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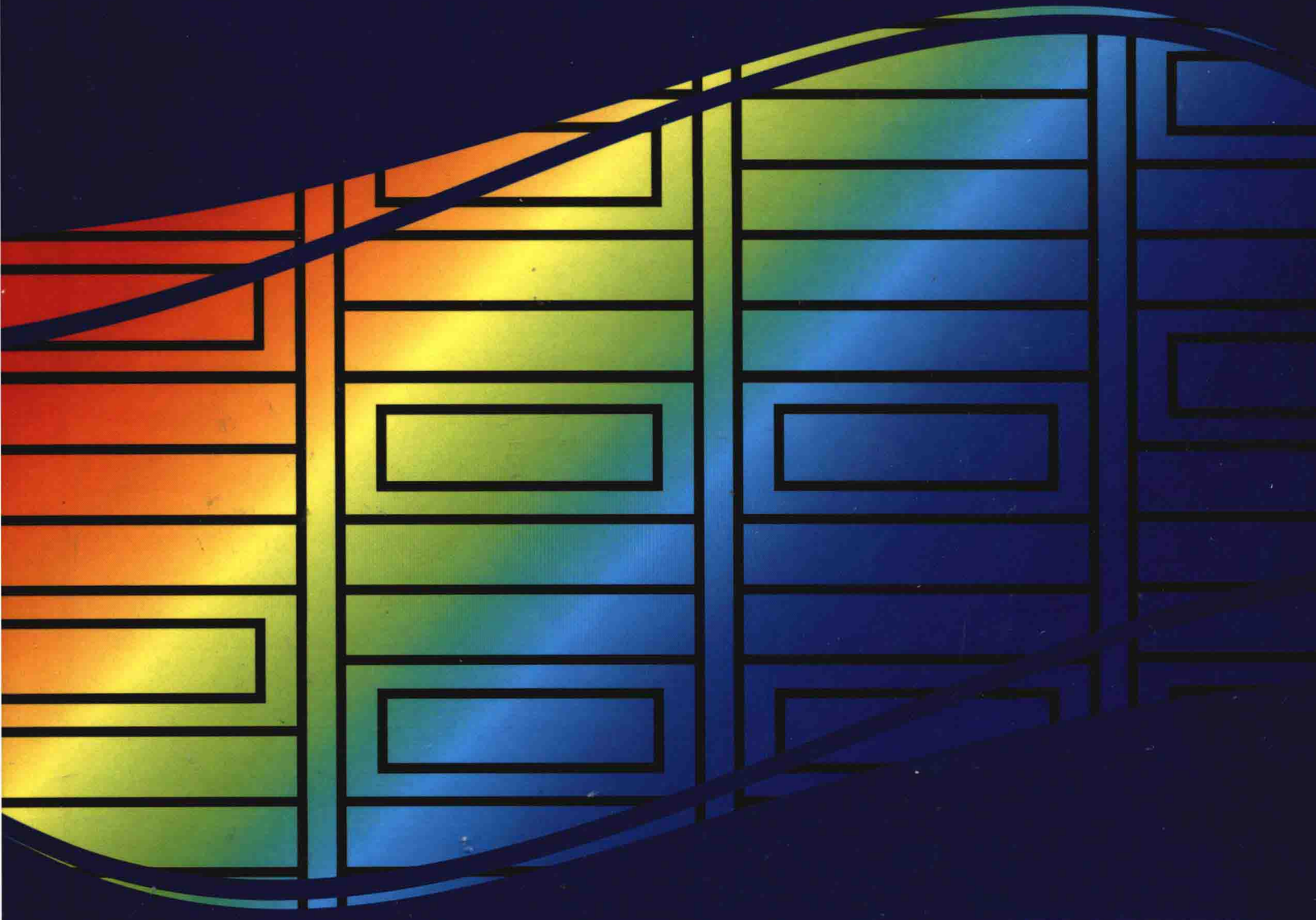
Industrial Applications and Performance Models



Shahriyar Kaboli and Hashem Oraee

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Reliability in Power Electronics and Electrical Machines:

Industrial Applications and Performance Models

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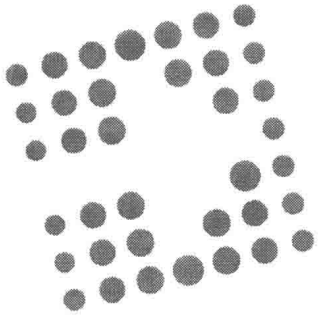

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Preface

In modern industries, electrical energy conversion systems consist of two main parts: electrical machines and power electronic converters. Electrical machines act in the conversion of electrical energy to mechanical one as a generator and vice versa as a motor. Power electronic converters are used for electrical energy conditioning. It is notable that electrical motors consume about half of the total generated electrical energy in the world. Regarding to the fast and wide usage of electrical energy, it is obvious that these two parts deal with considerable amount of energy. Thus, the uninterrupted operation of these power converters is very important.

Basically, reliability concept is a scale for evaluating the proper operation of systems. Reliability calculation is a method that estimates the effective and useful operative life of the systems. Especially, this scale is very important for the systems which are not practically repairable. In addition, this estimation is an important guideline in design process to design a reliable system. The performance of many industrial processes mainly depends on the quality of electric power converters. Switching power electronic converters and electrical machines are increasingly used for electrical energy conditioning and electromechanical energy conversion, respectively. The existence of high value of energy losses leads to generating hot spots at high temperature in power electronic systems. Temperature rise is one of the most important factors which reduce the operative life. Hence the useful life of such systems with high value of energy loss is decreased. As the effective operative life can not be examined immediately, there are some theoretical and experimental methods for predicting the reliability. In addition, reliability calculations help the designers to estimate the useful life of their designed systems. They can correct their design methodology if the estimated life is smaller than acceptable value. Thus, design for reliability is an important strategy.

On the other hand, methods for improving the reliability such as derating concept can be used in operation process to extend the useful life by proper application of electric power converters. In addition, derating algorithm can be used to continue the operation of an electric power converter under negligible faults.

This book deals with reliability and effective operative life concepts in the field of power electronics and electrical machines. In view of the extensive use of the aforementioned systems in industries, reliable design and an estimation of their effective operative life is considered to be crucial.

The aim of this book is to present a view about reliability in the field of "Electrical Energy Conversion". Based on this view, some of well-known strategies in design of power electronic converters and electrical machines should be reviewed. For example, application of high frequency switch mode power supplies is a common method. But, it may be replaced with a simple linear power supply with poor regulation but with high reliability in a reliable system.

HISTORY OF DEVELOPMENT OF THE BOOK

This book was developed based on teaching the related courses about power electronics and electrical machines in School of Electrical Engineering, Sharif university of Technology. A long term study about these electric power converters shows that a proper power system design and operation procedure is a chain which is led to reliability considerations. The main text of this book is resulted from class notes of related courses. This text core saw enormous changes during developing process of the book during the past 5 years. We tried to present a well-illustrated book to show the practical real examples of each section of the book. These figures were collected during an about 20 years of our activities in this field. Marker arrows were drawn for many figures to emphasize on the related topic of the figure. Developing process of this book was programmed for one year. But it take 5 years of our academic time with two times extension of our contract with IGI Global. It is a disadvantage but we are satisfied because the book in the present form is much more interesting than its initial planned form. Chapters 9 and 11 were not in the first draft and were added during modifications. Contribution of chapter 3 about MIL-HDBK-217 was also added to the final form of the book.

OBJECTIVES OF THE BOOK

This book is presented with the following overall objectives:

- To show the importance of reliability considerations in electric power converters.
- To present the calculation methods of reliability in electric power converters.
- To propose the techniques for improving the reliability in electric power converters

In this publication, methods for reliability calculation in electrical machines and power electronic converters are presented. Furthermore, thermal modeling is explained to determine the hot spot temperature since this temperature is a key factor in estimating the reliability of power electronic converters and electrical machines. In addition, the difference between high reliability and high efficiency systems is described. It is shown that high efficiency is not equivalent to high reliability in complex systems consisting of both the power electronic converters and electrical machines such as adjustable speed drives. Finally, various methods are presented to improve the reliability of the above mentioned systems such as derating method and load sharing method.

In modern industries, there are some new generated problems that affect reliability. Wide usage of adjustable speed drives for speed control of general purpose electrical motors leads to higher loss in these motors because of voltage harmonics fed into the motor. These problems are also considered and discussed in the book.

We should note that this book is not an encyclopedia about reliability. There are many high quality technical references for each chapters of the book. However, none on them deals with complete chain of reliability in the field of electric power converters. We tried to give not only a general system view but also a detailed technical view about complexities in electric power converters.

STRUCTURE OF THE BOOK

All of the materials used in this book are original. All of diagrams were drawn by authors and all of photos were prepared individually. Some of chapters use parts of our previous publications and they supported via proper referring. We use assistance of some companies and organizations via using their publications for presenting in the book. Copyright permission was received from them for all of the items used in the book. Here, we appreciate them for their kindly helps. We also planned to present several examples from other companies but they did not answer to our copyright permission request.

This book consists of 12 chapters which are divided to 5 different parts as shown in the flowchart of the book in Figure 1. Both reliability calculations and reliable design are considered.

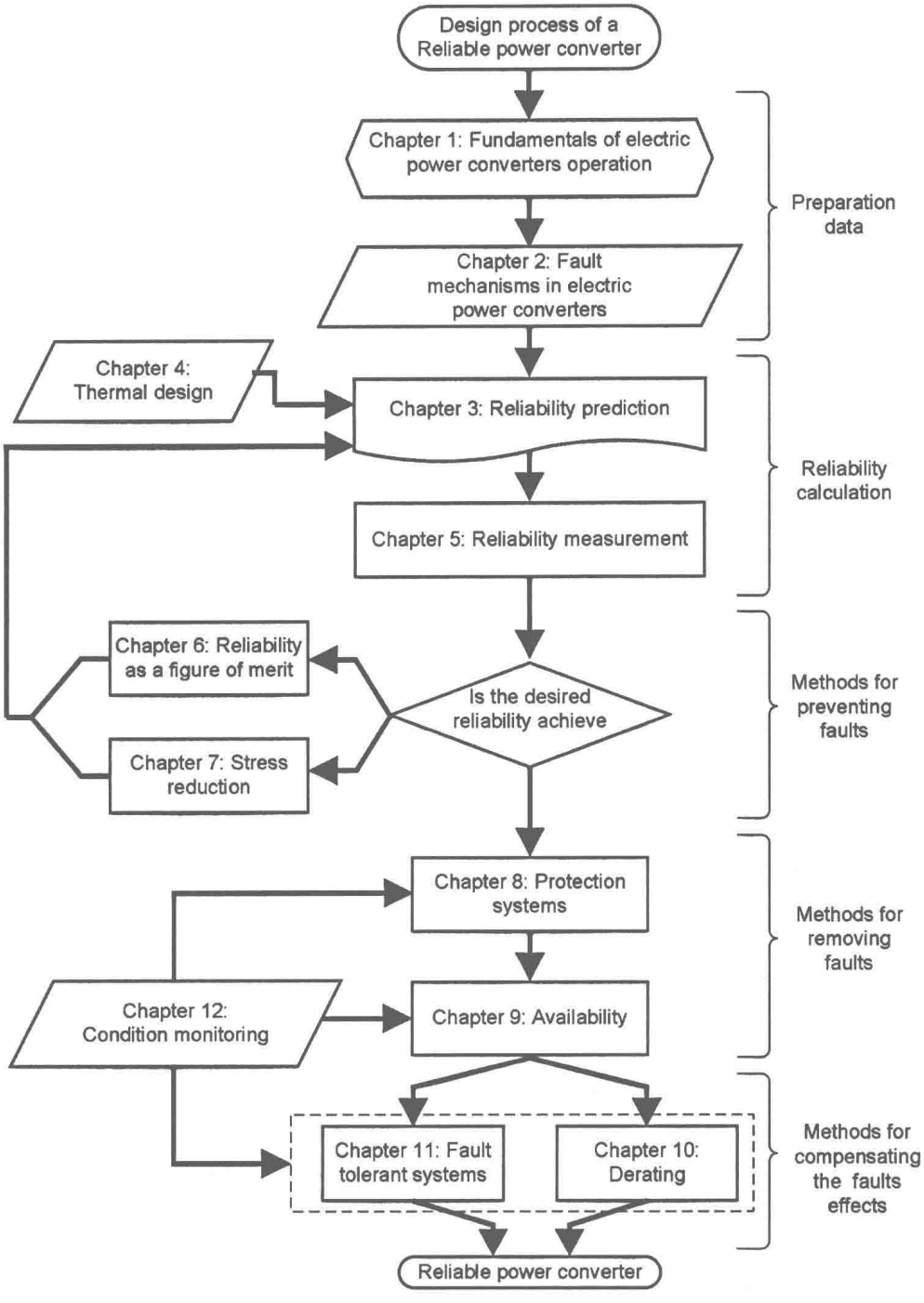
Section 1, "Data Preparation," is about fundamental concepts of reliability with the following details:

- Chapter 1, "Electric Power Converters in Industries," presents a brief introduction about importance of electrical energy conversion in the modern industries. The aim of this presentation is showing the dependence of various industrial functions to conversion of electric power. Basic relations of various electrical machines as well as power electronic converters are presented. In each section, some typical industrial examples are presented. This background will be used in the next chapters for reliability calculation and improvement. In fact, this chapter is an introduction about reasons of writing an individual book about reliability of electric power converters. Some examples of reliability importance in various industries are presented.
- Chapter 2, "Fault Mechanism," describes the reason of failure in electric power converters. All of the failure factors which are described in this chapter are catastrophic factors and leads to destructive damage in the systems. Other types of failure without destructive effect on converter like electromagnetic interference will be presented in the next chapters. All of descriptions are based on details of operation of the converters which were presented in the previous chapter. Over temperature, over voltage, Mechanical forces and environmental effects like humidity are the main factors of failure in systems. Origins of these factors are described in this chapter. Over temperature is a special factor among them. Because other failure factors finally act as over temperature in failure process of the converters. Since the over temperature is the main failure factor in electric power converters, loss model of components in electric power converters are presented in details. In addition, the practical technique for measuring the power loss is described. Sample industrial examples of damaged equipments due to these failure factors are shown to give a real sense to reader about failure results.

Section 2, "Reliability Calculation," is about reliability calculations with the following details:

- Chapter 3, "Reliability Prediction," uses probability calculation to predict the failure rate of the converter. The formulation of these calculations are based on the concepts of failure factors which were described in the previous chapter. Some detailed examples are presented to show the power of probability tool for analyzing the behavior of complex systems. This chapter covers the methods for reliability calculation from component to system level. Some standards of reliability are presented. One can use the information from a reliability prediction to guide design decisions throughout the development cycle. MIL-HDBK-217 is described in details as a well-known standard for reliability prediction in component level. Reliability modeling is introduced for calculat-

Figure 1. Flowchart diagram of the book



ing the reliability in system level. Difference between system block diagram and reliability model is presented. The reliability models of various static and rotary power converters are expressed. Some sample examples are presented to demonstrate the procedure of calculations for a simple

converter with its auxiliary components. This chapter give a quantitative view to reader about evaluation of reliability and its can be used in the next chapters for reliability improvement.

- Chapter 4, "Thermal Analysis," presents thermal analysis as the most important factors in failure of the converters. Two main approaches for this goal are presented: numerical and lumped mode. Principles of these methods are described with various examples and a comparison is presented. Basic principles of thermal modeling are described and concept of sample node in this model is explained. Methods for thermal management of an electric power converter are described. These methods are in both component and system levels and contain various heat transfer mechanism like conduction and convection. Theoretical methods and practical considerations for heat sink selection and proper mounting of it are presented. Thermal insulation classes and various standards related to thermal management topic are expressed. Industrial samples are presented to show application of theoretical topics in real world.
- Chapter 5, "Reliability Measurement," presents various methods of tests for this goal. The main approach is accelerated aging test that reduce the time need for failure in a system. In this method, the device is tested under condition beyond its defined nominal specifications. Limits for this harsh condition is determined based on the calculations which are presented in the chapters 3 and 4. If a problem occurs in implementing and operating process of the converter, accelerated aging tests decrease the time to failure. Theoretical concept of accelerated aging tests is described. Standard tests of electric power converters are presented. Equipment and test chambers for standard tests are explained. These tests contain all of four various failure factors which are presented in chapter 2. Sample industrial examples are presented to demonstrate the procedure of the tests. Some of accelerated aging tests may lead to destroy the converter. Difference between destructive and nondestructive tests is presented. Sample devices after accelerated aging tests are shown. Measuring devices for system parameter identification are introduced. Various types of tests are expressed in details for some of the most important tests like electric withstand tests.

Section 3, "Methods for Preventing Faults," is about reliability improvement in design stage with the following details:

- Chapter 6, "Reliability as a Figure of Merit," presents reliability as a figure of merit in design of a system and compares it with other indexes. We want to highlight the effect of reliability consideration on the design methodology of a power converter. The most important specification of a power supply or power converter is its robustness. Because any failure in power supply leads to failure of the whole of the system. A power converter may have poor performance but operates very reliable and vice versa. In fact, this is a reliability based design approach to achieve a long useful life. It is shown that in many systems, high efficiency is not a good choice for selection of system operating point. A system can be inefficient but very reliable. Two complex examples are presented to show undesired results of neglecting reliability in design process. Methods for more reliable operation of electric power converters than high performance operation are proposed. A discussion about correct and intelligent optimization of a system parameters and operating set point is presented.
- Chapter 7, "Stress Reduction," presents guidelines for improvement of reliability. These methods are used in both design and operation process of the converter. The focus of this chapter is on the component stress reduction in design process. Based on background of chapter two, reliability of

a converter increases if it operates in a set point with low stress. It is assumed that the converter is under design process or operates without fault. The methods for reliability improvement in faulty converters are discussed in the next chapters. In this chapter, methods for reducing electric field are described in both system and printed circuit board level. Low temperature operating conditions for an electric power converter are described and tools for this goal are presented. Series connection for voltage sharing and parallel connection for current sharing is explained. Novel control methods of power converters for reducing the complexity and reliable operation are presented. Control of inrush current as a typical transient problem in electric power converters is presented. Methods for preventing the over stress condition on the components in faulty cases are described. Techniques for reducing mechanical and environmental stress are expressed. Mechanical dampers for preventing the high amplitude vibration and insulating colors against humidity are presented. Industrial and real samples are presented to demonstrate application of the proposed methods.

Section 4, "Methods for Removing Faults," is about reliability improvement in operation stage when a fault without damaging effect occurs with the following details:

- Chapter 8, "Protection Systems," assumes that a fault occurs in the converter but there is a short time interval between fault occurrence and catastrophic damaging of the converter. Therefore, the topic of this chapter is the methods for saving the converter in this condition. In this chapter, protection methods for saving the system against damaging faults are presented. Based on background of chapter two, protection systems should be able to bypass the effect of failure factors on electric power converter. Methods for current limiting and voltage clamping as the usual factors of failure in converters are described. Circuit diagram of a snubber is presented and its operation is described based on safe operating area of solid state power switches. Operating diagrams of fuse as emergency circuit breaker are presented. Measurement methods and devices used in protection systems are explained. Experimental samples and standard diagrams are presented to clear the theoretical notes in all cases.
- Chapter 9, "Availability": Protection methods, which are described in the previous chapter, save the converter against non-catastrophic faults. However, this method saves the converter but causes to idle the converter out of the service. Subject of this chapter is about these converters that are not damaged but cannot operate normally. In this chapter, availability of electric power converters as a most important but usually forgotten parameter is described. The concept of availability was originally developed for repairable systems that are required to operate continuously. It is explained that a system may be unavailable while none of its parts damaged. In fact, there is an important difference between reliability and availability. A converter may be very high reliable but very unavailable and vice versa. One of the most important factors for this undesired state is influence of noise. In this chapter, electromagnetic interference and certain methods for reducing its undesired effects on electric power converters are presented. Electric power converters are usually the source of electromagnetic noise due to high operating voltage and/or current. Various techniques for safe operation of sensitive systems that operate close to these converters are described. In the last part of this chapter, alarm management is presented based on availability concept. This method is used to prevent fast shutdown of important systems due to dispensable faults.

Section 5, "Reliability in Operation Process," is about reliability improvement in operation stage with the following details:

- Chapter 10, "Derating," investigates uninterrupted operation of a faulty power conversion system with catastrophic damages in some of its parts. It is shown that a faulty electric power converter can continue to work with degraded specifications. This algorithm named derating for accessibility. This technique can be used for both a faulty system because of its uninterrupted operation and a normal system because of extensive life time. Algorithms for derating of a faulty electric machine and a power supply are described. Derating for increasing the useful life of a motor drive system is presented. A novel method for switching frequency selection in a switching power supply is proposed based on derating concept. Derating is introduced as a technique to compensate additional losses in an electric power converter operating in a harsh environment (for example: a motor drive which is supplied with a non-sinusoidal voltage waveform). Real industrial examples are presented in details for better understanding the derating concept. Some of the presented examples contain novel idea for derating and others are well known in industries.
- Chapter 11, "Fault Tolerant Systems": Fault tolerance is the property that enables a converter to work properly with failure in some of its components. Fault tolerant systems are systems that can be operating after fault occurred with no degraded performance in their basic functional requirements. This is the main difference between fault tolerant systems and derated systems. In this chapter, some of methods for fault tolerance in electric power converters are presented. Fault tolerance is almost the only method for achieving a desired reliability in a converter that operates with non-zero fault probability. There are two main approaches for this aim: re-configuration of the faulty system and using redundant systems. Redundancy is the provision of functional capabilities that would be unnecessary in a fault-free environment. Various types of redundant systems as passive and active redundancy are described and their application in power converter systems is presented. A new approach for a reliable and fault tolerant power supply is proposed and justify with experimental results. Concept of fault tolerance in electrical machines is presented.
- Chapter 12, "Conditions Monitoring": Implementation of all of the previously methods for reliability improvement needs to have an enough information about condition of the converter. This is the topic of the last chapter of this book. Condition monitoring is the process of monitoring a parameter of condition in machinery (vibration, temperature etc.), in order to identify a significant change which is indicative of a developing fault. The use of conditional monitoring allows maintenance to be scheduled, or other actions to be taken to prevent failure and avoid its consequences. In this chapter, commonly used methods for condition monitoring of the converters and electric machines are presented. The aim of this job is producing an alarm in converter before failure factor damage the system. Sensor based and sensor less methods for converter and motor parameter monitoring are described. The data obtained from sensor based methods is real but sensor is a weakness point in a converter. On the other hand, sensorless methods give estimated information but they are very reliable. Temperature as the most important parameter from reliability point of view is a common parameter for monitoring in all of systems. Other parameters like vibration, harmonics and others can be used for monitoring of various faults inside the system. Many typical cases are presented to well demonstrate the techniques.

FEATURES OF THE BOOK

Most of the recent texts on reliability are limited to a particular topics and they are very general without focus on power electronics and electrical machines. These documents do not provide comprehensive coverage of the field. Having a single comprehensive reference for the reliability in power electronics and electrical machines represents a significant advantage for the reader. Indeed, several topics in reliability are routinely encountered in a power electronics and electrical machines design and operation. This book includes the material that after several years of reliability problems has been found both theoretically sound and practically significant.

There are many published books about "Power Electronics" and "Electrical Machines". However, up to now, there are a few books published specifically in the field of "reliability in power electronics and electrical machines" which may be due to the fact that modern power electronics is young and is only used widely in industries in recent years. However, the importance of publishing such books should not be neglected since there are a number of well-known books published in similar research areas such as "power system". However, there is a great difference between "power system" and "power electronics". There are many reliability control tools in power electronics and electrical machines such as "switching frequency" which is fixed in "power systems". Thus, a dedicated reference is needed to use these tools and estimate the reliability value in power electronics and electrical machines. In addition, it should be mentioned that the other existing books in reliability field usually consider reliability concepts without a focus on lossy systems such as electric power converter or reliability at the device level that they are not applicable for reliability determination at the system level.

Other books in this field deal with only one of the topics in reliability. For example, there are many books in the field of condition monitoring. Springer has book series in the field of reliability. All of these book cover a portion of the chain of reliability in the field of power converters. This book covers the complete chain of failure to reliability in electrical machines and power electronics.

In addition to this main feature, we tried to give some other benefits to the book which are listed in the following.

- This book includes many real industrial examples. There are more than 600 figures and photos in the book. Real examples of faulty electric power converters are presented in details. Real examples of reliability calculations are expressed. This is a different presentation methodology in comparison to similar books. In each chapter, we present an explanation in the beginning of each section and expand our expression in an application example about the subject of the section.
- This book includes some new aspects in this field like chapter 6. In this chapter, traditional methodology of high efficiency in electric power converters is challenged. We show that a converter can be very reliable but with low efficiency.
- We prepared an illustrated presentation of MIL-HDBK-217 which is known as "Bible" of reliability.
- There are many useful references for each chapter to give a fresh state of the art view to reader about topic of the chapter. In addition, a comprehensive list of related documents is prepared for interested readers.
- We study many standards like IEC to give some guidelines to the readers about using standards in reliability study.

- The existing books are divided into two main categories. Some of these books have a general view to reliability like production. Others dedicate to an individual step and not overall view. Both system view and component view are covered in this book.
- In power electronic we have not a book covering reliable design methodology. This book is presentation of design and operation methodology to achieve an electric power converter with high reliability. There are certain steps toward this goal and there are many research books about these steps. However, each of these references focuses on one of these steps. We recognized that there is not proper reference that it covers all of required steps toward a reliable power electronic converter or electrical machine. These books do not give a big picture about the topic.

RELATED READERS

This book can be used by the following groups of readers:

- Electrical engineers: The publication can be used by electrical engineers in operation processes of power electronic converters and electrical machines in industries. For example, derating concept can be used by these engineers to prevent a fault in electrical systems in the near future.
- Designers of power electronic converters and electrical machines: The publication gives useful hints to consider reliability in design processes. Thus, designed systems will be reliable with a long effective operative life.

Since the effect of poor reliability is not seen immediately, reliability is often a forgotten index of quality in electric power converters. Therefore, the challenges in reliability are important especially in the field of electric power converters. Researchers are working with enthusiasm, tenacity, and dedication to develop new methods of analysis and provide new solutions to achieve a reliable converter. In this atmosphere, it is necessary to provide both professionals and students with state-of-the art knowledge on the frontiers in power converter reliability. This book is a good step in that direction

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Data Preparation

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