

# Reliability Model of Power Transformer with ONAN Cooling

M. Sefidgaran\*, M. Mirzaie\* and A. Ebrahimzadeh\*

**Abstract:** Reliability of a power system is considerably influenced by its equipments. Power transformers are one of the most critical and expensive equipments of a power system and their proper functions are vital for the substations and utilities. Therefore, reliability model of power transformer is very important in the risk assessment of the engineering systems. This model shows the characteristics and functions of a transformer in the power system. In this paper the reliability model of the power transformer with ONAN cooling is obtained. The transformer is classified into two subsystems. Reliability model of each subsystem is achieved. Markov process representation and the frequency/ duration approach are employed to obtain a complete reliability model of the subsystems. By combining these models reliability model of power transformer is obtained. The reliability model associated with the transformer is then proposed combining the models of subsystems. The proposed model contains five states. To make the model more applicable, the 5-state model is alleviated to a 3-state one. Numerical analysis and sensitivity analysis relevant to the proposed reliability model are performed for evaluating the numerical values of the model parameters and the impact of different components on the reliability of the model.

**Keywords:** Power Transformer, ONAN Cooling, Reliability, Markov Model.

## 1 Introduction

In electrical power network, the transformer is the most crucial and the most device and its proper functions is very critical for the utility. So, Evaluation and improvement of the reliability of transformers are very important. The first step for obtaining this purpose is to find out the causes of transformer failures and to determine transformer outage. In [1] more than 1000 failures, that had occurred between 1968 and 1978, are collected. It has been found that, in general, the failure rate of a transformer is about 2% per unit-year. In this paper, failures have been categorized by failed components, failure origins and failure causes of autotransformers, power station and substation transformers. In [2] the fault tree diagram of transformer is described. The fault tree model consists of the possible systems that could cause a transformer failure, subsystems that could fail and consequently leads to a system failure and potential root causes of the subsystem failures.

Monitoring and diagnostic method is one way for improving the reliability of transformers. In [3] traditional diagnostic methods and nontraditional transformer monitoring techniques are investigated. It declares that, monitoring and diagnostic techniques monitor and predict the transformer failures, so that appropriate actions can be taken before the occurrence of forced outage. Using this method, reliability of transformers could be increased. Evaluating the life and predicting the reliability of transformers are alternative, useful techniques for improving their reliability. In [4] novel techniques for life assessment of the transformer insulation have been presented and estimated by using of load and ambient temperature. This estimating residual life of insulation can enhance maintenance and repairing action of transformer owners. In [5], based on the mechanical strength of winding insulation paper (degree of polarization), the reliability of a power transformer is determined. In the paper a validation method for the modeling technique has been presented and also degree of polarization insulation paper has been estimated by load pattern and ambient temperature. In [6] Fault Tree Analysis (FTA) and Monte Carlo algorithm are combined to analyze the reliability of transformer. Fault trees are built. By using the fault tree, Monte carlo is applied to quantitatively analysis the model. Then the reliability index and cell importance

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parameter help to find out the weak link of the system. result show that the method has guiding significance for System Reliability Analysis.

One of the important methods in reliability investigation and the first step in system risk evaluation is to determine the components outage models [7]. This model is also known as Markov model and achieved for many equipment. In [8], [9] and [10] Markov models of protection device, transformer protection and unified power flow controller (UPFC) have been achieved. [11] Presents new probabilistic methodologies for computing the optimal number of transformer spares for power distribution substations. Two new models are proposed for the reliability evaluation step. In the first one, the system operational states are represented by a Markov process. The second one uses a chronological Monte Carlo simulation model to assess the reliability performance of a system with inventory of spares. Sensitivity analyses showed that the proposed models are capable of satisfactorily identifying the optimal inventory, considering parameters such as failure and replenishment rates of the inventories, besides costs associated with system operation and investment in the procurement of new equipment. But no work has been done on markov model of power transformer yet. In this paper reliability model of the power transformer with ONAN (Oil Natural Air Natural) cooling is presented. The transformer is categorized into two subsystems. First, a reliability model associated with each subsystem archived. The reliability model of the power transformer is then proposed by combining the models of subsystems. Outage model and frequency-duration approach applied to achieve a complete model of power transformer.

The paper is organized as follows. In Section 2 structure of a power transformer is analyzed and it is classified it into two subsystems. In Section 3 and 4 reliability model of each of two subsystems have been obtained. The complete reliability model of a transformer is presented in Section 5. Section 6 represents with the numerical study on reliability data and finally the paper is concluded in Section 7.

## 2 Power Transformer

Power transformers consist of different parts. Core and winding are two main components of the transformer, belonging to the part known as the active part of the transformer. The core has the role of carry magnetic flux. The windings are arranged as cylindrical shells around the core, each one is covered with insulation paper. The function of the windings is to carry current. Active part of the transformer is contained inside the tank which physically protects it. The tank is also the container of the oil. On-load tap-changer (OLTC), by adding or subtracting turns of the windings, regulates the voltage level of the transformer. Bushings, one of the important components of the transformer, connect the windings and the power system. Cooling

system is used to cool the active part of the transformer. Power transformers utilize different class of cooling systems. In this paper the transformer with ONAF cooling is considered.

Components of the power transformer are grouped into three subsystems; the core, windings, tank and dielectric fluid as the subsystem 1, bushing, tap-changer and cooling system 3 as the subsystem2. At first, models for the two subsystems are proposed, then using these models, complete reliability model for the power transformer is obtained.

It should be noted that the loading type affects the reliability model. In this paper, loading is assumed to be the normal life expectancy loading. The main challenge of the normal life expectancy loading is to perform continuous loading at the rated output under the usual conditions. Operation under usual conditions is equivalent to the operation in the average ambient temperature of 30 °C for cooling air or 25 °C for cooling water [12].

## 3 Reliability Model of Subsystem 1

Subsystem 1 consists of the windings , core, tank and dielectric fluid. To achieve a model for this subsystem, two models for windings and the resting components are proposed in the following subsections.

### 3.1 Winding State-Space Model

Large amount of failures occur in winding, the most prevalent one is short circuit. If short circuit is severe, it will damage the transformer. In this situation, the system fails or it must be immediately removed from service. But some faults do not cause the outage of the transformer and just disturb the normal operation of the system. Preventive tests and on-line monitoring help us to diagnose these types of faults. The most successful technique for on-line fault diagnosis is dissolved gas-in-oil analysis (DGA). By the aid of the DGA results, several types of faults in the transformer can be detected. One of these fault is thermal fault with temperature in the range of 300 and 700 (T2). When this fault occurs while transformer in operation, discission should be taken based on the required loading of the power network and type and location of the fault. If the utility does not need the transformer forcedly, it is removed from service for repairing actions. Even if the utility trend is to hold it in the network, only in some cases it is possible to keep it in the network. It is possible when fault is placed in the area, in which by reducing load can be result in diminishing temperature of the hot spot. In [13], typical locations of power transformer faults are mentioned. Abraded insulation between adjacent parallel conductors in windings is one of the faults that lead to T2. When this fault occurs, by reducing load to about 20-50 percent of rated power, the transformer can be remained in service.

According to above statements, state-space reliability model of windings contain three state is

shown in Fig. 1. State 1 is related to the condition in which no fault occurs in windings. State 2 shows the status that windings failure leads to removal of the transformer from service. State 3 demonstrates the condition that windings have fault but by reducing the load, transformer will remain in service. Parameters in Fig. 1 are as follows:

- $\lambda_{wd}$  : winding failure rate
- $\lambda_{1wd}$  : winding fault rate that does not cause removal of the transformer from the service
- $\lambda_{2wd}$  : faulty winding failure rate
- $\mu_{wd}$  : winding repair rate

### 3.2 Core, Tank and Dielectric Fluid State-Space Model

In this section, reliability model of core, tank and oil of the transformer is obtained. Core has two states, up and down. Tank and oil together have two similar states, and they are considered as one component. Also, by increasing viscosity of oil, cooling reduces and subsequently load of transformer must be reduced, but this situation rarely happens and so it is negligible. If faults occur in one of the core or tank and dielectric fluid, the transformer fails, therefore these are series components. The set of equations for these components are [7]:

$$\lambda_{ctd} = \lambda_{core} + \lambda_{ta\&de} \quad (1)$$

$$r_{ctd} = \frac{\lambda_{core} r_{core} + \lambda_{ta\&de} r_{ta\&de} + \lambda_{core} r_{core} \lambda_{ta\&de} r_{ta\&de}}{\lambda_{core} + \lambda_{ta\&de}} \quad (2)$$

$$U_{ctd} = U_{core} + U_{ta\&de} - U_{core} U_{ta\&de} \quad (3)$$

where  $\lambda_{core}$  and  $\lambda_{ta\&de}$  are failure rates of the core and tank & dielectric fluid.  $r_{core}$ ,  $r_{ta\&de}$ ,  $U_{core}$  and  $U_{ta\&de}$  are repair times of core and tank & dielectric fluid and unavailability of core and tank & dielectric fluid, respectively. Space-state of these components are shown in Fig. 2.

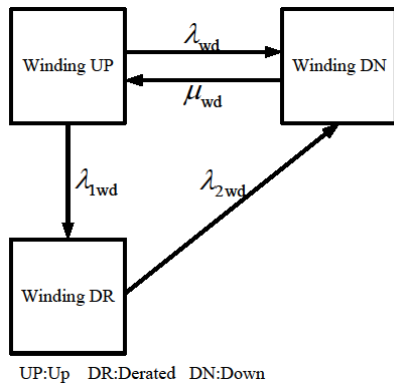
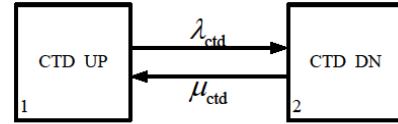


Fig. 1 State-space model of winding.



CTD: Core, Tank and Dielectric fluid

Fig. 2 State-space model of core, tank and dielectric fluid.

### 3.3 Complete Reliability Model of Subsystem 1

Reliability models of winding and other components of this subsystem (core, tank and dielectric fluid) are combined to establish the reliability model associated with the entire subsystem 1 (Fig. 3).

In this Markov representation, it is assumed that when subsystem fails as a failure of one component, no subsequent fail occurs in other components until the subsystem comes back to service. Another remark in Fig. 3 is about transferring from the state C to D. In state C, although fault has been occurred in windings, subsystem still works. However due to this fault, transformer operates in a derated state. Other components of this subsystem are healthy. As the fault occurs in the healthy components of this subsystem, the subsystem enters into the state D. This state is a zero capacity state for the subsystem. Therefore, the transformer will be removed from service. Although the fault occurring in state C is a kind of fault that can remove subsystem from service, but for force need it still remains in service. Thus when subsystem is removed from service, winding is completely failed, too and repairing actions on this winding are similar to fail winding.

The complete state-space model of the subsystem 1 can be reduced to three states as shown in Fig. 4. States 1, 2 and 3 represent full, zero and derated capacity, respectively.

Indices of Fig. 4 can be by achieved using the frequency balance approaches follows [14]:

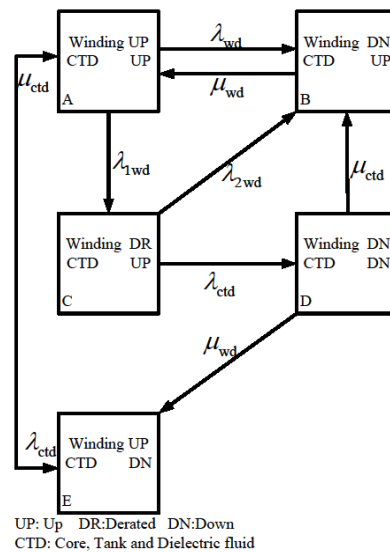


Fig. 3 Complete state-space model of subsystem 1.

$$P_1 = P_A \quad (4)$$

$$P_2 = P_B + P_E + P_D \quad (5)$$

$$P_3 = P_C \quad (6)$$

where  $P_1, P_2$  and  $P_3$  are the probabilities of full, zero and derated capacity. The frequencies of transferring from one state to another of Fig. 4 are:

$$f_{12} = f_{AB} + f_{AE} \quad (7)$$

$$f_{13} = f_{AC} \quad (8)$$

$$f_{21} = f_{BA} + f_{EA} \quad (9)$$

$$f_{32} = f_{CB} + f_{CD} \quad (10)$$

The failure rate and repairing rate of the complete reliability model of the subsystem 1 are:

$$\lambda_{11} = \frac{f_{12}}{P_1} = \frac{f_{AB} + f_{AE}}{P_A} = \quad (11)$$

$$\frac{\lambda_{wd}P_A + \lambda_{ctd}P_A}{P_A} = \lambda_{wd} + \lambda_{ctd}$$

$$\lambda_{12} = \frac{f_{32}}{P_3} = \frac{f_{CB} + f_{CD}}{P_C} = \quad (12)$$

$$\frac{\lambda_{2wd}P_C + \lambda_{ctd}P_C}{P_C} = \lambda_{2wd} + \lambda_{ctd}$$

$$\lambda_{13} = \frac{f_{13}}{P_1} = \frac{f_{AC}}{P_A} = \lambda_{1wd} \quad (13)$$

$$\mu_{11} = \frac{f_{21}}{P_2} = \frac{f_{BA} + f_{EA}}{P_B + P_E + P_D} = \quad (14)$$

$$\frac{\mu_{wd}P_B + \mu_{ctd}P_E}{P_B + P_E + P_D}$$

#### 4 Reliability Model of Subsystem 2

This subsystem includes bushings, tap-changer and cooling system. Bushings may damage because of several reasons. Its state is considered as up and down. The faults of tap-change are one of the major problems in the transformer. Two states are considered for tap-changer, too. It can be assume that two components are series. The other part of this subsystem is the cooling system. Although cooling system influences on the loading, but because of our assumption in this paper that the transformer utilizes ONAN cooling, this part of subsystem 2 has two states, too. Therefore three sections of this subsystem are series components as shown in Fig. 5. In this figure  $\lambda_{bsh}, \mu_{bsh}, \lambda_{tc}, \mu_{tc}, \lambda_{clg}$  and  $\mu_{clg}$  are failure rate and repair rate of bushing, tap-changer and cooling system respectively.

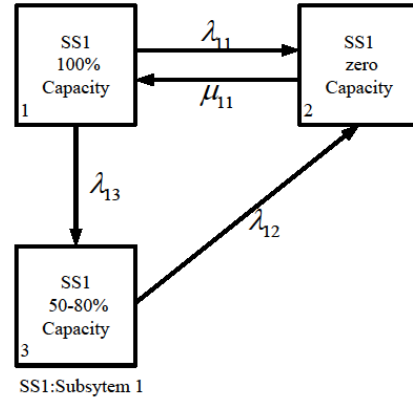


Fig. 4 Equivalent three-state model of subsystem 1.

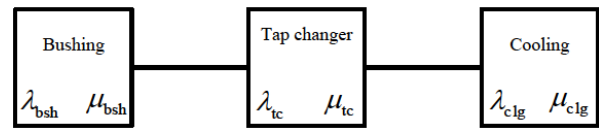


Fig. 5 series components of subsystem 2.

In order to achieve equivalent indices for this subsystem, first by replacing core and tank with bushings and tap-changer in equations 1 and 2, failure rate and repair time of these two components will be achieved. Then assume that we have two components: cooling system and the equivalent of bushings and tap-changer. By the same procedure, equivalent parameters of Fig. 6 will be achieved.

#### 5 Complete Reliability Model of Transformer

In order to achieve complete reliability model of the power transformer with ONAN cooling, the three subsystems must be combined. Space-state model of the power transformer is shown in Fig. 7. In this figure when system transfers from the state C to D, a process similar to Fig. 3 occurs.

The complete reliability model of the transformer, shown in Fig. 7, can be reduced to three states as shown in Fig. 8. The equivalent parameters are obtained by applying the frequency balanced approach. This process is similar to the Eqs. (4)-(14) because the same constructions of Figs. 3 and 7.

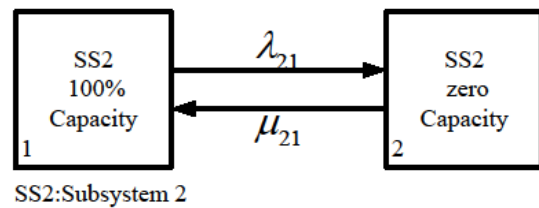
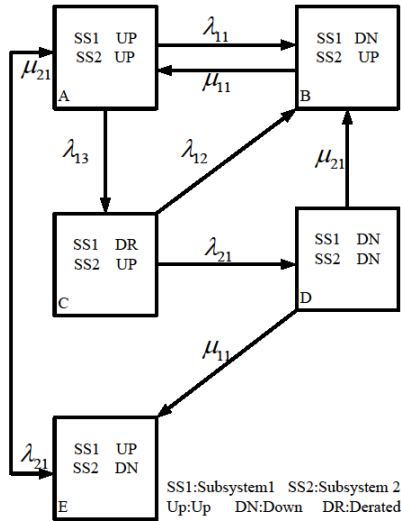
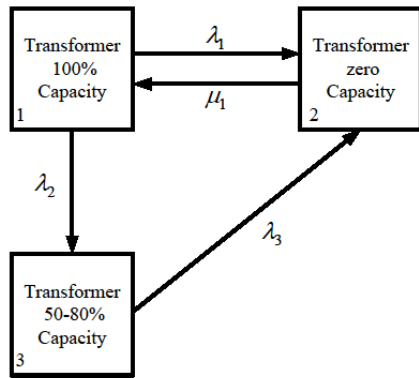


Fig. 6 Equivalent two-state model of subsystem 2.



**Fig. 7** Complete state-space model of power transformer.



**Fig. 8** Equivalent three-state model of power transformer.

The obtained model can be used by both manufacturers and power system planners/operators. Using this model, manufacturers will be able to recognize the critical components and could offer a system with a specific level of reliability. System planners also must evaluate the reliability of the system and maintain a specific level of power system reliability. Reliability model of components is required for this purpose as parts of the system [10].

## 6 Numerical Study

In this section numerical analysis and selected sensitivity analysis relevant to the reliability model of the transformer are performed. Using these analyzes, the impacts on transformer availability of variations in the components failure rates will be illustrated. The reliability data for the power transformer components is given in Table 1.

In Table 2 the calculated departure rate for the Markov models of subsystems and their related models is demonstrated. By using these parameters the probability, frequency and duration of the different states can be calculated for each model.

**Table 1** Reliability data of components.

| Parameters       | Value  | Unit  | Description  | Component              |
|------------------|--------|-------|--------------|------------------------|
| $\lambda_{wd}$   | 0.0045 | f/yr  | Failure rate | Winding                |
| $\lambda_{1wd}$  | 0.0002 | f/yr  | Failure rate |                        |
| $\lambda_{2wd}$  | 0.045  | f/yr  | Failure rate |                        |
| $r_{wd}$         | 2400   | hours | Repair time  |                        |
| $\lambda_{core}$ | 0.0005 | f/yr  | Failure rate | Core                   |
| $r_{core}$       | 480    | hours | Repair time  |                        |
| $\lambda_{tank}$ | 0.003  | f/yr  | Failure rate | Tank& dielectric fluid |
| $r_{tank}$       | 385    | hours | Repair time  |                        |
| $\lambda_{bsh}$  | 0.003  | f/yr  | Failure rate | Bushings               |
| $r_{bsh}$        | 48     | hours | Repair time  |                        |
| $\lambda_{tc}$   | 0.0085 | f/yr  | Failure rate | Tap-changer            |
| $r_{tc}$         | 960    | hours | Repair time  |                        |
| $\lambda_{clg}$  | 0.001  | f/yr  | Failure rate | Cooling system         |
| $r_{clg}$        | 72     | hours | Repair time  |                        |

**Table 2** Failure and repair rates of Markov models.

| Parameter       | Value (occ/yr) | Parameter      | Value (occ/yr) |
|-----------------|----------------|----------------|----------------|
| $\lambda_{ctd}$ | 0.0035         | $\lambda_{21}$ | 0.0125         |
| $\mu_{ctd}$     | 18.24          | $\mu_{21}$     | 13.07          |
| $\lambda_{11}$  | 0.008          | $\lambda_1$    | 0.0205         |
| $\mu_{11}$      | 5.54           | $\mu_1$        | 8.55           |
| $\lambda_{12}$  | 0.0485         | $\lambda_2$    | 0.0002         |
| $\lambda_{13}$  | 0.0002         | $\lambda_3$    | 0.061          |

The obtained probability and frequency values for the transformer model shown in Fig. 8 are presented in Table 3. This table shows that, in most of the time the transformer works in full capacity state.  $\lambda_1$  in Fig. 8 is the failure rate of transformer. It can be seen that this failure rate is close to the failure rate declared in [1].

Comparative studies are performed to illustrate the impact of the failure rates of different components on the reliability of the transformer. The result is shown in Table 4 for two different failure rates correspondent to the winding, tank and oil and tap-changer. In each case, the failure rate of only one component is changed, both to one-thousandth and to ten times of the base value presented in Table 1. Variations in failure rates of tank and oil lead to relatively little change in the probability and frequency values. But the impacts of varying the failure rates of the winding and tap-changer on the state probabilities and frequencies are significant.

**Table 3** Probability and frequency of the power transformer model states.

| Probability | Value (%) | Frequency | Value (occ/yr)        |
|-------------|-----------|-----------|-----------------------|
| $P_1$       | 99.43     | $F_1$     | 0.0206                |
| $P_2$       | 0.24      | $F_2$     | 0.0206                |
| $P_3$       | 0.32      | $F_3$     | $1.98 \times 10^{-4}$ |

## 7 Conclusion

This paper presents a new reliability model for a power transformers with ONAN cooling. Markov models have been applied for modeling the two subsystems of the transformer. By combining these two

subsystems, the three-state Markov model of the power transformer is achieved. This 3-states model can be used to calculate the probability, frequency and duration of the states. In order to evaluate numerical values of the model parameters and the impact of different components on the reliability of the model, a numerical analysis and sensitivity analysis are presented. Numerical study illustrates that the transformer works most probably in up state. Results also show that failure rate of transformer is 0.0205 which is close to practical results. Sensitive analysis show that winding and tap-changer have significant effect on the probability and frequency indices of a power transformer.

**Table 4** Probability and frequency of transformer model states against different component failure rates.

| Component    | Winding               |                       | Tank and oil          |                       | Tap-changer           |                       |
|--------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| Failure rate | 0.00045               | 0.045                 | 0.0003                | 0.3                   | 0.0085                | 0.85                  |
| $P_1$        | 99.54                 | 88.67                 | 99.43                 | 98.11                 | 99.46                 | 91.33                 |
| $P_2$        | 0.13                  | 11.03                 | 0.22                  | 1.83                  | 0.157                 | 8.64                  |
| $P_3$        | 0.32                  | 0.29                  | 0.34                  | 0.05                  | 0.372                 | 0.02                  |
| $F_1$        | 0.0166                | 0.4134                | 0.0179                | 0.311                 | 0.013                 | 0.787                 |
| $F_2$        | 0.0166                | 0.4134                | 0.0179                | 0.311                 | 0.013                 | 0.787                 |
| $F_3$        | $1.99 \times 10^{-4}$ | $1.77 \times 10^{-4}$ | $1.98 \times 10^{-4}$ | $1.96 \times 10^{-4}$ | $1.98 \times 10^{-4}$ | $1.82 \times 10^{-4}$ |

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