A Reliability-Centered Maintenance Framework for Distribution Grids Based on Fault-Tree Analysis

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ABSTRACT

Reliability is the key issue in the supply of electrical energy in modern society, which is jeopardized by the failures occurring in different sections of distribution grids. To address this challenge, this paper presents a reliability-centered maintenance framework for transformers, switchgear panels and power cables in medium-voltage distribution grids. First, fault tree models for the different equipment are established in this paper, with which the impacts of different failures and the effects of maintenance actions are analyzed in a quantitative manner. Using the fault tree models, the influences of different maintenance strategies on the reliability indexes of equipments in long-term operations can be estimated, which provides references for the selection and prioritization of preventive maintenance actions. This research work provides a generalized and practical framework for designing reliability-centered maintenance plans for distribution grids.

1. INTRODUCTION

The key task of distribution grids is to deliver high-quality electric energy to customers uninterruptedly. However, modern distribution grids are complex networks composed of numerous components, in which various failures can occur at different locations and jeopardize the reliability of the power supply. Meanwhile, the electric power industry has undergone a transformation into a competitive environment where it is necessary to maintain the desired level of reliability while reducing maintenance costs.

As a way to optimize maintenance plans, reliability-centered maintenance (RCM) was first introduced in the 1970s within the commercial aviation industry (Brauer & Brauer, 1987). Later, RCM is widely accepted in different industries. The standard SAE JA1011 established a definition for RCM, outlining the minimum requirements for the implementation of RCM techniques (SAE JA1011_200908, 2009). And the standard IEC 60300-3-11 describes the basic steps in implementing an RCM program (IEC 60300-3-11:2009, 2009).

Recently, RCM has been drawing attention in the research field of power systems. Ozdemir and Kuldasli (2010) develop the RCM plans for the equipment in Turkish National Power Transmission Company. (Dhaliwal, Schumann, & McNichol, 2008) introduces the development of RCM plans for high-voltage DC systems, which was carried out by Manitoba Hydro in Canada. RCM frameworks have also been applied to the distribution grids in Algeria (Yssaad, Khiat, & Chaker, 2014; Yssaad & Abene, 2015).

In this work, an fault-tree analysis (FTA)-based RCM framework is developed for the equipment in medium-voltage distribution grids. To this end, the failures in transformers, switchgears and power cables of distribution grids are first studied. Then, a quantitative analysis of the impacts of different failures on the reliability of equipment is carried out. On this basis, an RCM workflow is established, in which two different maintenance strategies are considered. At last, the effects of the RCM with the different maintenance strategies are studied through numerical simulations.

The remainder of the paper is structured as follows: Section 2 introduces the fault tree (FT) models for the equipment in distribution grids. Section 3 presents the developed RCM framework based on FTA. Section 4 presents the simulation results. Section 5 concludes the paper.

2. FTA

FTA is a top-down approach that is used to investigate potential failures, and to quantify their contribution to system

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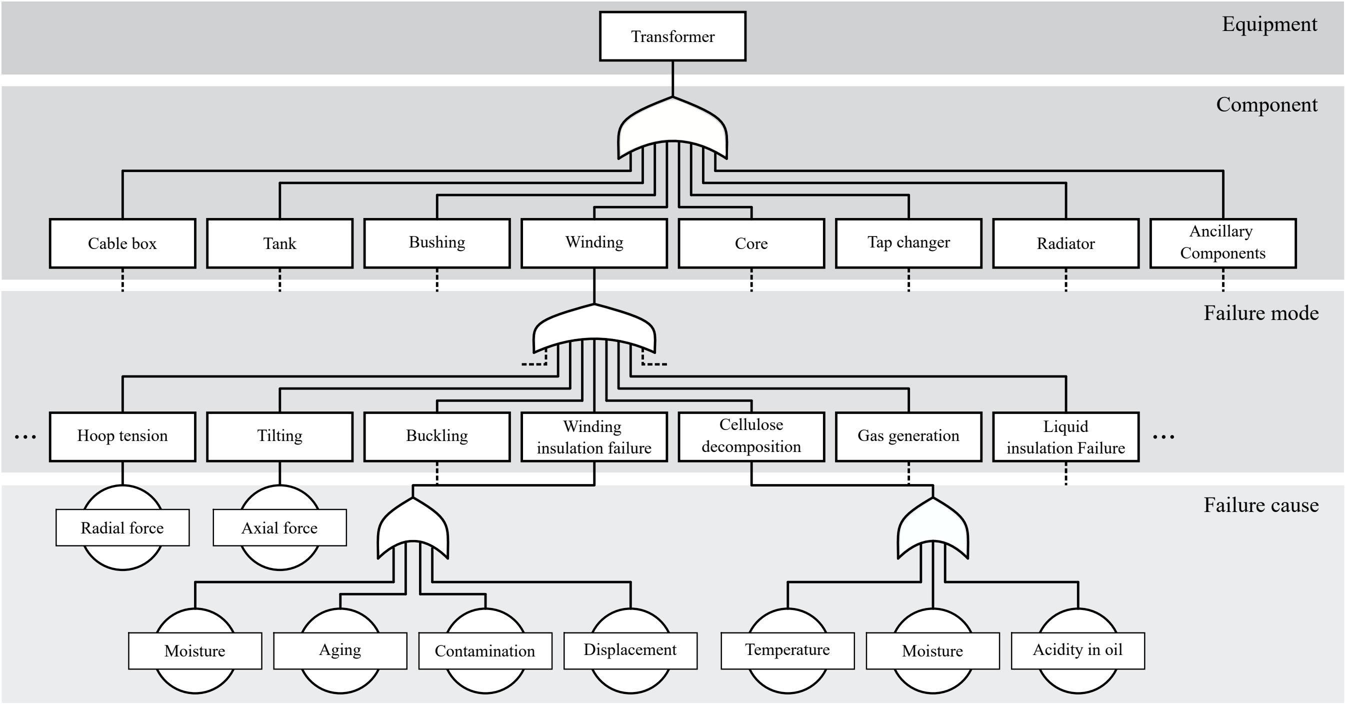


Figure 1. Fault tree model of distribution transformers.

unavailability (IEC 61025:2006, 2006).

The research scope of this work covers the key equipment, including transformers, switchgears and power cables, in medium-voltage distribution grids. Transformers convert different voltage levels in power distribution. In this work, the mainstream oil-immersed transformers are studied. Switchgears are responsible for switching on and off power supply and providing protection to other equipment. In modern medium-voltage distribution grids, SF6 gas-insulated panels are the commonly used switchgear technology. Power cables transmit electric power over a long distance. In this work, commonly used Cross Linked Polyethylene (XLPE) cables as well as their accessories are studied.

In the following, the FT models of the different equipment are built, based on which quantitative FTAs are carried out.

2.1. FT Model

In this work, the FT models for the different assets in distribution grids are built. Yet due to the limitation of space, only the FT model of transformers is presented in Fig. 1, which is mainly based on CIGRE TB 761 (CIGRE TB 761, 2019).

As we can see that the FT is composed of four layers. On the top layer is the equipment to analyze, which is transformers in this case. On the second layer, the analyzed equipment is decomposed into multiple components (e.g. tank, winding, bushing, etc. in the case of transformers). For each component, possible failure modes are presented on the third layer. On the bottom layer, the causes of each failure mode are presented.

2.2. Quantitive FTA

Based on the FT model, the risks of failures in components as well as equipment are quantified. For this purpose, the Weibull model is adopted, which is a statistical tool for failure observation (Lai, Murthy, & Xie, 2006). With the two-parameter Weibull model, the hazard rate h_i of Component i is defined as (Kızılersü, Kreer, & Thomas, 2018):

$$h_i(t) = \frac{\beta_i}{\eta_i}\left(\frac{t}{\eta_i}\right)^{\beta_i - 1} \tag{1}$$

where β_i and η_i denote the shape parameter and the scale parameter of the two-parameter Weibull model for Component i, respectively. The hazard rate $h_i(t)$ is the instantaneous rate of failure for Component i surviving to time t, which provides a quantitative index of risk.

It is assumed that the equipment fails when a single component of it fails (e.g. a transformer fails when a winding fails). In other words, the reliable operation of the equipment is depending on the functioning of all components. This relation is described by a series system shown in Fig. 3. The hazard rate h of such a series system is represented as (Boland, 1997)

$$h(t) = \sum_{i=1}^{N} h_i(t) \tag{2}$$

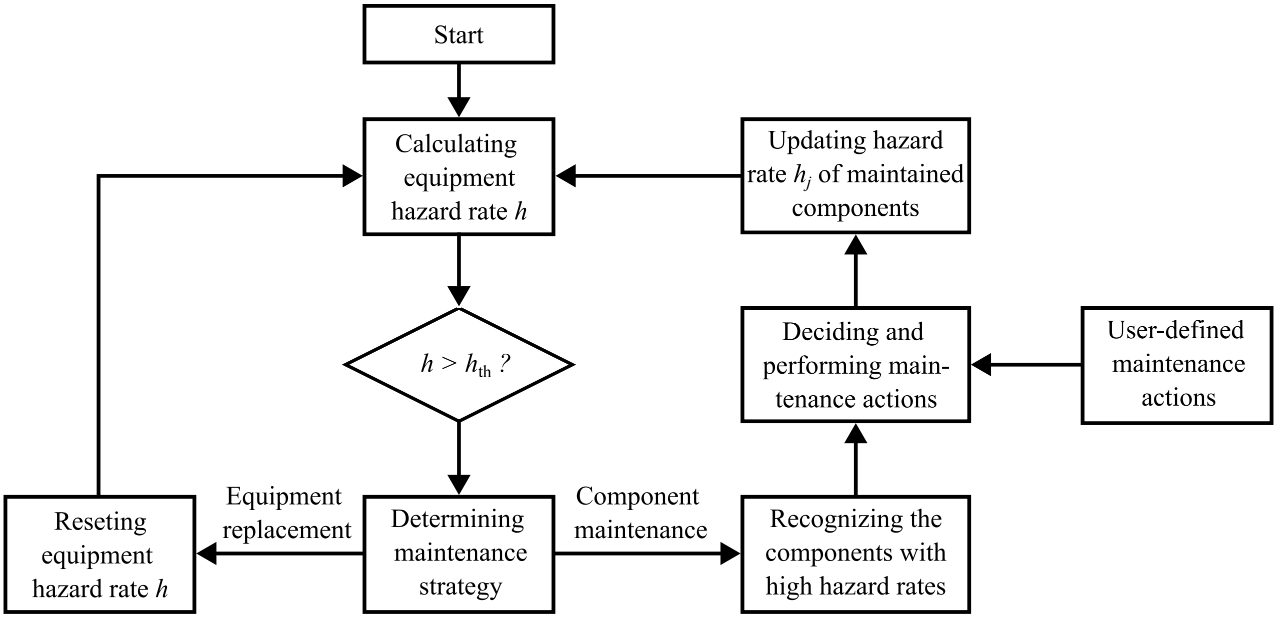


Figure 2. Workflow of RCM.

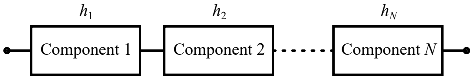


Figure 3. Reliability block diagram of a series system.

The mean time to failure (MTTF), which measures the average time of continuous operation of a non-repairable equipment before it fails, can be derived as (Lienig & Bruemmer, 2017):

$$\lambda(t) = \frac{1}{h(t)} \tag{3}$$

2.3. Effect of Maintenance

Through the quantitative FTA presented above, the effects of maintenance actions can be estimated.

In Eq. (2), the hazard rates h_i of all the components ($i = 1, 2, \ldots, N$) are affected by the ages and operating conditions of the components. Suppose that Component j is replaced through proper maintenance at time t_0, the hazard rate of the equipment after time t_0 needs to be updated since the hazard rate h_j of Component j has been changed at the time of maintenance. This process can be mathematically represented as

$$h'(t) = \sum_{\substack{1 \le i \le N \\ i \notin M}} h_i(t) + \sum_{\substack{1 \le j \le N \\ j \in M}} h'_j(t),\ t \ge t_0 \tag{4}$$

Where M denotes all the components that are replaced through maintenance. h'_j denotes the hazard rate of Component j after maintenance, which can be derived as:

$$h'_j(t) = h_j(t - t_0),\ t \ge t_0 \tag{5}$$

Correspondingly, the updated MTTF of the equipment after the maintenance is:

$$\lambda'(t) = \frac{1}{h'(t)} \tag{6}$$

3. RCM FRAMEWORK

Based on the FTA introduced in the preceding Section, a workflow of RCM framework is designed for the equipment in distribution grids, which is presented in Fig. 2. A step-by-step explanation is provided in the following.

Initialization

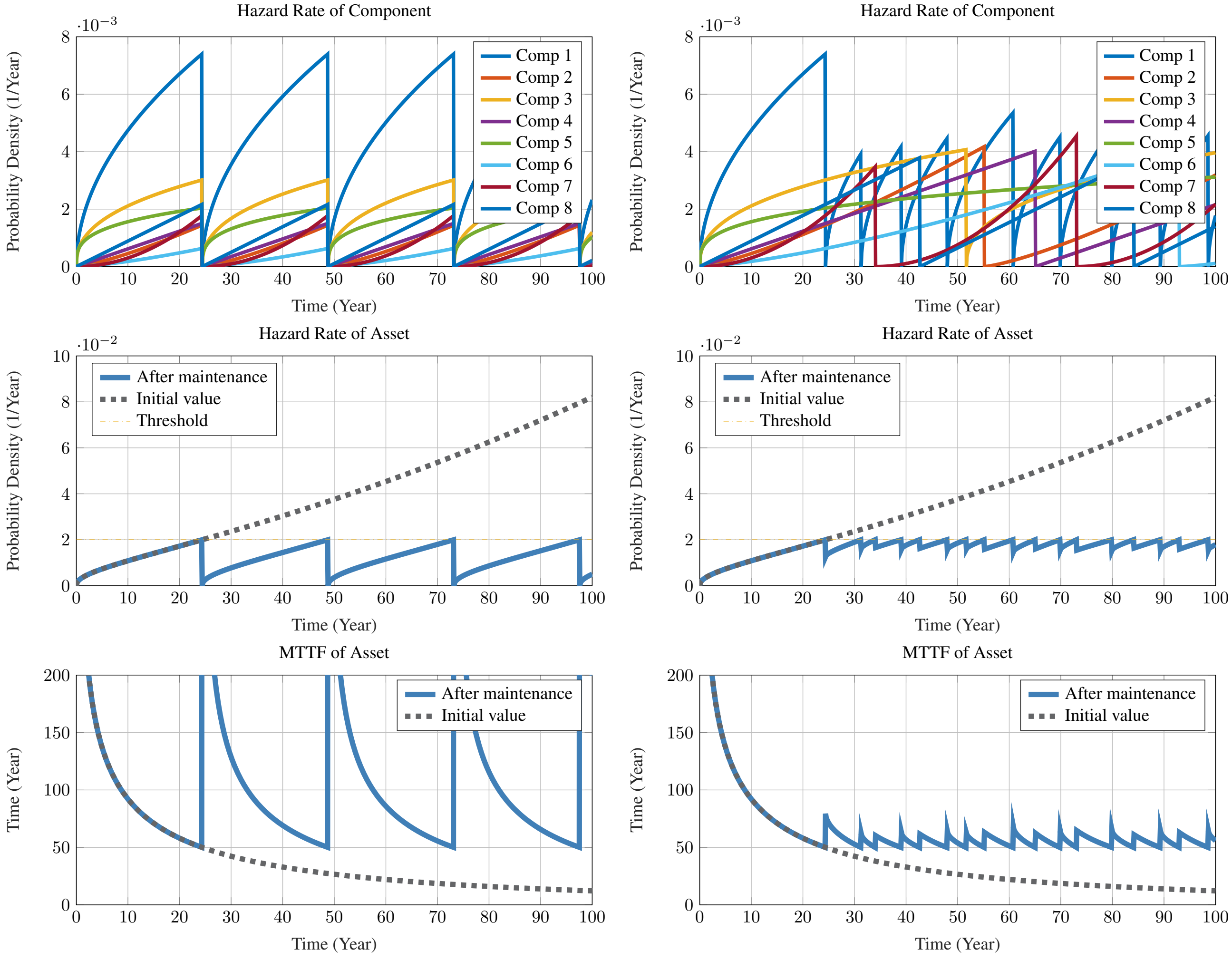
Based on the Weilbull models of failures in the components, the initial hazard rate h of the analyzed equipment is calculated with Eq. (2). By default, h for a brand-new healthy equipment starts from 0.

Activation of maintenance actions

The primary goal of the RCM is to reduce the hazard rates of equipment. To this end, a threshold h_{th} is set on h as the triggering condition of the RCM process. If h_{th} is exceeded during the operation of the equipment, maintenance measures should be carried out to mitigate the potential risk. Two optional maintenance strategies are introduced in the following.

Equipment-level maintenance

With the equipment-level maintenance strategy, the equipment with a hazard rate exceeding h_{th} gets directly replaced with a new one. After the replacement, the hazard rate h of



(a)

(b)

Figure 4. Simulation results under (a) equipment-level maintenance strategy and (b) component-level maintenance strategy.

the equipment is reset to the initial value starting from 0.

Component-level maintenance

With the component-level maintenance strategy, only specific components are replaced during the maintenance. To prioritize component-level maintenance actions, the components with high hazard rates h_j are first recognized. The higher the hazard rate, the higher the priority for maintenance. According to the quantified risks of components, the final decision on maintenance plans should be made by users. In addition, other user-defined maintenance actions that are not within the proposed RCM workflow should also be known, which is necessary for keeping the FT models up-to-date. After all onsite maintenance works are accomplished, the hazard rates of affected components are updated with Eq. (5). Then the hazard rate of the equipment is updated with Eq. (4).

4. SIMULATION

4.1. Simulation setup

In this section, the proposed RCM workflow is simulated with the dummy data of an equipment composed of eight components, whose Weibull model parameters are listed in Table 1. The threshold λ_{th} of MTTF of the equipment is set to be 50 years, from which $h_{\text{th}} = 0.02$ year^{-1} is derived with Eq. (3). And the equipment is in perfect condition at the beginning of the simulation. An operation time of 100 years is simulated.

The effects of the two different maintenance strategies, i.e. equipment-level and component-level maintenance, are simulated individually. Specifically, it is assumed that only one component is replaced each time under the component-level maintenance strategy. The hazard rates and the MTTF obtained from the simulations are plotted in Fig. 4.

Table 1. Simulation parameters.

Parameter	Value
No. of component	8
$\{\beta_i, \eta_i\}$ $(i = 1, 2, \ldots, 8)$	$\{1.5, 100\}$, $\{2.3, 150\}$, $\{1.4, 200\}$, $\{2.0, 180\}$, $\{1.3, 300\}$, $\{2.4, 200\}$, $\{3.0, 100\}$, $\{2.0, 150\}$
λ_{th}	50 years
h_{th}	0.02 year^{-1}
Simulation time	100 years

4.2. Simulation Results

We can see in Fig. 4(a) that under the equipment-level maintenance strategy, the hazard rates of the eight components and the equipment drop to zero when the threshold h_{th} is reached. Meanwhile, the MTTF is sustained above 50 years. For comparison, we also provided the initial values of the hazard rate and MTTF of the equipment without any maintenance actions. We can see that the RCM effectively reduces the hazard rate and extends the MTTF. Over the operation time of 100 years, the equipment has been replaced for four times.

Fig. 4(b) shows the simulation results of the same equipment under the component-level maintenance strategy. As we can see, only one hazard rate of a component drops to zero when h exceeds h_{th} in this scenario. This is because, under the component-level maintenance, only the component with the highest failure rate is replaced when maintenance is triggered. The results in Fig. 4(b) show that both the hazard rate and MTTF of the equipment are sustained in the safe range.

4.3. Discussion

Comparing the simulation results in Fig. 4(a) and Fig. 4(b), we can see that both maintenance strategies are effective to guarantee the reliability of the equipment. But the frequency of the component-level maintenance [Fig. 4(b)] is much higher than that of the equipment-level maintenance [Fig. 4(a)]. This is because the improvement of equipment reliability through replacing only a single component at each maintenance is less significant than replacing the equipment. The latter is, however, much more costly. Therefore, the selection of maintenance strategy and threshold value should consider both the effect and costs. But this is beyond the range of this paper.

5. CONCLUSION

This paper puts forward an FTA-based RCM framework for the assets in distribution grids. This work integrates two-parameter Weibull models into an FT model, which can estimate the reliability of equipment and the effects of maintenance actions. The proposed RCM workflow provides two different failure mitigation strategies and prioritizes maintenance actions according to the improvement of equipment reliability. In the future, optimization algorithms should be developed to decide the reliability targets and maintenance strategies, in which the costs of maintenance actions and the benefits of reliability improvement should be considered.

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