IDENTIFICATION OF FAILURE MECHANISMS TO ENHANCE PROGNOSTIC OUTCOMES

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Abstract— Predicting the reliability of a system in its actual life-cycle conditions and estimating its time to failure is helpful in decision making to mitigate system risks. There are three approaches to prognostics: the physics-of-failure approach, the data-driven approach, and the fusion approach. A key requirement in all these approaches is identification of the appropriate parameter(s) to monitor to gather data that can be used to assess impending failure. This paper presents a physics-of-failure approach, which uses failure modes, mechanisms and effects analysis (FMMEA) to enhance prognostics planning and implementation. This paper also presents the fusion approach to prognostics and the applicability of FMMEA to this approach. An example case of generating FMMEA information and using that to identify appropriate parameters to monitor is presented.

Index Terms—Failure mechanisms, precursor parameters, physics-of-failure, remaining life, fusion prognostics

1. Introduction

The reliability of a product is defined as the ability of the product to perform its intended functions for a specific period of time in its life cycle application conditions [1]. Current reliability assessment techniques cannot account for real-time changes in environmental and operational conditions of products in the field. Prognostics and health management (PHM) is an enabling discipline consisting of technologies and methods to assess the reliability of a product in its actual life cycle conditions to determine the advent of failure and mitigate system risk. The prognostics of a system can yield an advance warning of impending failure in the system and thereby help in taking appropriate corrective actions. PHM can help to prevent catastrophic failures and reduce unscheduled maintenance expenses.

Prognostics and health management has become the preferred approach to achieve efficient system-level maintenance and reduce the life cycle costs of systems [1][3]. The U.S. Department of Defense 5000.2 policy document on defense acquisition states that program managers should utilize diagnostics and prognostics to optimize the operational readiness of defense-related systems [2].

Typically, a combination of sub-systems and parts constitute a product. For example, a cell phone today is not just a means to talk with someone else; it can also be used to take pictures and videos, browse the web, send text messages, listen to music, and watch videos. All these functions necessitate the inclusion of different sub-systems within the cell phone. As the product becomes more complex in function, it comprises more and more sub-systems. All of these sub-systems and parts in a product may fail by various failure mechanisms in the product's life-cycle environment. Identification of possible failure mechanisms under different application conditions in the design and development phase of a product has become the norm in industry.

The approaches adopted for conducting prognostics for a product include: (1) the physics-of-failure (PoF) based approach, which includes the use of canaries to provide advance warning of failure and the modeling of life cycle environment stress to compute accumulated damage [3]; (2) the data-driven approach, which involves the monitoring and analysis of a product's functional parameters; and (3) the fusion approach, which combines the PoF and data-driven techniques to provide an accurate estimate of remaining useful life.

In order to provide an accurate prediction of remaining useful life of a product, it is essential to understand what is causing damage to the product and how the damage is manifested in the product. For addressing the root cause of failure it is necessary to know not only the failure mode but also the failure mechanism that causes the failure. If the failure mechanisms and modes are not known, then the sensors for monitoring, the location of monitoring, and the models to analyze the collected data may be selected erroneously.

If the identification of a precursor parameter is not based on the fundamental understanding of failure mechanisms of a product, an erroneous parameter may be monitored. Monitoring such a parameter may not provide the appropriate precursor and may lead to faulty prediction and therefore improper or delayed corrective actions. In the case of a canary device embedded in a product, if the canary does not fail due to the most critical failure mechanism that affects the product, then the prediction obtained from the device will not be as useful as it could have been.

Knowledge of the failure mechanisms that are likely to cause the degradation that can lead to failure in a product is important. There are different failure signatures for different failure mechanisms, and without knowledge of the failure mechanisms the accuracy of the prognosis is questionable.

This paper presents in brief the methodology of failure modes, mechanisms, and effects analysis (FMMEA) and the physics-of-failure based prognostics approach, which explicitly involves the application of FMMEA. The potential application of FMMEA in the fusion based prognostics approach is also discussed in this paper. The process of selecting critical parameters, based on FMMEA, for health monitoring is presented with a case study on a switch mode power supply.

2. Failure Modes, Mechanisms, and Effects Analysis (FMMEA)

Failure modes, mechanisms, and effects analysis (FMMEA) is an method based on assessing the root cause failure mechanisms of a given product [4]. A potential failure mode is the manner in which a failure manifests itself in the product. Failure mechanisms are the processes by which physical, electrical, chemical, and mechanical stresses induce failures individually or in combination. FMMEA is based on an understanding of the relationships between product requirements and the physical characteristics of the product (and their variation in the production process), the interactions of product materials with loads (stresses at application conditions), and their influence on the product susceptibility to failure with respect to the use conditions [5]. A schematic diagram showing the steps in FMMEA is shown in Figure 1.

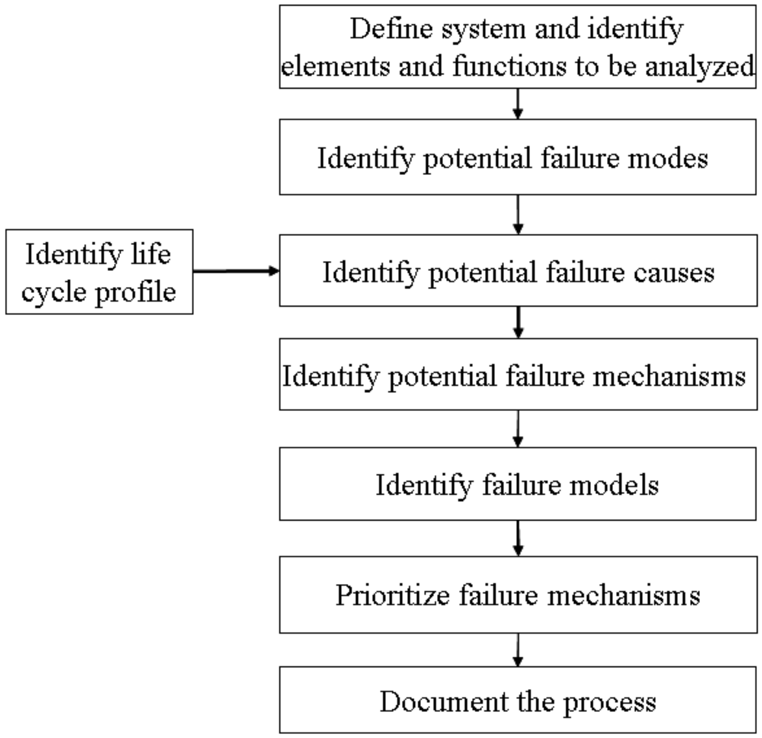

Figure 1: FMMEA Methodology [5]

Ganesan et al. [5] have provided a detailed description of the FMMEA methodology. FMMEA uses life cycle environmental and operating conditions and the duration of the intended application with knowledge of the active stresses and potential failure mechanisms. The purpose of FMMEA is to identify potential failure mechanisms and models for all potential failures modes and prioritize failure mechanisms. To ascertain the criticality of the failure mechanisms a risk priority number (RPN) is calculated for each mechanism. The higher the RPN the higher it is ranked among the failure mechanisms.

The RPN is the product of the probability of detection, occurrence, and severity of each mechanism. Occurrence describes how frequently a failure mechanism is expected to result in failure. Severity describes the seriousness of the effect of the failure caused by a mechanism and detection describes the probability of detecting the failure modes associated with the failure mechanism. Figure 2 shows the axis of a three-dimension risk matrix.

Form the estimation of the critical/dominant failure mechanisms that affect a product, the appropriate environmental and operational loads and performance parameters can be selected for health monitoring of the product. FMMEA is a major improvement over traditional deign for reliability methods since it internalizes the concept of failure mechanisms at every step of decision making. Utilization of failure mechanisms as the basis of reliability assessment has been accepted in standards by major technical organizations such as IEEE [6], EIA/JEDEC [7]–[12], and SEMATECH [13]–[16].

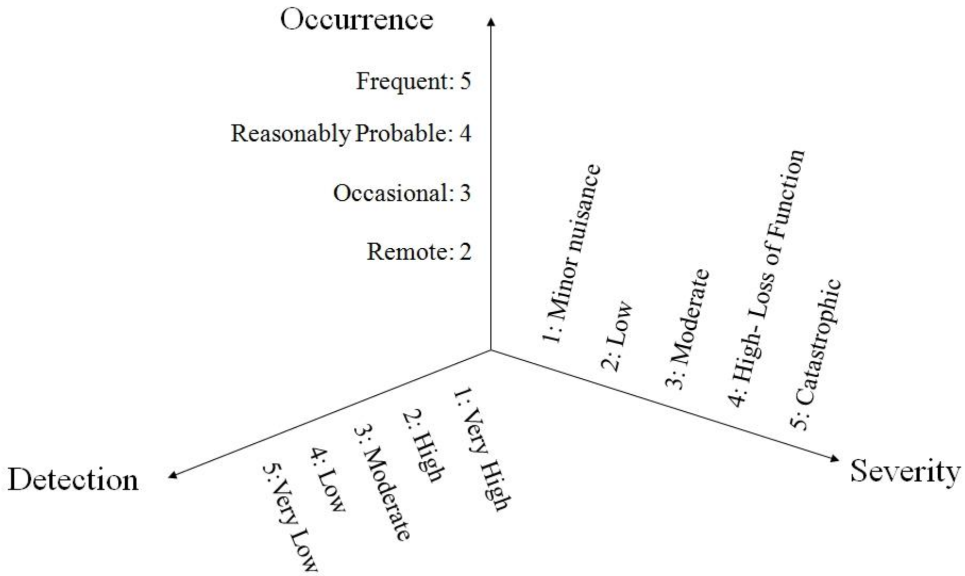

Figure 2: Risk matrix.

3. FMMEA in Physics of Failure Based Prognostic Approach

Physics-of-failure (PoF) based PHM is an approach that utilizes knowledge of a product's life-cycle loading and failure mechanisms to assess product reliability. PoF methodology is based on the identification of potential failure mechanisms and failure sites for a device, product, or system. Figure 3 shows the PoF-based PHM methodology.

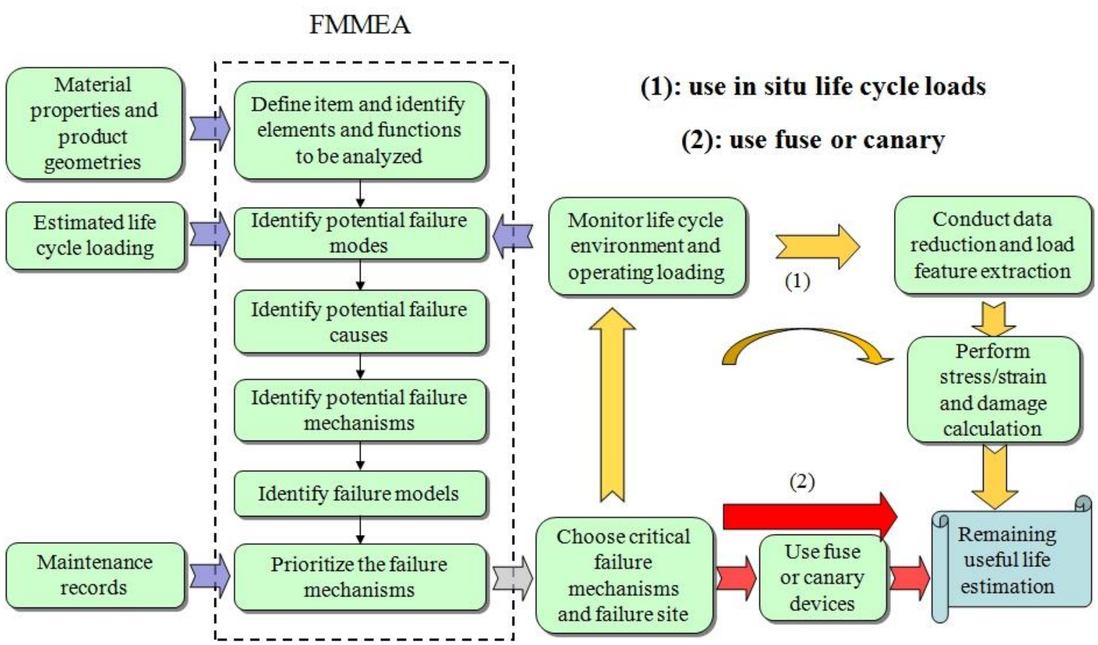

Figure 3: PoF based prognostics approach [17].

The first step in PoF based PHM involves FMMEA, where design data, expected life-cycle conditions, and PoF models are the inputs for assessment. As shown in the figure in path 1, based on the FMMEA the critical mechanism can be selected and the life cycle operating and environmental conditions that propagate the mechanism are monitored. The life-cycle environment of a product consists of manufacturing, transportation, storage, handling, operating, and non-operating conditions. Life-cycle load can be mechanical, thermal, chemical, or electrical in nature. In-situ measurement of the life cycle loads helps in determining the frequency and severity with which the loads are applied on a product. The life cycle loading data is used in failure models to derive the extent of degradation under the given conditions and from which the remaining useful life of the product can be estimated.

Path 2 is to use canary devices to estimate the remaining useful life of a product. A canary device behaves similar to the "canary bird" in a coal mine. Because the canary bird is more sensitive to hazardous gases than humans, death or sickening of the bird indicated an impending hazardous environment for humans. Canary devices are designed to fail due to the same failure mechanism that the product would fail by if the product were subjected to extended life cycle loads. Under the same environmental and operational loading conditions the canary devices are designed to fail faster than the actual product. Canary devices embedded in a product provide advance warning of failure due to specific wear-out failure mechanisms. A canary device fails much earlier than the actual product. By knowing the acceleration factor between the canary device and the product, the time to failure of the actual product can be computed.

4. FMMEA for Fusion Approach

The fusion PHM approach shown in Figure 4 combines the benefits of the PoF and data-driven techniques to provide an estimate of remaining useful life.

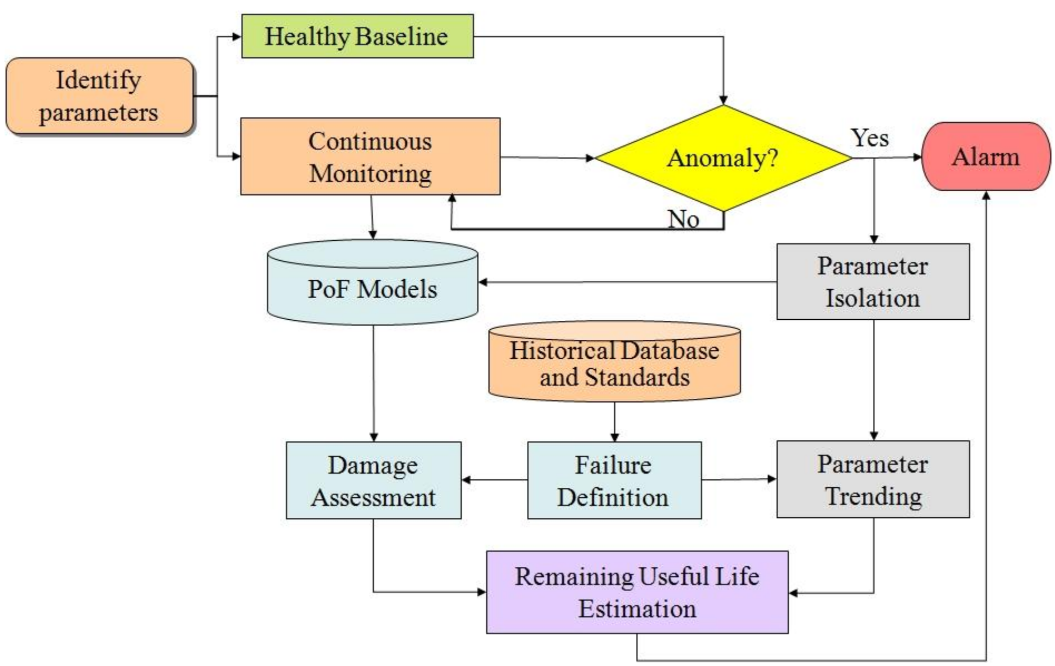

Figure 4: Fusion approach [18].

The first thing needed is to identify the parameters that can be continuously monitored to estimate the health of the product. An FMMEA provides information about the critical failure mechanisms that may affect the product in its life cycle conditions and the critical failure sites/components. From this information the appropriate parameters—either material or functional parameters—can be selected for monitoring. Information from an FMMEA also helps in the selection of appropriate PoF models for degradation analysis.

The fusion approach utilizes data-driven techniques for anomaly detection and classification to detect early degradation of a product. Once the anomalous behavior is detected, the parameters that indicate the anomalous behavior can be identified. Knowledge of the physics-of-failure of the product helps in narrowing in on the root cause of product failure. PoF models are used estimate the damage caused by the operational and environmental loading conditions. Based on the failure definitions the remaining useful life of the product is calculated.

The PoF knowledge can be used to determine the failure thresholds for the measured product parameters. This input of the failure threshold and labels of healthy and unhealthy states is used to trend the monitored parameters after they cross the threshold for anomalous behavior. The time to failure is estimated based on the trend of the parameters and the failure threshold. The conservative value of the RUL estimate from the data-driven technique and the PoF model is reported. Alarms are provided after detection of anomalous behavior and after reaching the critical RUL estimate. This provides adequate time for repair or replacement of the product depending on the criticality of the application.

5. FMMEA for a Switch Mode Power Supply (SMPS)

In this section an FMMEA of a switch mode power supply (SMPS) is presented as a case study. It is to be noted that FMMEA requires knowledge of the system that is being analyzed. Further, the more knowledge there is regarding the life cycle loads, material properties, and geometry, the more accurate the analysis will be. The in-depth analysis of a given product by an experienced operator/designer will cover the failure mechanisms that can affect a given product better than an analysis conducted by a novice.

In this work the SMPS in a personal computer was taken as the system on which FMMEA was conducted. The power supply in a personal computer uses switcher technology to convert the input AC voltage to output DC voltage (which is lower than the input voltage). Figure 5 shows a typical SMPS used in a computer. An SMPS can be divided into two basic parts according to their functions: the cooling unit and the voltage regulation unit. The cooling is provided by the fan. The electrical components of the power supply produces heat, which must be removed to ensure proper functioning of all these components. The cooling unit consists of the fan blades, bearings, wires, and a controlling circuit. The voltage regulation unit converts the 110/240 volt AC input to a lower voltage (5–12 volts) DC output, which is used to power the electronics in the computer. The voltage regulation unit consists of a printed circuit board with components such as resistors, capacitors, diodes, power MOSFETs, ICs, wires, metallization, heat sinks, and solder interconnects.

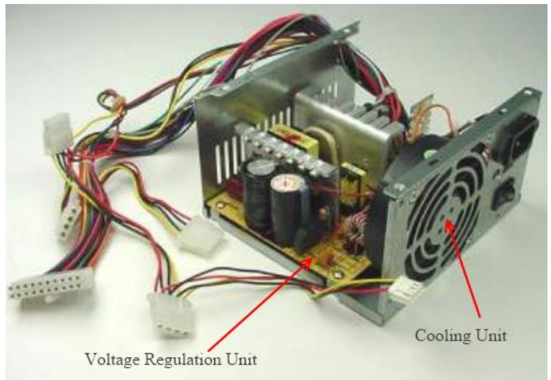

Figure 5: Power supply [19].

The possible life cycle loads on the power supply include voltage, current, temperature, humidity, vibration, shock, and contaminants. Only the voltage regulation unit of the power supply is considered for further analysis. Some of the failures that the components of the voltage regulation unit may experience are explained in below. Resistors may fail by the overstress failure mechanism when an overload voltage is applied. Electrolytic capacitors can be affected by the operation conditions, such as voltage, current, frequency, and temperature. These capacitors may fail as a result of dielectric breakdown or aging of the electrolyte, causing an increase in the output ripple voltage [20]. Inductors can fail by wear-out of the wiring insulation, which can lead to a short circuit or an open circuit across the wirings of the inductor. Diodes may fail due to mechanisms such as thermal runaway and contact migration. Failure of the diodes will affect the output voltage and current [21]. Power MOSFETs may fail due to thermal runaway, hot carrier injection, time dependent dielectric breakdown, or electrostatic discharge. Since the power MOSFET is the main switching element, its failure can vary the output voltage [22]. Integrated circuits can fail due to the following reasons: wire bond melting due to current overload or thermal cycling, electromigration, hot carrier, time dependent dielectric breakdown, or crack initiation and propagation. Failure of an IC will lead to incorrect switching, which will eventually result in incorrect voltage at the output. The failure mechanism for printed circuit boards (PCB) includes, fatigue cracking due to vibration and shock loads and conductive filament formation. Metallization on a PCB can fail by short circuiting or open circuit. Failure mechanisms can be electromigration and corrosion. Solder joints can fail due to fatigue cause by temperature cycling and vibration. This may introduce an open circuit in the power supply.

Knowledge of the failure modes, mechanisms, and operating conditions can be used to estimate the frequency of occurrence of a particular failure mechanism. This frequency can be used to estimate the extent of severity of that failure mechanism. Knowledge of past failure occurrences from experience or from maintenance and failure logs will also help in estimating the severity of a failure mechanism. The RPN and the risk associated with each failure mechanism were characterized. For simplicity, in this case the probability of detection all the failure mechanisms were assumed to be same. The RPN is the product of severity, occurrence, and the probability of detection of a particular failure mechanism. The higher the RPN, the higher the risk associated with the particular failure mechanism. Table 1 shows the FMMEA of the voltage regulation unit of the SMPS.

Table 1: FMMEA of Voltage Regulation Unit of SMPS

Element	Potential Failure Mode	Potential Failure Cause	Potential Failure Mechanism	Mechanism Type	Severity	Occurrence	Risk
Resistor	Open Circuit	High Temperature	Over voltage	Overstress	Low	Remote	Low
Capacitor	Drop in Capacitance	Electrolyte Leakage	Aging of Electrolyte	Wearout	High	Reasonably Probable	High
	Short Circuit	High Voltage	Dielectric Breakdown	Overstress	Moderate	Remote	Low
Inductor	Short/Open between Windings and Core	High Temperature	Wearout of Winding Insulation	Wearout	High	Remote	Moderate
Input/ Output Fuse Wire	Open Circuit	High Temperature	Wire Melting due to Current Overload	Overstress	High	Reasonably Probable	High
Diode	Die Fracture	Temperature Cycling	Thermal fatigue	Wearout	High	Reasonably Probable	High
	Short Circuit	High Temperature, Current Density	Contact Migration	Wearout	High	Reasonably Probable	High
	Thermal Runaway	High Temperature due to Resistive Heating	Thermal Runaway	Overstress	High	Remote	Moderate
Power MOSFET	Gate Oxide Short	High Temperature and Voltage	Time Dependent Dielectric Breakdown	Wearout	High	Reasonably Probable	High
	Gate Oxide Breakdown	High Voltage	EOS, ESD	Overstress	High	Remote	Moderate
	Change of Leakage Current	High Current Density	Hot Carrier	Wearout	High	Remote	Moderate
	Thermal Runaway	High Temperature Because of Resistive Heating	Thermal Runaway	Overstress	High	Remote	Moderate
Transformer	Short/Open between Windings and Core	High Temperature	Wearout of Winding Insulation	Wearout	High	Unlikely	Unlikely

Element	Potential Failure Mode	Potential Failure Cause	Potential Failure Mechanism	Mechanism Type	Severity	Occurrence	Risk
Metallization	Electrical Short/Open, Change in Resistance in Metallization Traces	High Temperature	Electromigration	Electrical Wearout	Moderate	Unlikely	Low
		High Relative Humidity	Corrosion	Chemical Wearout	Moderate	Unlikely	Low
		Ionic Contamination	Contamination	Chemical Overstress	Moderate	Unlikely	Low
Integrated Circuit	Open Circuit in Wirebond	High Temperature	Wire Melting due to Current Overload	Overstress	High	Remote	Moderate
		Temperature Cycling	Wire breakage due to thermal cycling	Wearout	High	Remote	Moderate
	Open Circuit/Short Circuit in Die Metallization	High Temperature	Resistive Heating	Overstress	High	Unlikely	Low
		High Temperature	Electromigration	Wearout	High	Unlikely	Low
	Change of Leakage Current	High Electric Field	Hot Carrier	Wearout	High	Remote	Moderate
	Gate Oxide Short Circuit	High Voltage	Time Dependent Dielectric Breakdown	Wearout	High	Reasonably Probable	High
	Die Fracture	Temperature Cycling	Crack Initiation and Propagation	Wearout	High	Reasonably Probable	High
Printed Circuit Board	Crack/ Fracture	Sudden Impact	Shock	Overstress	Low	Unlikely	Low
		Random Vibration	Fatigue	Wearout	Low	Unlikely	Low
	Loss of Polymer Strength	High Temperature	Glass Transition	Overstress	Low	Unlikely	Low
	Short circuit	Humidity and Current	Conductive Filament Formation	Electrical Wearout	High	Unlikely	Low

From the results of the FMMEA it can be seen that the high risk components include capacitors, diodes, the power MOSFET, and the integrated circuit chip. Based on the failure cause, mechanism, and mode, the potential parameters that need to be monitored for health assessment can be selected. In the case of the voltage regulation unit, parameters such the temperature of the integrated circuit chip, the temperature of the power MOSFET, the output voltage, the output ripple voltage, and the output current seem to be critical and can be used for health assessment. The values of these parameters are expected to undergo a shift from their normal value before failure. The idea is to identify these failure precursors for diagnostics and prognostics.

6. Summary and Conclusions

In order to generate an accurate prediction of the time to failure of any given product it is essential to understand what is causing damage to the product and how the damages are manifested in the product. Before implementing a health monitoring system for the product it is important to select the right parameters of the product to be monitored. Knowledge of the critical failure mechanisms and modes will assist in proper selection of these parameters. Knowing the parameters to monitor helps in the selection of the right sensors and sensor systems for health monitoring. The failure modes, mechanisms, and effects analysis (FMMEA) of the product generates a ranked list of critical failure mechanisms that affect the product. This information is used in conjunction with a physics-of-failure (PoF) based prognostics approach for failure prognosis.

The applicability of FMMEA to identify parameters as a first step in the fusion prognostics approach is presented in this paper. Conducting FMMEA helps in selecting the relevant parameters of the product. When these parameters are continuously monitored and compared to a baseline performance, they can help to detect anomalous behavior of the product. Knowledge of the life cycle loads, history of failures for previous models of the product or for similar products, and experience with operating/ designing the product are factors that will help in conducting an accurate FMMEA. An example of FMMEA for a voltage regulation unit of a power supply was presented. FMMEA is a complicated process, but it generates valuable information for implementation of prognostics for a given product.

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