Fuzzy Lifetime Analysis of a Fault-Tolerant Two-Phase Interleaved Converter

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Abstract -- Interleaved converters are used in photovoltaic (PV) applications to handle high power conditions with high reliability. To improve the reliability of these converters, redundant switch configuration can be employed which reduce the failure rates of the power switches significantly. However, evaluation reliability of the interleaved converters equipped with redundant switch configurations may be complex. This paper aims to simplify the reliability analysis of interleaved converters considering mission profile and redundant switch configuration. Different possible configurations of the studied converter are shown as Markov chain states in the proposed method, which simplify the reliability and failure rates analysis. The effect of different parameters such as the converter power level, switch configuration type, and operation modes are derived and a better insight into the effectiveness of the switch configuration on improving the reliability is provided.

Index Terms-- Interleaved converters, photovoltaic applications, redundant switch configurations, reliability.

I. INTRODUCTION

POWER electronic converters are used in wide ranges of power levels, voltage, and current rates for distributed energy applications. With the progress in manufacturing technology of power converters, grid-connected interfaces for the distributed power sources have been developed in recent decades [1]-[5]. By increasing roles of power converters in vital and high-power applications, reliability of these systems is becoming an important issue [6]-[9]. The semiconductor power switches that are the most vulnerable elements must be investigated from the reliability point of view [10]-[14]. One of the solutions is employing redundant switch configuration. However, the reliability analysis of converters equipped with redundant switch configurations are complex. In [15], the mean time to failure (MTTF) of two- and three-phase interleaved boost converters is evaluated to determine the best configuration with considering the cost and reliability. In [16], the fault-tolerant operation of a single-switch converter using redundant switches is realized. However, the reliability analysis of converters equipped with redundant switch configurations may be complex.

A well-known method for evaluating the lifetime of converters is the Markov-based analysis. In this method, the reliability and lifetime of a system are analyzed in the useful period of that system [17], [18]. Thus, the failure rates for special power and ambient conditions can be considered constant. There are different uncertainties in the manufacturing process of the devices which must be considered in the lifetime evaluation [19]. Fuzzy logic is a power full tool that can be used in reliability and lifetime evaluation in many industry applications. Fuzzy-based reliability evaluation of transmission system using fuzzy Markov model [20], a substation automation case study [21], [22], hybrid molten carbonate fuel cell (MCFC) and gas turbine system [23], are addressed in previous papers. An extended fuzzy-based fault tree analysis [24], reliability analysis of a robotic system using fuzzy numbers [25], and the fuzzy probability of unit reliability [26] are investigated in previous papers. In [27], to model uncertainty in load forecast, a fuzzy membership function of peak load is proposed. A fuzzy-Markov model is applied in [28] to incorporate fuzzy mean time to failure and fuzzy mean time to repair. However, fuzzy reliability analysis of power electronic converters using Markov chain theory is rarely discussed in previous papers. In this paper, the Markov model is based on the two-phase converter's electric model. This model helps the researchers understand how to handle the faulty switches. The converter is equipped with redundant power switch configurations. The fuzzy-logic-based Markov model is a powerful analysis tool that covers the reliability Analysis gap that is not considered in other literature.

II. CASE STUDY WITH REDUNDANT SWITCH CONFIGURATION

The conventional two-phase dc-de boost converter is considered in this paper, as shown in Fig. 1(a).

Interleaved operation has attractive benefits on efficiency, size, thermal management, and ripple cancellation input current. Fault detection and isolation mechanism for each power switch can be implemented by using the auxiliary switches (S1a, S2a). These auxiliary switches can manage the faulty conditions appropriately. Parallel and standby switch configurations are shown in Fig. 1(b). It is assumed that the converter can operate in one-phase operation mode.
Fig. 1. (a) two-phase interleaved boost converter and redundant switch configurations. (b) Parallel and (c) standby configurations.

Fig. 2. Ambient temperature and output PV power distributions.

However, the junction temperatures of the switches should be calculated for this operation mode to ensure that the power switches operate in safe conditions.

Failure rates of power switches depend on the power dissipation and ambient temperature. Fig. 2 shows the clustered converter power level and temperature. This 3D-figure shows different monitored ambient temperature and power ranges and the corresponding percentage values of all conditions during a day. In fact, this temperature and power distribution profile is used to accurately estimate thermal stresses on the power switches. Considering participation of each power and temperature state in the failure rate calculations, the following equation can be obtained:

$$\lambda = \sum_{i=1}^{n} \lambda_i \times \mu_i$$  \hspace{1cm} (1)

where $\mu_i$ is the probability and $\lambda_i$ is the failure rate of the power switch in the state $(i)$, respectively.

III. MTTF Analysis

In this paper, a two-phase interleaved boost converter is evaluated from the point of view of MTTF. Figs. 3 and 4 show the Markov reliability modes of the case study equipped with parallel and standby switch configurations. As illustrated in these figures, three possible operation states can be defined for the case study as follows:

- Three phases are healthy.
- One phase has failed. Then, the faulty phase is cleared, and the system operates as a two-phase converter.
- All phases failed.

The failure rate of the system when operating as a $k$-phase converter, is $\lambda^{(k)}$ and it is constant all the time. In the case of a fault occurrence, the probability of the mechanism that manages the fault is considered by $P_C$. For example, according to Fig. 4, the rate of transition from state $(n$-phase converter) to state (one-phase converter) is $2P_2\lambda^{(2)}$ in the Markov chain. If the strategy of the fault management fails, the probability of the transition from state (two-phase converter) to (fail state) is $2(1-P_2)\lambda^{(2)}$.

The base failure rate is considered as a fuzzy function as shown in Table I. With respect to Table I, the ambient conditions and PV power profile (Fig. 2), the failure rates of power switches in the used redundant configuration can be obtained. As seen in Fig. 3 and 4, to calculate the MTTF values of the two-phase converter, $\lambda^{(1)}_{H(i)}$, $\lambda^{(2)}_{F(i)}$, $\lambda^{(1)}_{H(i)}$, and $\lambda^{(2)}_{F(i)}$ must be determined for each power and temperature state. These parameters are fuzzy and can be extracted as

$$\lambda^{(1)}_{H(i)} = \frac{2\lambda^{(1)}_{H(i)}(1-P^e)}{1 + 2\lambda^{(1)}_{H(i)}(1-P^e)P_C}$$

$$\lambda^{(2)}_{F(i)} = \frac{2\lambda^{(2)}_{F(i)}(1-P^e)}{1 + 2\lambda^{(2)}_{F(i)}(1-P^e)P_C}$$

$$\lambda^{(1)}_{F(i)} = \sum_{i=1}^{n} \lambda^{(1)}_{F(i)} \times \mu_i$$

$$\lambda^{(2)}_{F(i)} = \sum_{i=1}^{n} \lambda^{(2)}_{F(i)} \times \mu_i$$

Fig. 3. Markov chain and reliability curves of a two-phase converter with parallel switch structure.
follow:
\[
\dot{\lambda}_{sb}^{(1)} = \sum_{i=1}^{n} \lambda_{sb}^{(1)} \times \mu_{i}
\]

For each state, the probabilities of parallel and standby failures are calculated as follow:
\[
\dot{\lambda}_{p}^{(1)} = \frac{2\dot{\lambda}_{sb}^{(1)}}{1+P_{c}} = (ap_{A,(1)}, bp_{A,(1)}, cp_{A,(1)})
\]
\[
\dot{\lambda}_{sb}^{(1)} = \frac{\dot{\lambda}_{sb}^{(1)}}{1+P_{c}} = (as_{A,(1)}, bs_{A,(1)}, cs_{A,(1)})
\]

Hence, the total failure rates of the converter in each operation mode can be calculated as follows:
\[
\lambda_{p}^{(1)}(t) = \lambda_{p}^{(1)}(1-\frac{2P_{c}}{1+P_{c}})
\]
\[
\lambda_{sb}^{(1)}(t) = \lambda_{sb}^{(1)}(1-\frac{2P_{c}}{1+P_{c}})
\]

To calculate the MTTF of the two-phase converter, the probability of successful operation of fault manager is defined as seen in Table I. Therefore:
\[
MTTF_{p}^{(2)} = \frac{1+\frac{2\dot{\lambda}_{p}^{(2)}}{2\dot{\lambda}_{p}^{(2)}}}{2\dot{\lambda}_{p}^{(2)}} \hat{P}_{c}
\]
\[
MTTF_{sb}^{(2)} = \frac{1+\frac{2\dot{\lambda}_{sb}^{(2)}}{2\dot{\lambda}_{sb}^{(2)}}}{2\dot{\lambda}_{sb}^{(2)}} \hat{P}_{c}
\]

In each operation model of the converter, \( \dot{\lambda}_{p}^{(1)} \) and \( \dot{\lambda}_{sb}^{(1)} \) are triangular memberships that depend on three parameters as given by (4) and (5). Figs. (5) and (6) show the \( (ap_{A,(1)}, bp_{A,(1)}, cp_{A,(1)}) \) for parallel-based converter and \( (as_{A,(1)}, bs_{A,(1)}, cs_{A,(1)}) \) for standby-based converter) values for each power and temperature states when the converter operates in one-phase operation mode. Figs. (7) and (8) show \( (ap_{A,(1)}, bp_{A,(1)}, cp_{A,(1)}) \) for parallel-based converter, and \( (as_{A,(1)}, bs_{A,(1)}, cs_{A,(1)}) \) for standby-based converter) values for each power and temperature states when the converter operates in two-phase operation mode.

IV. RESULTS

With respect to Figs. 5-8 and considering (6)-(9), the fuzzy membership of the total failure rates of power switches in each operation mode can be calculated as follows:
\[
\lambda_{p}^{(1)}(t) = (1.0335, 1.8564, 3.2574)
\]
\[
\lambda_{sb}^{(1)}(t) = (1.6696, 2.9605, 5.1197)
\]
\[
\lambda_{p}^{(2)}(t) = (1.1793, 1.4937, 1.8452)
\]
\[
\lambda_{sb}^{(2)}(t) = (2.3718, 3.0043, 3.7112)
\]

The fuzzy memberships of different parameters that described in this paper are used to extract fuzzy curves of MTTF function of the studied topologies are extracted, as seen in Fig. 9. These fuzzy MTTF curves show MTTF distribution of the two-phase converter with the referred

![Fig. 4. Markov chain and reliability curves of a two-phase converter with standby switch structure.](image)

![Fig. 5. (a) \( ap_{A,(1)} \), (b) \( bp_{A,(1)} \), and (c) \( cp_{A,(1)} \) values for different power and temperature scenarios (one-phase operation mode).](image)
Fuzzy lifetime Analysis of fault-tolerant redundant power switch configurations. Defuzzification is the final step in Fuzzy-based reliability evaluation. Different defuzzification methods can be implemented. In this paper, the method proposed in [29] is used to map the fuzzy MTTF numbers to real values. The defuzzified central (Def value) of triangular fuzzy numbers \( \bar{R} = (a, b, c) \) can be determined from (16). The results of the defuzzified values for all the converters are provided in Table I.

\[
\text{Defvalue} = \frac{c^3 + bc - a^2 - ab}{3(c - a)} \tag{16}
\]

According to Fig. 10 and Table II, the following results can be summarized:

- In the converter with parallel switch configuration, it is likely that the lifetime of the converter is more than 5.7 years. While in the most optimistic case, the lifetimes of the proposed and standby-based converters are 5.7 and 3.4 years, respectively. This means that if the power converter is expected to work for a long time, the parallel switch-based topology should be used.

- In the most pessimistic case, lifetimes of parallel, standby and hybrid switch configuration-based converters are about 0.3144, 0.466, and 0.795 years, respectively. For low mission length, the MTTF of the parallel-switch configuration-based topology is the lowest one and the standby and hybrid switch configuration based-topology are the best topologies to use for low mission length.

- Generally, the lifetime of the parallel-switch configuration-based topology is more than the standby and hybrid ones.

V. CONCLUSION

Fuzzy lifetime Analysis of fault-tolerant the redundant switch configuration-equipped conventional two-phase interleaved converter have been performed in this paper. A converter topology-based Markov chain method is proposed...
to simplify the reliability and failure Analysis in comparison with the conventional Markov chain-based reliability Analysis that are reported in the literature. Using this method, all possible configurations of the studied converter equipped with redundant switch configuration are extracted as functions of power switch failure rates in different operation modes. The illustrated Markov chains consist of the topology of the case study in different operation modes and switch configurations, which give understandable insights to the research on reliability improvements.

VI. REFERENCES

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