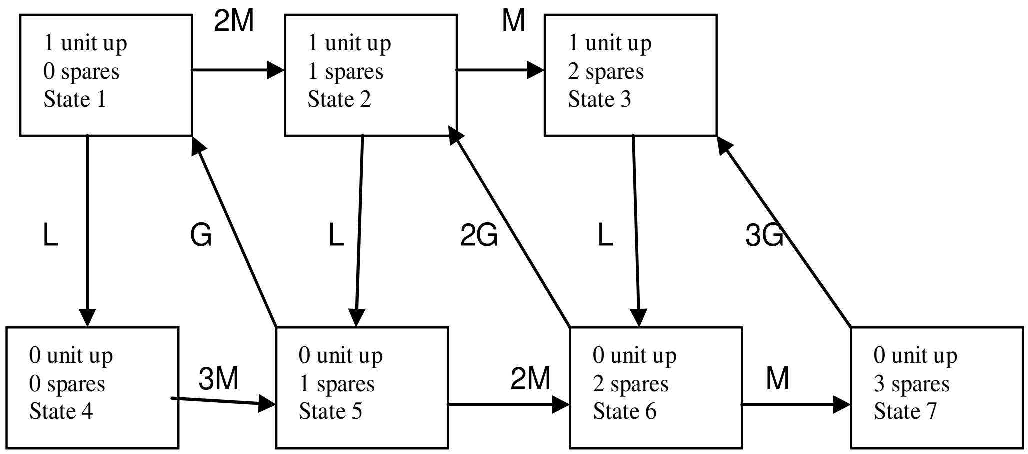

Figure 4. State space model of three phase three winding converter transformer with two spares.

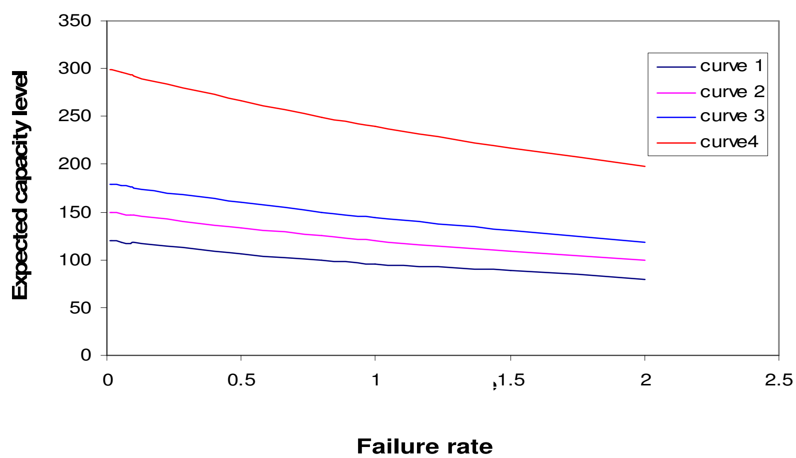

Figure 5. Expected capacity level of converter transformer without spare.

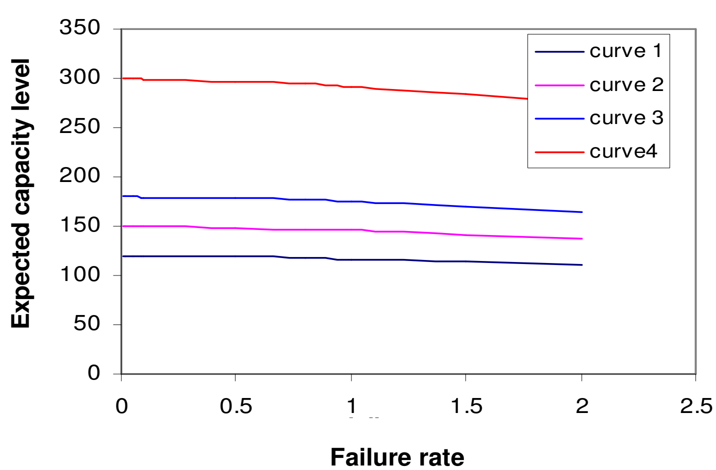

Figure 6. Expected capacity level of converter transformer with one spare.

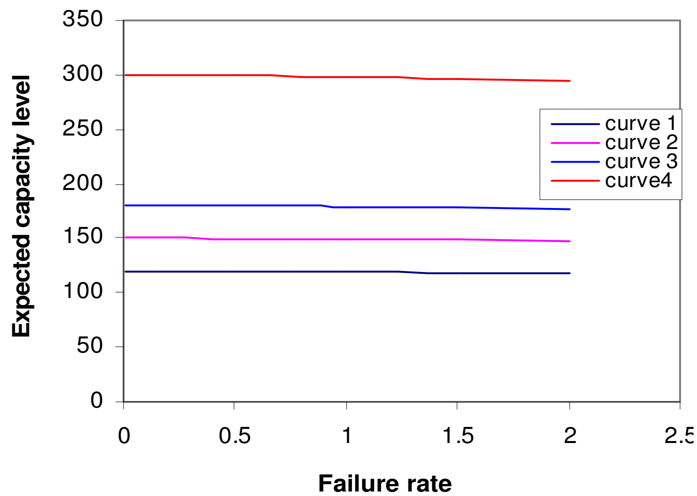

Figure 7. Expected capacity level of converter transformer with two spares.

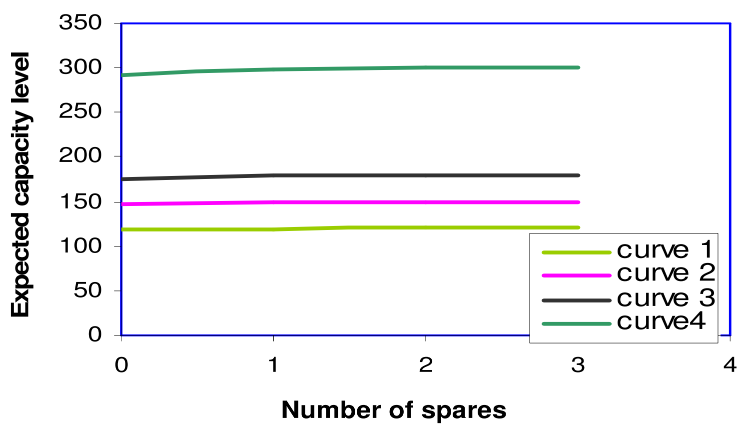

Figure 8. The effect of number of spares on expected capacity level of converter transformer.

According to the results it has been observed that increase in failure rate decreases the expected capacity level of the transformer. An attempt was also taken to reduce the effect of failure rate by increasing the number of spares which also concluded an increase in number of spares which increases the expected capacity level of the transformer.

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