Electrical Power and Energy Systems 55 (2014) 238–245

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Implementation of Reliability-Centered Maintenance for transmission components using Particle Swarm Optimization

J.H. Heo [a,1], M.K. Kim [b,*], J.K. Lyu [a]

[a] School of Electrical Engineering & Computer Science, Seoul National University, Gwanak-ro 599, Gwanak-gu, Seoul 151-744, Republic of Korea
[b] Department of Electrical Engineering, Dong-A University, 840 Hadan2-dong, Saha-gu, Busan 604-714, Republic of Korea

ARTICLE INFO

Article history:
Received 17 February 2012
Received in revised form 5 September 2013
Accepted 5 September 2013

Keywords:
Particle Swarm Optimization
Maintenance strategy
Reliability-Centered Maintenance
Transmission system

ABSTRACT

In a deregulated power industry, a maintenance strategy is of critical importance for transmission systems composed of aging components. Such a strategy can provide significant cost savings by optimizing maintenance decisions for power system operation. This paper presents a Reliability-Centered Maintenance (RCM) model for developing a maintenance strategy in a transmission system. This model is applicable to transmission components whose degradation can be classified according to the severity of the aging. Particle Swarm Optimization (PSO) is used to extract the optimal RCM strategy from a large class of possible maintenance scenarios. A numerical example shows that a maintenance strategy based on the proposed RCM model is more cost-efficient than traditional maintenance strategies.

1. Introduction

As part of the restructuring of the electric power industry, transmission utilities have tried to maximize profit while maintaining reliability. These systems must be operated to meet customer needs by reducing the cost of electricity. To accomplish this objective, maintenance strategies have been established to provide a tradeoff between cost and reliability [1–3].

Reliability-Centered Maintenance (RCM) has been used to develop maintenance strategies that provide an acceptable level of reliability in a cost-effective manner [4]. The RCM technique is a structured framework for analyzing the functions and potential failures of a transmission component, with a focus on preserving reliability. Thus, RCM must consider not only the condition of a piece of equipment, but also its importance in the power transmission system. The RCM concept and its application to power system facilities have been described in numerous studies [5–9]. In [5], an RCM-based maintenance strategy for circuit breakers was presented. In [6], the RCM model was used to determine the optimal maintenance interval in distribution protection systems. The RCM approach for transmission systems was introduced in [7]. However, this study does not provide a method for quantifying the impact of maintenance on reliability. In [8], an RCM strategy for substations was developed. Although this approach takes into account the importance of a substation in the system, the evaluation criteria are not discussed in detail. The quantified impact of planned transmission outages on overall system reliability was studied in detail in [9]. However, this article did not consider the state of a component, which varies over time.

The main objective of this work was to develop a comprehensive RCM model for a transmission system that focuses on preserving system functions and system reliability. The RCM model consists of a component state model and an impact model. The component state model represents levels of degradation, allowing aging transmission components to be handled, and the impact model analyzes the impact of component states and maintenance on the overall system. Using this RCM model, the optimal maintenance strategy can be determined via Particle Swarm Optimization (PSO). To develop an RCM-based maintenance strategy from a large class of possible maintenance scenarios, a heuristic approach is useful to find a feasible solution close to the optimal solution. Particle Swarm Optimization (PSO) is one of these heuristic approaches and is applied in the present research to efficiently find optimal maintenance strategies.

The remainder of the paper is organized as follows: The proposed RCM model is introduced in Section 2. Section 3 describes the PSO process used to determine the optimal maintenance strategy. In Section 4, a numerical example is presented, using an IEEE 30-bus system. The results obtained from the proposed maintenance strategy, including the PSO-based RCM model, are compared with Time-Based Maintenance (TBM) and Conditional-Based Maintenance (CBM). Conclusions are given in Section 5.

* Corresponding author. Tel.: +82 51 200 7733; fax: +82 31 200 7743.
E-mail addresses: jhheo78@snu.ac.kr (J.H. Heo), mkkim@dau.ac.kr (M.K. Kim), handyjack@snu.ac.kr (J.K. Lyu).
[1] Tel.: +82 2 880 7258; fax: +82 2 878 1452.

0142-0615/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijepes.2013.09.005

Nomenclature

N	normal state
$D1, D2, D3$	degradation states
$M1$	weak maintenance
$M2$	strong maintenance
$M3$	stronger maintenance
F	failure states
S	real-time sensor
C_T	total expected cost
C_G	generation cost function
C_O	system outage cost multiplier
C_M	maintenance cost
C_R	repair cost
P_G	active power of the generator
P_D	active power load of the load bus
P_{OUT}	amount of system outage
$P_{G,\min}$	lower limit for the generator
$P_{G,\max}$	upper limit for the generator
$LF_{\max}$	transmission capacity
N_d	the number of load busses
N_g	the number of generator busses
N_l	the number of lines
N_c	the number of components
W	inertia weight factor
$W_{\max}$	maximum weight
$W_{\min}$	minimum weight
V_j	velocity of the jth particle
$V_{\max}$	maximum velocity
$V_{\min}$	minimum velocity
$rand1, 2$	uniformly distributed random number [0,1]
P_j	position of the jth particle
$P_{\max}$	maximum position
$P_{\min}$	minimum position
$c1, c2$	acceleration constant
$iter$	iteration number
$iter_{\max}$	generation number
P_s	population size
T	random variable
R	uniformly distributed random number [0,1]
$F(t)$	cumulative distribution function
t	transition time from the present state to the next state
λ	transition rate
μ	repair rate

2. Reliability-Centered Maintenance model

2.1. Component state model

Many existing transmission components were installed several decades ago and have deteriorated over time. Component performance has diminished, and the component failure rate in transmission systems will increase. Further degradation may thus be unavoidable.

The conventional Markov model, which is based on the assumption of constant failure rates, has been appropriately modified to simulate the influence of component deterioration [10]. The operational state of a transmission component is classified according to the severity of the aging. We have proved that a component state model using modified Markov chains [11] is suitable for aging components. This model is used in the present work to determine varying probability states. The proposed component state model is illustrated in Fig. 1.

The operational state of a component is divided into sub-states with increasing levels of wear (normal state N, degradation states $D1$ to $D3$). State N represents a new system without degradation. The state transitions are governed by the transition rates λ_1, λ_2, λ_3, and λ_4, which are interpreted as the reciprocals of the mean times spent in the degradation states. A repair transforms a failure state F into the normal state N at repair rate μ (the reciprocal of the mean value of the repair duration). $M1$, $M2$, and $M3$ denote weak maintenance (dependent on $D1$), strong maintenance (dependent on $D2$), and stronger maintenance (dependent on $D3$), respectively. The component condition information ($D1$, $D2$, or $D3$) is taken from a real-time sensor (S) and delivered to an inspector. The inspector decides whether or not to perform maintenance. The maintenance order variables are given in:

$$d_{D1,i} = \begin{cases} 1 & \text{if } \textit{mainatenance order when the component state is } D1 \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

$$d_{D2,i} = \begin{cases} 1 & \text{if } \textit{mainatenance order when the component state is } D2 \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

$$d_{D3,i} = \begin{cases} 1 & \text{if } \textit{mainatenance order when the component state is } D3 \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

Here $d_{D1,i}$, $d_{D2,i}$, and $d_{D3,i}$ are the maintenance order variables when the ith component state is $D1$, $D2$, and $D3$, respectively.

If a maintenance procedure or repair is performed, the component state will become N at rate μ_1, μ_2, μ_3, or μ. This component state model can be adjusted by changing the number of degradation states. The number of degradation states is determined by the actual component aging levels and the possible maintenance procedures. A sample application to actual components is presented in Section 4.

2.2. Impacts model of components states and maintenance

Because a transmission system is a meshed network, analyzing the impact of component failure on a transmission system can be quite complicated. Component failure affects the adjacent bus as

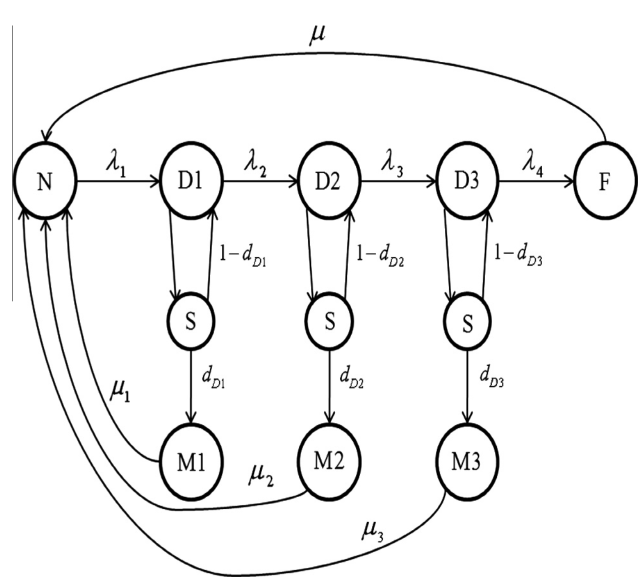

Fig. 1. The component state model using modified Markov chains.