RELIABILITY OF SMART GRID SYSTEMS WITH WARM STANDBY SPARES AND IMPERFECT COVERAGE

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Abstract: This paper models the reliability of a smart grid system with warm standby spares and imperfect fault coverage based on binary decision diagrams (BDD). In order to meet stringent reliability requirement, it is essential for a smart grid system to be designed with fault tolerance. The Warm standby SParing (WSP) is an important fault tolerance technique which compromises the energy consumption and the recovery time. For WSP, the standby units have different failure rates before and after they are used to replace the on-line faulty units. Furthermore a component failure may propagate through the grid and cause the whole system to fail if the failure is uncovered. Existing works on systems with warm standby spares and imperfect fault coverage are restricted to some special cases, such as assuming exponential failure time distribution for all components or only considering one spare. The BDD approach proposed in this paper can overcome the limitations of the existing approaches. Examples are shown to illustrate the application.

1 INTRODUCTION

It is crucial for a smart grid system to be designed with fault tolerance in order to reach high reliability (Coll-Mayor et al., 2004; Iwayemi et al., 2010; Wu and Zhou, 2011). There are different techniques to achieve fault tolerance in grid systems, typically hot, cold and warm standby sparing to adapt to different situations (Tannous et al., 2011b). Hot standby SParing (HSP) is used as a failover mechanism to provide reliability in system configurations. The hot spare is active and connected as part of a working system. This type of sparing is generally used for applications for which the recovery time is critical. For Cold standby SParing (CSP) the spare unit is powered up only when the online unit fails and needs to be replaced. CSP is typically used for applications for which energy consumption is critical. Warm standby SParing (WSP) compromises the energy consumption and the recovery time; the spare components are partially powered up when the primary component is operational and it is fully powered up only after the primary component fails. For WSP systems, the standby units have time-dependent failure behavior; they have different failure rates, in general, different time-to-failure distributions before and after they are used to replace the on-line faulty units.

Existing approaches for analyzing the reliability of systems with warm standby spares include Markov-based methods, simulation-based methods, and combinatorial methods. The Markov methods suffer from the well-known state space explosion problem (Ke et al., 2008a) and are typically applicable to exponential time-to-failure distributions for the system components. The simulation-based methods, for instance, Monte-Carlo simulations, are usually computationally expensive and time-consuming, especially when results of high accuracy are desired (Ke et al., 2008b). A combinatorial approach was proposed by Lee et al. (2009), which enumerates all the minimal cut sets or sequences, and then applies the inclusion/exclusion formula to calculate the system reliability. The enumeration of the minimal cut sets/sequences and the inclusion/exclusion expansion makes the complexity of the method doubly exponential. Another combinatorial approach based on binary decision diagrams (BDD) is proposed (Tannous et al., 2011a) to evaluate the

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reliability of WSP systems without consideration of imperfect fault coverage.

Even in case where a smart grid is designed with adequate redundancy, a single uncovered failure may propagate through the system and lead to the overall system failure (Pepyne, 2007; Dobson et al., 2007; Aranya and Marija, 2011). This occurrence is known as imperfect fault coverage (IFC), see Bouricius et al. (1969), Arnold (1973) and Xing (2007). Due to the imperfect fault coverage, the system reliability cannot increase unlimitedly with the increase of the system redundancy (Amari et al., 2004; Myers, 2008; Levitin, 2008; Peng et al., 2011). The simple and efficient algorithm (SEA) is a well-known approach used to incorporate imperfect coverage into combinatorial methods (Amari et al., 1999; Levitin et al., 2012). The SEA approach works well only for systems with static redundancy but doesn't work for systems with time or sequential dependency. Some researchers have studied the availability of a WSP system with repair distribution and imperfect coverage (Ke et al., 2008a; Ke et al., 2008b; Ke et al., 2010). But those works are limited to systems with only one spare. Some other studies of WSP with imperfect coverage are restricted to the case where the failure time of each component follows an exponential distribution (Lee et al., 2009; Hsu et al., 2009; Ke et al., 2008c).

Incorporating the imperfect fault coverage is a challenging task, especially, for the reliability analysis of a smart grid system with warm standby spares which is complex to start with. In this work, the BDD method (Tannous et al., 2011a) is extended to study the reliability of a smart grid system with WSP when imperfect fault coverage exists. Some new rules are introduced for the BDD construction and the system unreliability evaluation in order to capture the effect of imperfect coverage and the time-dependency of failures. The proposed approach is general and can be applied to any dynamic system, in particular the WSP, with components subject to imperfect coverage. It is not limited to WSP with only one spare but works as well for WSP with *n*-spares having any time-to-failure distribution.

Section 2 introduces the background of BDD. Section 3 presents the procedures of the BDD-based approach. A grid system with one warm standby spare and a grid system with two warm standby spares are presented in Section 4 to illustrate the proposed method. Section 5 summarizes the paper and points out some future directions.

2 BINARY DECISION DIAGRAM

The binary decision diagram (BDD) was initially developed as a tool for validating VLSI circuitry design by Bryant (Bryant, 1986). The BDD method provides an efficient and exact way to analyze static fault trees. In general, BDD requires less computational time than other existing fault tree reliability analysis methods as shown by many studies (Chang et al., 2005; Xing and Dugan, 2002; Yeh et al., 2002). BDD uses Shannon decomposition for its direct acyclic graph as:

$$f = x.f_{x=1} + \bar{x}.f_{x=0} = ite(x, f_{x=1}, f_{x=0}) \qquad (1)$$

where f represents a Boolean expression for a set of Boolean random variables X and x being a member of X. The two terminal nodes labelled "1" and "0" in the BDD represent the system being in the failure and operational states respectively. The advantage of this method is that the two sub expressions are disjoint. Therefore, the total failure probability of the system can be calculated as the sum of all the disjoint paths that lead to the sink node "1". These paths represent all combinations of the failure and non-failure of components that lead to the entire system failure.

The BDD is generated via a bottom-up traversal of the fault tree, applying the following manipulation rules (Bryant, 1986):

$$\begin{aligned} G \Diamond H &= ite(x, G_1, G_2) \Diamond ite(y, H_1, H_2) \\ &= \begin{cases} ite(x, G_1 \Diamond H_1, G_2 \Diamond H_2) & index(x) = index(y) \\ ite(x, G_1 \Diamond H, G_2 \Diamond H) & index(x) < index(y) \\ ite(y, G \Diamond H_1, G \Diamond H_2) & index(x) > index(y) \end{cases} \end{aligned} \qquad (2)$$

where G and H represent two Boolean expressions corresponding to the traversed sub-fault trees. The logical operation (AND, OR) is represented by ◊.

3 THE BDD-BASED APPROACH

The BDD method is usually used for static systems and some additional rules need to be applied to encompass the time dependency of warm spare failures and the effect of imperfect fault coverage in the smart grid system.

3.1 BDD Construction

An individual component is represented by BDD as shown in Figure 1. The BDD is constructed

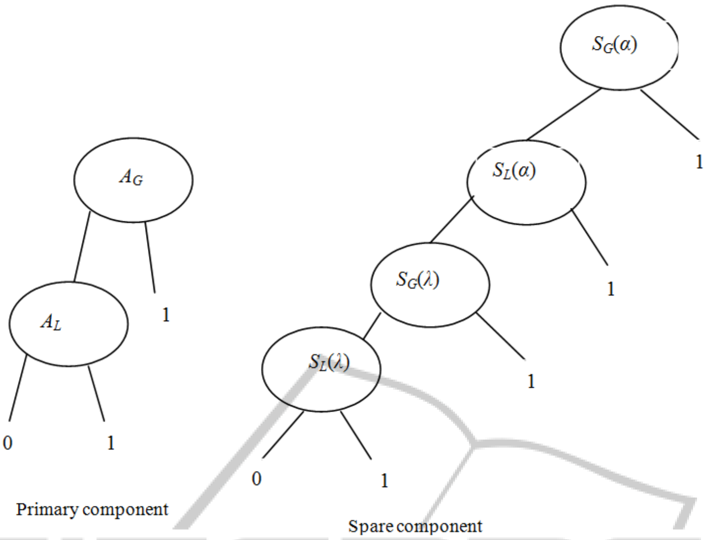

Figure 1: The representation of primary and spare components in BDD.

iteratively by combining the BDD representing A, S_1, …, S_n in sequence. Besides the basic Shannon decomposition rules represented by (2), the following additional rules need to be applied:

1. Since the system fails in case of any global failure regardless the status of any other component, the right child of X_G (which can be either A_G, $S_{iG}(\alpha)$, or $S_{iG}(\lambda)$) is always 1.
2. If the primary doesn't fail, only global failure of subsequent spares can cause the system to fail. Thus, following the left branch of $S_{iL}(\lambda)$ or A_L , there will only be $S_{jG}(\alpha)$, where $j>i$.
3. $S_{jG}(\alpha)$ cannot exist if all the components before it (A, S_1,...,and S_{j-1}) have failed locally. Actually when A, S_1,..., and S_{j-1} have all failed locally, S_j either has already failed locally or is powered up. In either case, $S_{jG}(\alpha)$ will not happen.

3.2 System Unreliability Evaluation

The unreliability of the smart grid system with warm standby spares can be evaluated as the sum of probabilities of all the disjoint paths from the root node to sink node "1" in the BDD model. Specifically we have to distinguish the three kinds of sequence $(S_L \to P_L)$, $(P_L \to S_G)$, and $(P_L \to S_L)$.

$$\Pr\{S_L \to P_L\} = \Pr\{\neg P_G \cdot P_L \cdot S_L(\alpha)\} = \int_0^t \int_0^{\tau_1} f_{P_L\lambda}(\tau_1) f_{S_L\alpha}(\tau_2) d\tau_2 d\tau_1 \tag{3}$$

$$\Pr\{P_L \to S_G\} = \Pr\{\neg P_G \cdot P_L \cdot \neg S_L(\alpha) \cdot S_G(\lambda)\} = \int_0^t \int_{\tau_1}^t f_{P_L\lambda}(\tau_1) f_{S_G\lambda}(\tau_2 - \tau_1)\left(1 - \int_0^{\tau_1} f_{S\alpha}(\tau) d\tau\right) d\tau_2 d\tau_1 \tag{4}$$

$$\Pr\{P_L \to S_L\} = \Pr\{\neg P_G \cdot P_L \cdot \neg S_L(\alpha) \cdot \neg S_G(\lambda) \cdot S_L(\lambda)\} = \int_0^t \int_{\tau_1}^t f_{P_L\lambda}(\tau_1) f_{S_L\lambda}(\tau_2 - \tau_1)\left(1 - \int_0^{\tau_1} f_{S\alpha}(\tau) d\tau\right) d\tau_2 d\tau_1 \tag{5}$$

where "$\neg$" denotes logical relationship "negation". The probability density function f can be in any distribution.

4 ILUSTRATIVE EXAMPLES

This section considers a smart grid system with one warm standby spare and a smart grid system with two warm standby spares for illustration.

4.1 Warm Standby with One Spare

The BDD for a WSP with one spare can be constructed by combining the BDD of the primary and the BDD of the spare, as shown in Figure 2.

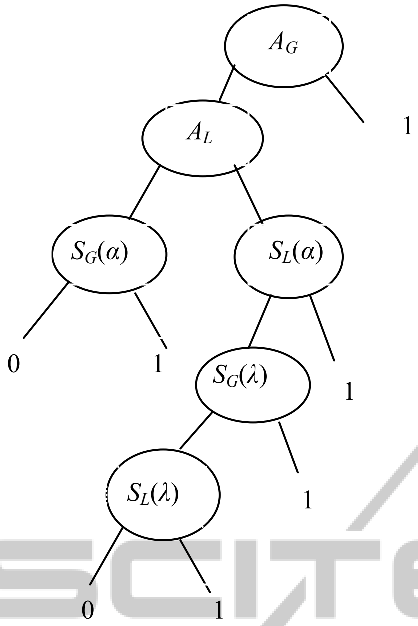

Figure 2: BDD of a WSP with one spare.

The system unreliability can be obtained by adding up the probabilities of all the paths leading to 1-terminal as

$$\begin{aligned}
UR &= \Pr(A_G) + \Pr\{\neg A_G \cdot A_L \cdot [S_L(\alpha) \\
&+ \neg S_L(\alpha) \cdot (S_G(\lambda) + \neg S_G(\lambda) S_L(\lambda))]\} \\
&+ \Pr[\neg A_G \cdot \neg A_L \cdot S_G(\alpha)] \\
&= \int_0^t f_{A_G\lambda}(\tau_1)\, d\tau_1 + \int_0^t f_{A_L\lambda}(\tau_1)[\int_0^{\tau_1} f_{S_L\alpha}(\tau_2) d\tau_2 + \\
&(1 - \int_0^{\tau_1} f_{S\alpha}(\tau_2) d\tau_2).\int_{\tau_1}^t f_{S\lambda}(\tau_2 - \tau_1) d\tau_2] d\tau_1 \\
&+ \int_0^t f_{S_G\alpha}(\tau_1)[1 - \int_0^{\tau_1} f_{A\lambda}(\tau_2) d\tau_2]\, d\tau_1
\end{aligned} \tag{6}$$

where UR denotes the system unreliability.

Due to imperfect fault coverage, the unreliability of a WSP with one spare may be even higher than the unreliability of the system with only the primary component, if the global failure rate of the spare is high. In real applications, it is advisable to take the cost and the uncertainty of the global failure rate and other parameters into consideration.

4.2 Warm Standby with Two Spares

The BDD for a WSP with two spares can be obtained by combining the BDD in Figure 2 with one warm standby spare as in Figure 3.

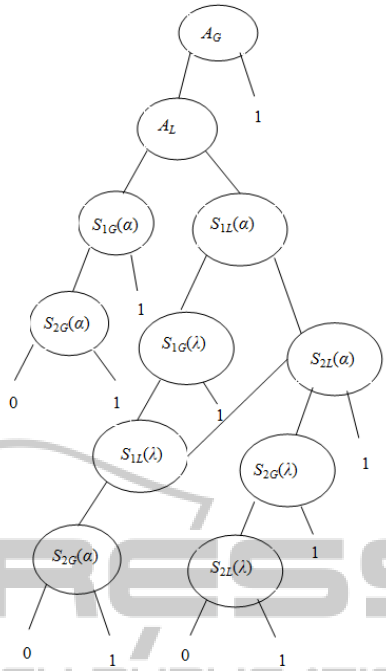

Figure 3: The BDD of a WSP with two spares.

According to the BDD, the system unreliability can be evaluated as

$$\begin{aligned}
UR &= \Pr(A_G) + \Pr\{\neg A_G \cdot A_L \cdot S_{1L}(\alpha) \cdot [S_{2L}(\alpha) + \\
&\neg S_{2L}(\alpha) \cdot (S_{2G}(\lambda) + \neg S_{2G}(\lambda) \cdot S_{2G}(\lambda))]\} \\
&+ \Pr(\neg A_G \cdot A_L \cdot \neg S_{1L}(\alpha) \cdot \{S_{1G}(\lambda) + \neg S_{1G}(\lambda) \cdot S_{1L}(\lambda) \\
&[S_{2L}(\alpha) + \neg S_{2L}(\alpha) \cdot (S_{2G}(\lambda) + \neg S_{2G}(\lambda) \cdot S_{2G}(\lambda))]\}) \\
&+ \Pr(\neg A_G \cdot A_L \cdot \neg S_{1L}(\alpha) \cdot \neg S_{1G}(\lambda) \cdot \neg S_{1L}(\lambda) \cdot S_{2G}(\alpha)) \\
&+ \Pr(\neg A_G \cdot \neg A_L \cdot S_{1G}(\alpha)) \\
&+ \Pr(\neg A_G \cdot \neg A_L \cdot \neg S_{1G}(\alpha) \cdot \neg S_{2G}(\alpha)) \\
&= \int_0^t f_{A_G\lambda}(\tau_1)\, d\tau_1 \\
&+ \int_0^t f_{A_L\lambda}(\tau_1) \int_0^{\tau_1} f_{S1_L\alpha}(\tau_2)[\int_0^{\tau_1} f_{S2_L\alpha}(\tau_3) d\tau_3 + \\
&(1 - \int_0^{\tau_1} f_{S2\alpha}(\tau_3) d\tau_3).\int_{\tau_1}^t f_{S2\lambda}(\tau_3 - \tau_2) d\tau_3] d\tau_2 d\tau_1 \\
&+ \int_0^t f_{A_L\lambda}(\tau_1)(1 - \int_0^{\tau_1} f_{S1\alpha}(\tau_2) d\tau_2) \int_{\tau_1}^t \{f_{S1_G\lambda}(\tau_2 - \tau_1) + \\
&f_{S1_L\lambda}(\tau_2 - \tau_1)[\int_0^{\tau_2} f_{S2_L\alpha}(\tau_3) d\tau_3 + \\
&(1 - \int_0^{\tau_2} f_{S2\alpha}(\tau_3) d\tau_3).\int_{\tau_2}^t f_{\lambda_{S2}}(\tau_3 - \tau_2) d\tau_3]\} d\tau_2 d\tau_1 \\
&+ \int_0^t f_{S2_G\alpha}(\tau_3) \int_0^{\tau_3} f_{A_L\lambda}(\tau_1)\ [1 - \int_0^{\tau_3} f_{S1\alpha}(\tau_2) d\tau_2] \\
&[1 - \int_{\tau_1}^{\tau_3} f_{S1\lambda}(\tau_2) d\tau_2] d\tau_1 d\tau_3 \\
&+ \int_0^t f_{\alpha_{S1_G}}(\tau_2)[1 - \int_0^{\tau_2} f_{\lambda_A}(\tau_1) d\tau_1]\, d\tau_2 \\
&+ \int_0^t f_{\alpha_{S2_G}}(\tau_3)[1 - \int_0^{\tau_3} f_{\lambda_A}(\tau_1) d\tau_1] \\
&[1 - \int_0^{\tau_3} f_{\alpha_{S1_G}}(\tau_2) d\tau_2]\, d\tau_3
\end{aligned} \tag{7}$$

Similarly the WSP with two spares does not necessarily have a lower unreliability than the WSP with only one spare or even no spare due to the propagation of global failure. An extreme case is that the primary is perfect and spare components only fail globally. Even in case when two spares are preferred, the system unreliability is influenced by the order of the two spares and the primary component. Parameters of component costs, failure time distributions, and global failure rate should be estimated. Sensitivity analysis is also required in real applications.

5 CONCLUSIONS

This paper studies the reliability of a smart grid system with warm standby spares and the existence of imperfect fault coverage. For warm standby sparing, the standby units have different failure rates before and after they are used to replace the on-line faulty units. Furthermore a component failure may propagate through the grid system and cause the whole system to fail if the failure is uncovered. It is a challenging task to incorporate imperfect fault coverage into systems with warm standby spares. The existing approaches are restricted to special cases, such as assuming exponential failure distribution for all the system components or limiting the number of spares to be one. A BDD-based approach is proposed and procedures for BDD construction and system unreliability evaluation are presented and illustrated. It can work well for warm standby systems with *n*-spares having any arbitrary type of time-to-failure distributions.

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