Simulation-based optimal replacement model for a PCS in the ESS under combination warranty policy

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Abstract. In this paper, we deal with a replacement strategy for a PCS (Power conditioning system) in the ESS (Energy storage system) under the combination warranty policy that has the non-renewing free warranty and pro-rata warranty policies. System availability and maintenance costs are considered as optimization criteria and estimated by simulation, *BlockSim*. The objective of the study is to determine the replacement times that minimize the maintenance costs and satisfy the target annual system availability during the warranty period. Alternatives for the replacement times are analyzed by a heuristic method with *BlockSim*. Numerical examples are studied to investigate the effect of the model parameters to the optimal solutions.

Keywords: ESS, PCS, Warranty, Replacement model, Simulation, *BlockSim*

1. INTRODUCTION

In practice, the energy storage system (ESS) is often used the various industries because energy need to be converted to stored form in chemical, electrical, kinetic, potential or thermal media. Sometimes, it is converted for the final use directly, for example when heat is generated from a thermal energy store while when electricity is generated by the generator of the storage system it may be converted indirectly. Also, the system includes a wide range of energies, technologies, scales and applications (Baker, 2008). Usually, the ESS is provided as either thermal or electrical and thermal energy has a somewhat more restricted applications domain, principally including the built environment, industry. In contrast, the electrical energy storage system contains a broad range of technologies which either directly or indirectly give electrical energy. Electrical energy storage system historically has been used to balance between supply and demand. For example, a power station may charge the energy at times of low demand typically at night while the energy can be discharged at times of peak daytime demand. Recently, the electrical energy storage system has been attention for providing high quality of power and the integration of renewable into power systems. Generally, an ESS consists of the battery, EMS (Energy management system) and PCS (Power conditioning systems) (Kwon, 2000). The battery is one of the most used energy storage technologies available on the market and stores in the form of electrical energy. It contains a set of multiple cells, connected in series or in parallel or both in order to provide the desired voltage and capacity. The EMS is a system used by operators of electric utility grids to monitor, control and optimize the performance of the generation and/or transmission system. The PCS converts direct current (DC) from an alternating current (AC) or charges AC current produced to match the voltage and phase conditions of the bulk electricity grid. Also, it includes system monitoring devices and isolation switches that can isolate the solar energy facility from the bulk electricity grid during off-normal conditions that could jeopardize or damage either the facility or the grid.

In recent years, the PCS has paid much attention because the current energy-conversion efficiency of the PV array is still low. Thus, the various techniques have been proposed in order to achieve the maximum possible power from the PV (Photovoltaic) array. As a result, numerous topologies of the power conditioning systems varying in cost and complexity have been developed for integrating the PV solar systems into the electric gird (Kim, 2013). However, most techniques are focused on the basic function enhancement and expansion. However, it is well known that RAM (reliability, availability and maintainability) is the key performance measures to evaluate the performance of the large-scale repairable systems quantitatively. Therefore, it needs to develop the reliable and maintainable power conditioning systems in the design and development phase. Also, it is important to maintain the systems periodically in order to keep high system reliability during the life cycle. In this paper, we focus on the inspection and maintenance of the power conditioning system with complex hierarchical structures.

In general, maintenance can be classified into corrective maintenance (CM) and preventive maintenance (PM). CM is unscheduled and is carried out when a system fails and the system must be restored from a failed state to a working state through either repair or replacement of the failed components. PM is scheduled and is carried out for operational systems. The goal of PM is to reduce the possibility of the failure and system downtime by improving system reliability. Therefore, system availability can be increased through maintaining the system preventively and periodically. Optimal PM policies aim to provide optimal system reliability and satisfy the required system performance with low maintenance costs (Høyland, 2009). Over recent decades, various repair models for a single-unit system have been proposed by researchers such as perfect, minimal, imperfect, worse and worst repair (Nakagawa, 2005). Also, there are various imperfect repair models such as the (p, q) rule, ($p(t)$, $q(t)$) rule and the virtual age model, as reviewed by Nakagawa (1979), Nakagawa (1980) and Pham *et al*. (1996). These PM policies can be applied to the multi-unit systems if there is no strong dependency (economic dependency, structural dependency, and stochastic dependency) between components in the system. Especially, economic dependency usually refers to the reduction of the maintenance costs through the application of group maintenance. Nicolai *et al*. (2008) also reviewed maintenance policies based on economic, structural and stochastic dependencies for multi-unit systems. A number of analytical studies have sought to optimize PM intervals for multi-unit systems, and in most cases, the authors have simplified optimization problems with strong assumptions, or dealt with particular systems in order to formulate the optimization problems with less mathematical difficulty. Duarte *et al*. (2006) considered a multi-unit system with linearly increasing hazard rate and constant repair rate, and proposed an algorithm to find optimal PM intervals that minimizes the maintenance cost. The non-repairable failure mode can only be maintained during overhaul periods with perfect repair and the optimal number of PMs was determined for situations where two failure modes are dependent. Tam *et al*. (2006) dealt with a PM intervals problem for a multi-unit system and determined a set of PM intervals that minimize the expected total cost including breakdown and maintenance costs. Zhu *et al*. (2010) proposed the maintenance and repair cost models for a competing risk (degradation and sudden failure) maintenance situation and determine optimal preventive maintenance threshold and PM intervals of the units that maximize the availability subject to repair cost constraint.

There is an increasing interest in optimum PM policies for multi-component systems with complex operation scenarios. In order to obtain optimal PM policies of complex large-scale systems, system behavior and operation scenarios must be represented in detail, and the system performance must be accurately evaluated. Simulation can evaluate the system performance and estimate the maintenance cost under various maintenance strategies. Borgonovo *et al*. (2000) used Monte Carlo simulation to model plant operations such as renovation, obsolescence, and aging under imperfect repair, for an evaluation of plant maintenance strategies. Wang (2012) proposed a simulation model with age and block based maintenance policies of complex systems and Monte Carlo simulation was used to estimate the renewal cycle cost and the life span of the system. Basically, simulation methods only provide limited statistics for system performance measures and require appropriate optimization methods to determine PM intervals optimally. Zile *et al*. (2010) proposed a modeling approach of maintenance strategies for multi-unit systems. They found the optimal maintenance duration which minimize system unavailability by using stochastic synchronized Petri nets and Monte Carlo simulation. Yun *et al*. (2013) considered a PM scheduling problem for a rolling stock with cyclic operation and proposed two methods to assign PM intervals to components in the system. A heuristic method and a genetic algorithm were used to find near-optimal solutions for PM intervals of components which minimize the life cycle cost and satisfy the target system availability.

In this paper, we deal with a replacement model for an ESS system and the system availability and maintenance costs that are the sum of warranty cost and preventive replacement costs are used as optimization criteria. This study aims to determine optimal replacement intervals of the components in the system that minimize the maintenance costs and satisfy the target system availability. The paper is organized as follow. Section 2 introduces the optimization model for the ESS PCS and the RAM analysis of the ESS PCS is explained in Section 3. Numerical examples are applied to investigate the effect of the model parameters on the optimal solutions in Section 4. Finally, concludes the paper

2. Configuration of ESS PCS

In practice, ESS PCS is used to control the active power flow exchanged with the electric distribution system. Usually, it contains many components as a DC input filter, a three phase inverter, an AC output filter, etc. For connecting the grid, a three-phase DC/AC voltage source inverter (VSI) using IGBT (Insulated gate bipolar transistors) is employed. The output voltage control of the VSI can be achieved through the pulse width modulation (PWM) techniques. Also, the VSI needs a fixed DC link in order to allow a decoupled control of both active and reactive powers exchange with the electric grid. According to the above sub-functions of the power conditioning system, the functional tree is built and the critical components in the power conditioning system are defined such as DC capacitor, power semiconductor switch like an IGBT, gate drive, interface board, sensing board, cooling FANs etc.

In this study, we want to find the appropriate preventive replacement policy that balance between maintenance frequency and maintenance cost. The appropriate replacement policy may depend on such factors as:

- The component has an increasing failure rate implying wear-out.
- The overall cost of the preventive replacement actions must be less than the overall cost of the corrective replacement action.

Usually, the cost of making preventive replacement is less than the cost of failure replacement because we can arrange for preventive replacements to be made so as to avoid loss of production. Also, if the components in the system are replaced preventively as part of a routine service or overhaul, the repair cost tends to be reduced because the replacement can be done as part of the other work. Two types of situations in which component replacement occur are considered: One is failure replacement that a component is replaced when the component fails in service. The other is preventive replacement that a component is replaced preventively although the component has not failed. Also, two types of component replacement policy are considered as follows:

- Replace-only-on-failure (***CASE 1***): Replacement is carried out when the component fails.
- Block replacement (***CASE 2***): Replacement occurs for all the components at regular intervals.

For age-based policy, it is necessary to keep records of the ages of particular components but the other do not need the age of particular components. In this paper, we consider block replacement policy because it is not easy to check the age of each component in the system.

3. RAM analysis of PCS

For finding optimal replacement intervals of the components in the ESS PCS, firstly we need to know whether the current system availability satisfies the target system availability or not. Therefore, the current system availability should be calculated accurately but there are some difficulties in evaluating the availability of the ESS PCS by analytical methods because the system consists of various components which perform different functions. Also, each component may follow a different failure distribution. Therefore, it is difficult to calculate the system availability and maintenance cost analytically and thus we use a commercial RAM simulation package, *BlockSim* to obtain the system availability and maintenance costs of the PCS. For establishing the simulation mode, firstly we define the functions and components in the PCS. The functions are the subset of activities of the PCS for converting from AC to DC. These functions are performed independently or complementary. These require one or more components that have the physical failure and repair process. It means that the actual failures and repairs perform at this level in the PCS (Yun *et al*., 2008). In this study, we analyze the reliability structure of components and functions through fault tree analysis. As a result, there are 9 functions and 15 components with series structure. Among them, 8 components have the mechanical failure modes such as fatigue, corrosion and crack. Hence we consider that the failure times of 8 components follow a Weibull distribution that the values of the shape parameter, $\beta > 1.0$ while those of the others follow an exponential distribution that have the constant failure rate. For restoring the PCS correctively, the failed modules or components are replaced by new ones at the operational site (Perfect repair) in practice. It requires less maintenance times but incurs higher maintenance costs. Also, the failed modules or components may be discarded and a new module needs to be ordered prior to replacement because it cannot be restored.

On the other hand, when we calculate the maintenance costs, the combination warranty policy that consists of free warranty and pro-rata warranty is considered. The free warranty policy is that the free maintenance cost during 3 years and the penalty cost subject to the target annual system availability, 90% during 12 years. The fee maintenance cost is the sum of CM costs of all the components in the PCS. The penalty cost is defined as the repayment of the project amount and is calculated that the project amount multiplies by lack of system availability. In this study, the project amount is assumed to be 10 billion.

Under operation environment, and maintenance and warranty policies, the system availability and maintenance costs are estimated by *BlockSim*. In this case, we consider that the maintenance resources such as spare parts, maintenance equipment and engineers are always available. The current annual system availability does not satisfy the target system availability, 90% and it incurs the penalty cost as shown in Table 1.

Table 1. Current average system availability and maintenance costs

		Result
System availability		64.05%
Maintenance costs	Total cost	4,574,481,337
	Free maintenance cost	2,735,453,328
	Penalty cost	1,839,028,009

The objective of the study is to find the replacement intervals that minimize the maintenance costs and satisfy the target annual system availability. In Section 4, we will determine the optimal replacement intervals of the components which have the increasing failure rate function.

4. Optimal replacement strategies

Usually, simulation can only estimate the system availability and maintenance cost and hence we need the optimization method to determine the replacement intervals of the components optimally. In this study, we prose a heuristic method that can give most cost-effective alternatives and the detail procedure is as follows.

Step 1: Input the information of the failure and repair of each component to simulation.

Step 2: Estimate the system availability and the warranty period.

2-1: If the target annual system availability is satisfied, stop the procedure. Otherwise, go to 2-2.

2-2: Set that all the components have same replacement intervals and go to Step 3.

Step 3: Find the longest replacement interval that the target annual system availability is satisfied.

4-1: Calculate the decrement of the annual system availability per unit cost when the replacement interval of each component is lengthened 1 year.

4-2: If the target system availability is not satisfied any component, stop the procedure. Otherwise, go to Step 5.

Step 5: Lengthen the replacement interval of the component with the lowest decrement 1 year. Go to 4.1

In the numerical experiments, the optimal replacement intervals of the components are determined individually. The simulation length is 12 years (105,120h) and the number of replications is 100 times. We then compare the maintenance costs of ***CASE 1*** and 2 for the different target system availability, 90%, 95% and 99%. Generally, the maintenance costs should increase as the target system availability increase because the maintenance costs is increased by performing more frequent PM of the system in order to satisfy the target system availability. As a result, Table 2 show the maintenance costs of ***CASE 1*** and 2, and ***CASE 2*** result in a lower maintenance costs than that of ***CASE 1***.

Table 2. Maintenance costs for different target availability

	Target system availability		
	90%	95%	99%
CASE 1	3,867,037,962	4,386,732,185	4,699,192,115
CASE 2	2,212,888,241	2,247,399,021	2,527,519,199

The total CM cost of ***CASE 2*** is lower than that of ***CASE 1*** because the components are replaced by new ones more frequently and preventively. As a result, the total PM cost of ***CASE 2*** increases as the target system availability increases as shown in Table 3.

Table 3. CM and PM costs of ***CASE 2*** for different target availability

	Target system availability		
	90%	95%	99%
CM cost	1,807,659,004	1,479,532,635	1,553,844,105
PM cost	405,229,237	767,866,386	973,675,094

Table 4 shows the optimal replacement intervals of 8 components in the system and these are reduced as the target system availability. Especially, #7 component needs only to be replaced preventively in order to satisfy the target system availability, 99%. However, # 8 component does not need to be replaced because it is higher reliable than other components.

Table 4. Optimal replacement intervals of 8 components

Component	Target system availability		
	90%	95%	99%
# 1	12y	10y	8y
# 2	1y	1y	1y
# 3	2y	1y	1y
# 4	3y	2y	2y
# 5	6y	5y	3y
# 6	6y	5y	3y
# 7	-	-	9y
# 8	-	-	-

5. Conclusion

In this study, we dealt with a replacement policy for a PCS in the ESS under combination warranty policy. System availability and maintenance costs are considered as optimization criteria. The objective of this study was to determine the replacement intervals of the components with increasing failure rate function that satisfy the target annual system availability and minimize the maintenance costs including the warranty costs. The warranty costs were the sum of the free maintenance costs of the components and the penalty cost which was added when the target annual system availability does not be satisfied. The commercial RAM simulation package, *BlockSim* was used to estimate the system availability and maintenance costs. Also, we found the optimal replacement intervals of the components individually by the heuristic method with simulation, *BlockSim*. By numerical examples, two CASEs were compared for the different target system availability, 90%, 95% and 99% in order to investigate the effect of the preventive replacement. ***CASE 2*** gave a lower maintenance costs than that of ***CASE 1*** and increased as the target system availability increased. It required replacing the components more frequently and preventively in order to satisfying the target system availability. As a result, the total maintenance cost of ***CASE 2*** increased.

In these numerical experiments, we considered to determine the replacement intervals of the components individually. However, when there is economic dependency between the components in the system, the group maintenance can be applied to reduce the maintenance cost. For further study, we will find the economic dependency in the ESS PCS and consider the group maintenance problem for the system.

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