An Industry-Based Survey of Reliability in Power Electronic Converters

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***Abstract*—A questionnaire survey was carried out to determine the industrial requirements and expectations of reliability in power electronic converters. The survey was subjective and conducted with a number of high-profile semiconductor manufacturers, integrators, and users in the aerospace, automation, motor drive, utility power, and other industry sectors. According to the survey, power semiconductor devices ranked the most fragile components. It was concluded that main stresses were from the environment, transients, and heavy loads, which should be considered during power electronic system design and normal operation. This paper has also highlighted that there is a significant need identified by the responders for better reliability-monitoring methods and indicators.**

***Index Terms*—Converter, failure rate, power electronics, power semiconductor device, reliability.**

I. Introduction

RELIABILITY for power electronics has been an important issue since the early power electronic applications. In recent years, the reliability of power devices has been greatly improved. For example, the average failure rate for power modules in traction dropped from 1000 failures in time (FITs) in 1995 to 20 FITs in 2000 [1], where 1 FIT $=$ 1 failure per 10^9 device hours. Meanwhile, power device failure mechanisms have been closely examined in recent years. Methods of detecting both bond wire lift-off and solder cracking have been greatly improved [2]–[6], using accelerated failure tests to demonstrate such improvements [7]–[9].

Recently, there has been interest in developing better design tools to consider device reliability during the converter design stage [3], [10], [11]. There has also been interest in developing methods to detect imminent device failure, i.e., condition monitoring of converters [12], which offer the means to reduce failure costs by replacing devices before damage occurs or maintenance is required. However, there has been no study of the converter reliability issues that industry actually experiences. Pertinent questions exist, such as the following.

1) Are power semiconductor devices the only components worth considering, or should components such as capacitors and gate drives be considered too?
2) Are the reliability concerns the same across all power electronic applications, or do they change depending on power rating?
3) What are the demands from industry for better condition monitoring and reliability prediction tools?
4) What methods are used by designers to achieve better reliability?

A questionnaire survey is an effective way to collect reliability information from power electronic industries. Surveys have been carried out to study the impact of operating conditions and maintenance on reliability in high voltage direct current (HVdc) converters [13] and motor reliability [14]. As for the reliability for general power electronic converter applications, such a survey has not been published.

Therefore, a comprehensive survey to determine the requirements and expectations of power electronic reliability is needed. In this paper, a questionnaire was designed to address concerns such as those previously listed. The questionnaire was sent out by e-mail; the survey took 3 mo and was completed in March 2008. A total of 295 questionnaire documents was sent out, and 56 effective responses were collected, giving a response rate of 19%. (An effective response means that the responder has answered more than 80% of the questions.)

This paper will present the key results from the questionnaire. The aim of this paper is to establish the reliability-related needs of power electronic applications and to influence the direction of condition-monitoring research.

II. Questionnaire Structure

As illustrated in [13] and [14], application category, operating range, stress level, duty time, and maintenance all have impact on system reliability. All these factors were considered when designing the questionnaire survey document. The questionnaire included five parts, each consisting of several questions:

1) Responder sectors and attitudes:
   a) Question 1: the types of company/industry;
   b) Question 2: the attitudes to power electronic reliability.

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2) Reliability status and power device operating conditions:
   a) Questions 3–4: system lifetimes and scales;
   b) Question 5: satisfaction of reliability-monitoring methods;
   c) Question 6: acceptable failure rates;
   d) Question 7: weak points in power electronic systems;
   e) Questions 8–10: power devices and operating conditions (load current and switching frequency).
3) Main stresses and deterioration indicators:
   a) Question 11: most likely failure reasons;
   b) Question 12: indicators of deterioration;
   c) Question 13: stresses from the environment.
4) Load profiles, including load levels and duty times:
   a) Questions 14-15: power ratings and load levels;
   b) Question 16: overload or overvoltage durations;
   c) Question 17: temperature swing scales;
   d) Questions 18–19: duty days per year and duty hours per day.
5) Failure counteraction and costs:
   a) Question 20: improvements or remedies for the least reliable components;
   b) Question 21: voltage and current operating margins;
   c) Question 22: failure costs.

Most questions in the questionnaire document used check boxes to allow responders to conveniently provide answers. Several questions used ranks, open answers, and value inputs to gather detailed information. Some key results from the survey will be described and analyzed in the following sections.

It should be noted that more than one choice to a question may be selected in the responses. For example, a company may have more than one application area or type of product. In these cases, the response can be spread across the selected choices by assigning them a value less than one; for example, 0.5 would be assigned if the responder selects two choices. Here, this is described as a *weighted average*.

III. Key Results

A. Characterization of Industries, Components, and Power Ratings

The responders were classified into six categories by Question 1: component manufacture, aerospace, automotive, motor drive, utility, and others. Nearly all the responses were from power electronic industries, as shown in Table I. The survey included participation from staff at device manufacturers, drive and converter manufacturers, and plant operators. Since an enterprise may cover more than one category, the total number is more than 56. All the responders regard power electronic reliability as an important issue (Question 2), with 93% of those considering it a "very important" issue.

Questions 8 and 14 examine the types of power devices used and the rated power levels of the converters, respectively. Fig. 1 shows that insulated-gate bipolar transistors (IGBTs) were the most used devices, followed in rank order by MOSFETs, thyristors, p-i-n diodes, gate turnoff thyristors, and integrated gate-commutated thyristors. Fig. 2 shows that the distribution among power levels is relatively uniform, giving confidence—in addition to that of Table I—to the survey being representative of most power electronic applications. The ranges of current levels recorded are shown in Fig. 3, with switching frequencies shown in Fig. 4. The latter indicates that frequencies in the range 500 Hz to 20 kHz dominate the responses received. The voltage and current margins, from Question 21, had averages of 41% and 47%, respectively, for the 40 out of the 56 responders giving an answer to this question. Most responders gave margins less than 50% for each; however, four responders gave voltage margins above 100%, and two gave current margins above 100%. These were peak or pulse applications that typically experience large transients.

TABLE I
RESPONDER SECTOR STATISTICS

Responder sectors	Numbers
Component manufacturer	17
Aerospace	6
Automotive	7
Motor drive	16
Utility power	13
Others - marine	1
Others - lighting	2
Others - traction	3
Others - IC manufacturer	1
Others - power supplies	1

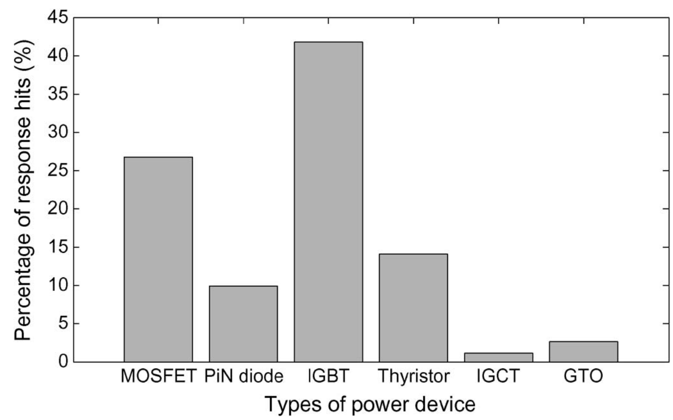

Fig. 1. Types of power devices used, Question 8.

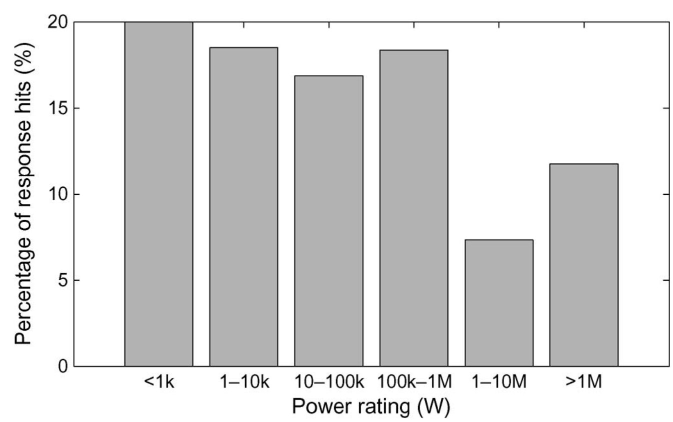

Fig. 2. Rated power levels of converters, Question 14.

B. Component Failure

The distribution of the acceptable converter failure rates is shown in Fig. 5. Approximately half of the responders

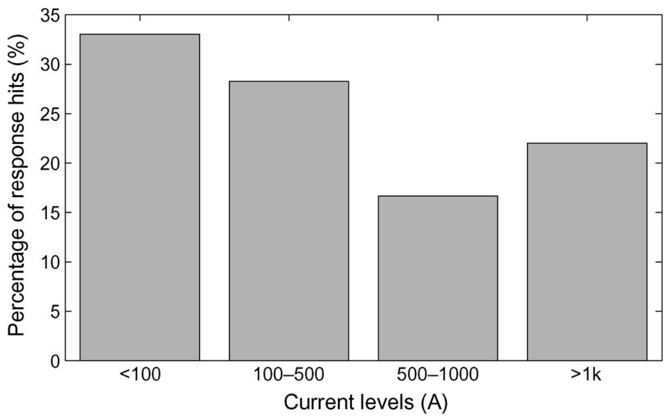

Fig. 3. Converter current levels, Question 9.

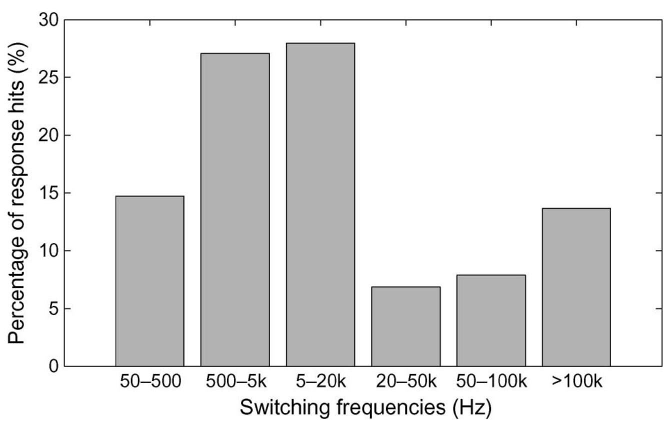

Fig. 4. Converter switching frequencies, Question 10.

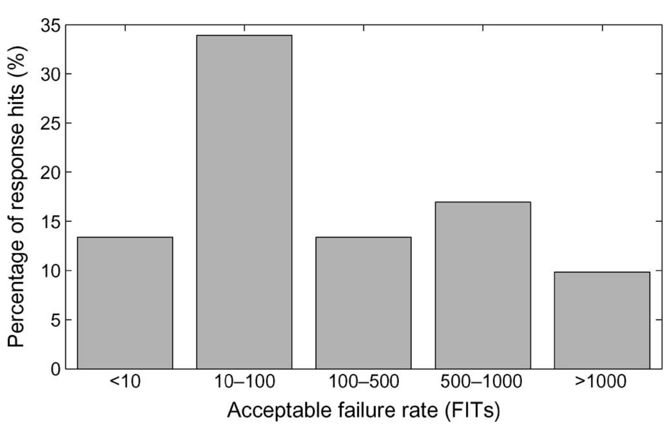

Fig. 5. Acceptable failure rates, Question 6.

observed a low failure rate of < 100 FITs. Among the responders which could tolerate > 500 FIT failure rates, 50% were utility power industries, 25% were motor drive industries, and the remainder were lighting and consumer electronic industries.

Fig. 6 shows the distribution of fragile components. "Semiconductor power device" was selected by 31% of the responders as the most fragile component, which was followed by "capacitors" and "gate drives." Failures associated with "resistors" and "inductors" are clearly quite rare and only observed in a few applications.

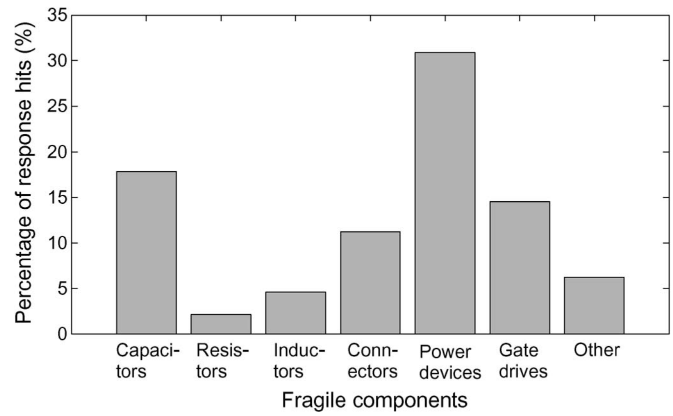

Fig. 6. Fragile components, Question 7.

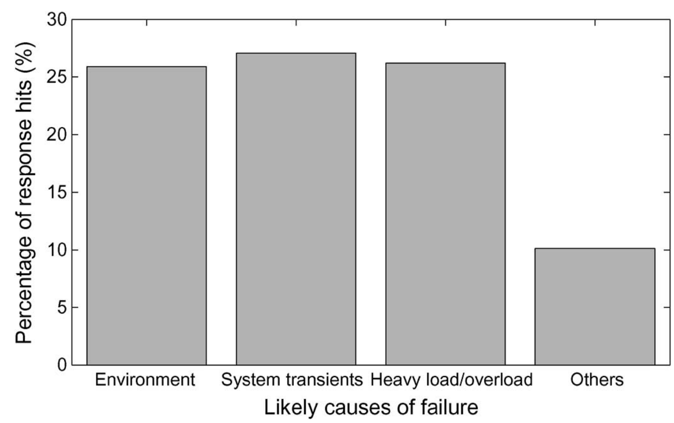

Fig. 7. Failure causes, Question 11.

TABLE II
INDICATORS OF DETERIORATION

Indicators	Response Numbers
Leakage current	2
Temperature	4
Thermal resistance	1
Voltage drop V_{CE}	3
Lifetime of capacitors	1
Standard semiconductor life tests	1
Power quality deviation	1
Total	13

Fig. 7 shows the distribution of failure causes. The first three types—"environment," "system transient," and "heavy load/overload"—are similar in number, each selected by around 26%–27% of the responders. "Others" include two factors: component design/manufacturing and power/thermal cycles.

For Question 12, "indicators of deterioration," only 29% of the responders suggested indicators, shown in Table II, and most responders selected "no indicator." Where an indicator is used, thermal and electrical signals dominate in details given by responders; further information would be useful in this aspect. It should be noted that the indicators noted in Table II are used in industry; however, the application extents vary depending upon the cost and the knowledge of deterioration. There are other indicators which exist, such as gate voltage and switching time, but no responders mentioned them. For these indicators, further details and examples are given in [15].

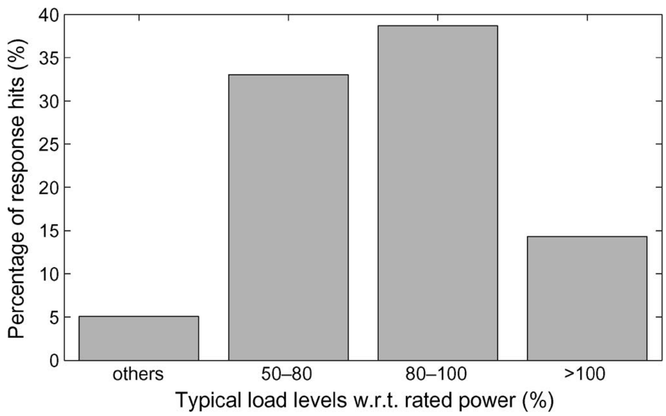

Fig. 8. Load level distribution, Question 15.

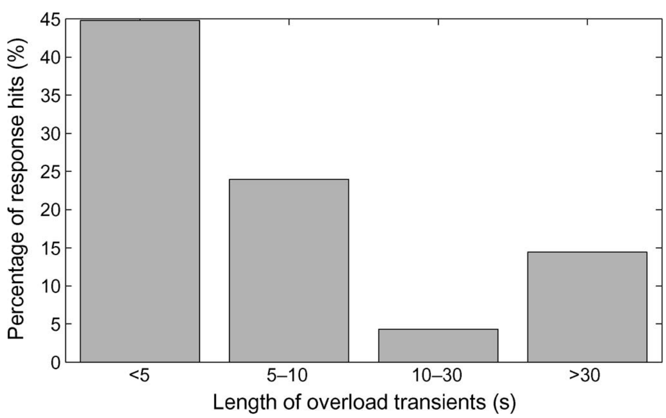

Fig. 9. Overload transient duration, Question 16.

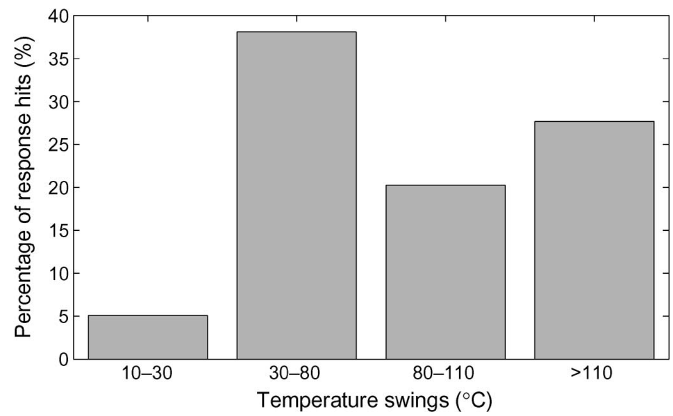

Fig. 10. Temperature swing distribution, Question 17.

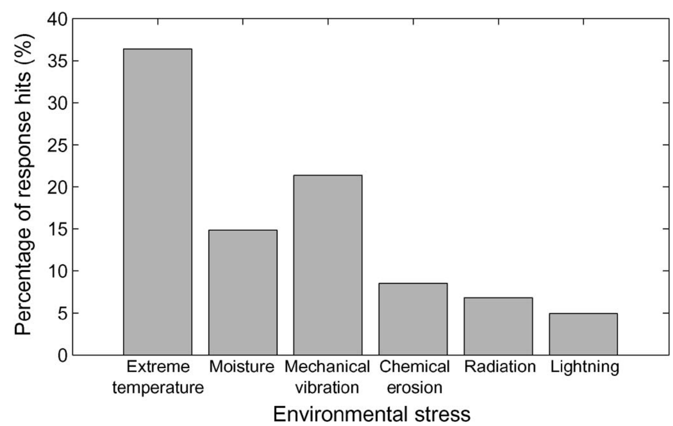

Fig. 11. External environmental stresses, Question 13.

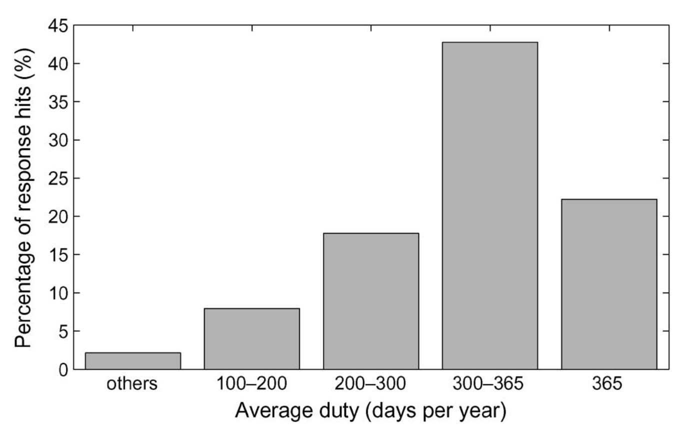

Fig. 12. Duty days per year, Question 18.

C. Load and Temperature Variations

The distribution of load levels with respect to rated power is shown in Fig. 8. It can be seen that overload operation, i.e., above 100% rated power, is selected by approximately 14% of the responders.

The overload transients themselves are considered in Question 16. The typical duration of these transients is shown in Fig. 9. Clearly, the bulk of the transients lasts for less than 10 s. However, there is a significant proportion that lasts for longer than 30 s. Further analysis of these long overload transients shows that approximately half of them were from respondents operating in the 100-kW–10-MW range and a third of them were from those operating in less than 10 kW. Very few were in the 10–100-kW and $>$ 10-MW ranges (approximately 6% each).

Fig. 10 shows the distribution of temperature swings during operation. Nearly half of converter operation is subjected to junction temperature swings larger than 80 °C, which occur in heavy cycling applications, such as traction and wind power. Low junction temperature swings less than 30 °C are rare; these only occur for some power transmission applications and outdoor lighting systems.

There are other stresses that power converters experience other than overload transients and thermal stresses. These are shown in Fig. 11. Significantly more than half of the stresses are extremes in ambient temperature, moisture, and mechanical vibration; these are expected for most converter applications. Lightning, the smallest of environmental stresses, may be expected to be dominated by the aerospace and utility industries; however, respondents selecting this category were spread evenly between industries.

From Fig. 12, it is noted that almost a quarter of the enterprises run 365 d annually, among which just over a third of them are utility power industries. These high-duty-cycle industries require very reliable systems since out-of-service or emergency maintenance incurs extra cost.

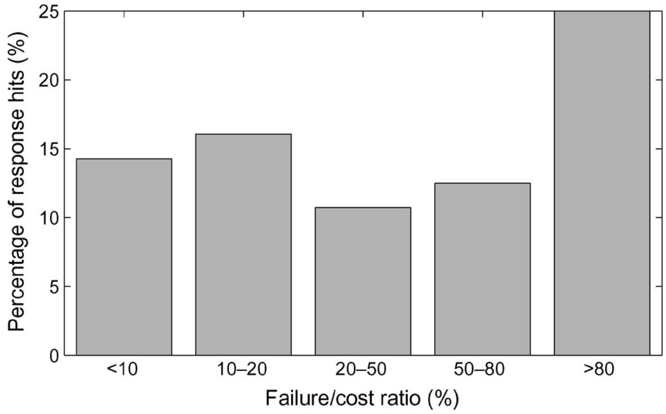

Fig. 13. Failure cost distribution, Question 22.

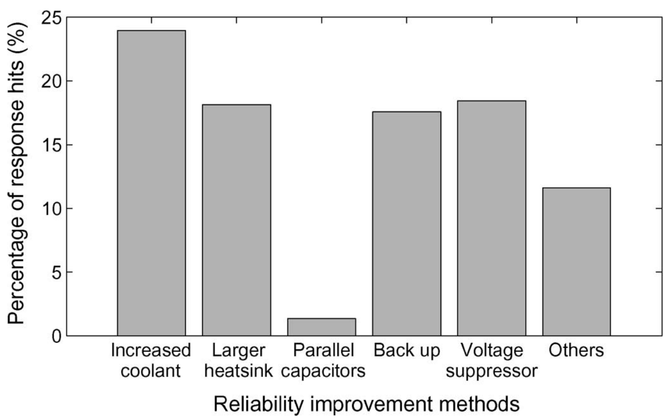

Fig. 14. Methods to improve reliability, Question 20.

D. Impact and Management of Reliability

The distribution of failure costs relative to system costs, shown in Fig. 13, appears somewhat bimodal: 25% for high costs (80%–100%) and 30% for low costs ($< 20\%$). The failure costs are related to the product types and their applications. (Note that "failure:cost ratio" is defined as failure cost divided by original system cost.) According to the comments in the responses, highly integrated products are designed to be maintenance free. However, a system field failure may be higher than the cost of a single system, which includes replacement free of charge, travel cost, maintenance personnel, and penalty charges.

Fig. 14 shows the methods to improve power electronic reliability. The first two choices emphasize improved cooling to reduce the device temperature, i.e., "increased coolant flow" and "larger heat sinks." "Overvoltage suppressors" are also popular. The "backup system" is chosen mainly by utility power industry, rail, space, and aerospace applications, where out of service may cause a significant operational or economic impact. "Others" include thermal management systems and improved design optimization.

Finally, in Question 5, "satisfaction with reliability-monitoring methods," approximately half of the responders were dissatisfied with their reliability-monitoring systems. Clearly, this indicates that reliability concerns are high in the power electronic industry, and further work is necessary to address some of these issues.

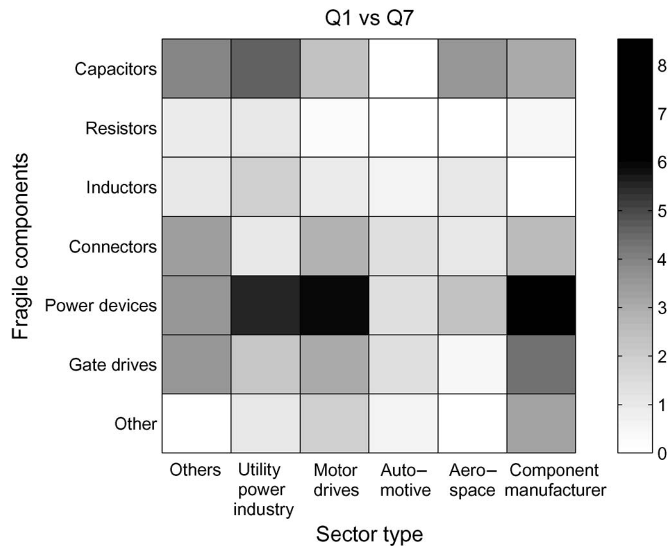

Fig. 15. Correlation between responder sectors and fragile components.

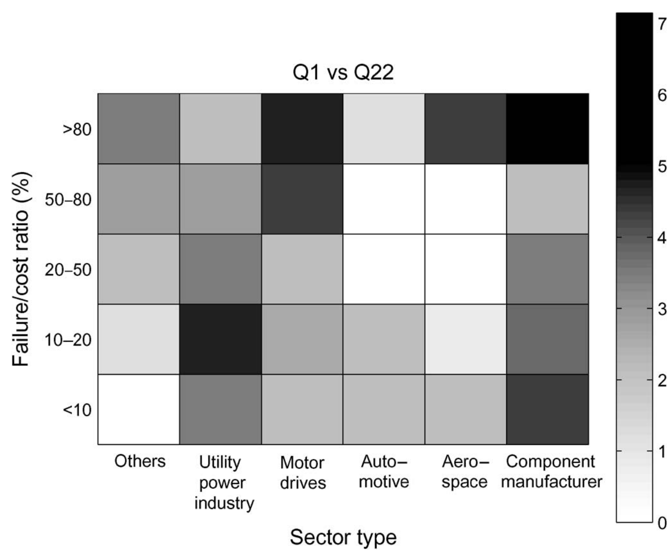

Fig. 16. Correlation between responder sectors and failure/cost ratio.

IV. Correlation Between Questions

The correlation between questions is calculated using the combinations of choices selected by the responders. In the case where a responder selects more than one choice for a question, the same approach as in Section III-A is used regarding the weighted average. Note that, in Figs. 15–32, the right-hand scales indicate the percentage of responses for each combination of categories.

A. Importance of Power Electronic Reliability

Fig. 15 shows that power devices are the most fragile components across all industry sectors. Capacitors and gate drives are considered to be fragile by some responders, particularly capacitors for the utility power industry. However, the indication that power devices are the most fragile devices strongly supports the assertion that device reliability is considered to be more of a risk or problem than for other components.

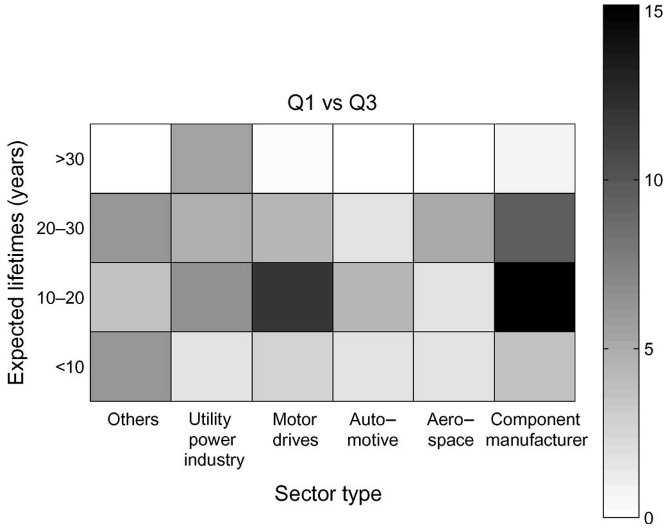

Fig. 17. Correlation between responder sectors and lifetimes.

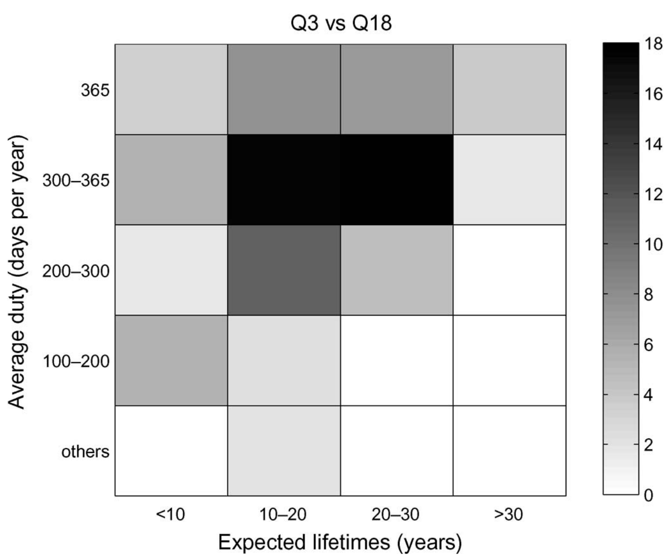

Fig. 18. Correlation between lifetime and annual duty.

In Fig. 16, the failure/cost ratio is shown against industry sector. (Note that "failure:cost ratio" is defined as failure cost divided by original system cost.) The utility power industry has a low failure/cost ratio at only 10%–20%. This suggests that redundancy is built-in, for example, in long series chains of thyristors used in HVdc converters. However, the high failure/cost ratio in the motor drive and aerospace sectors indicates that a failure in a converter here would not be accommodated and result in converter failure and subsequent damage. Indeed, redundancy may not be built-in to such converters.

Fig. 17 shows that the utility power industry clearly expects the longest lifetime of all the categories, with many converters designed for lifetimes in excess of 30 years. This would be expected given the long lifetimes required in the utility power sector. Motor drives and individual components have a strong concentration of 10–20 year lifetime, with a reduced proportion having a lifetime of 20–30 years.

Fig. 18 shows a further trend related to converter lifetime. It indicates that the average duty (days per year) increases

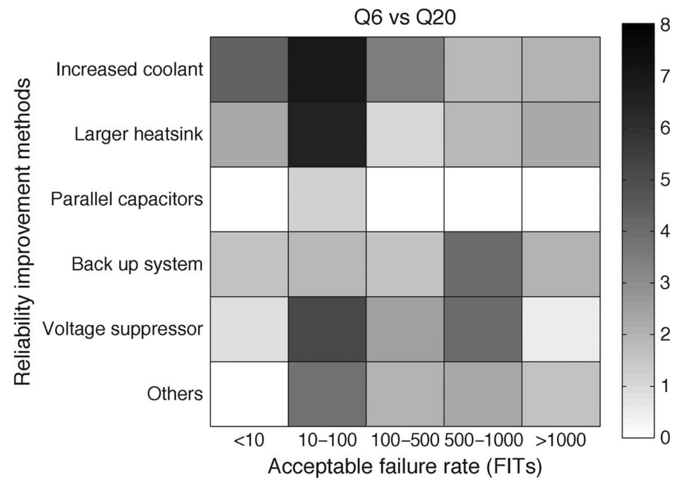

Fig. 19. Correlation between acceptable failure rate and measures to improve reliability.

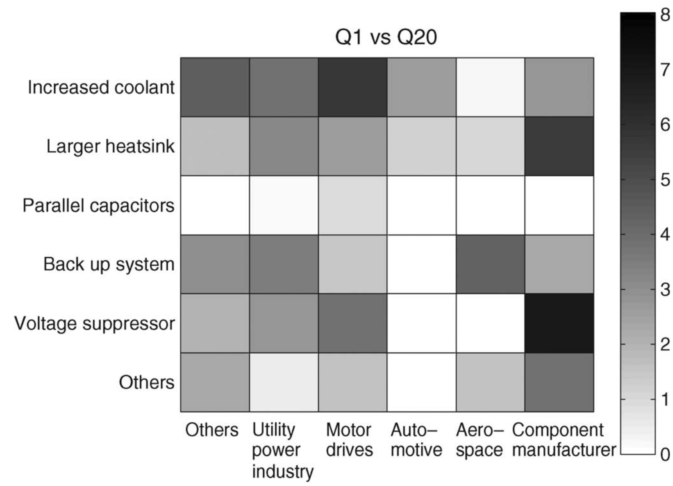

Fig. 20. Correlation between responder sectors and measures to improve reliability.

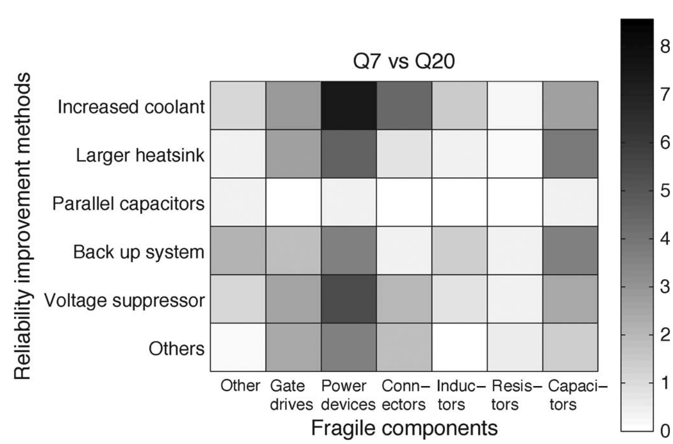

Fig. 21. Correlation between fragile components and measures to improve reliability.

with converter lifetime. This places extra demands on the converters with long lifetimes (e.g., those in the utility power industry) since they must have both high availability and long lifetime.

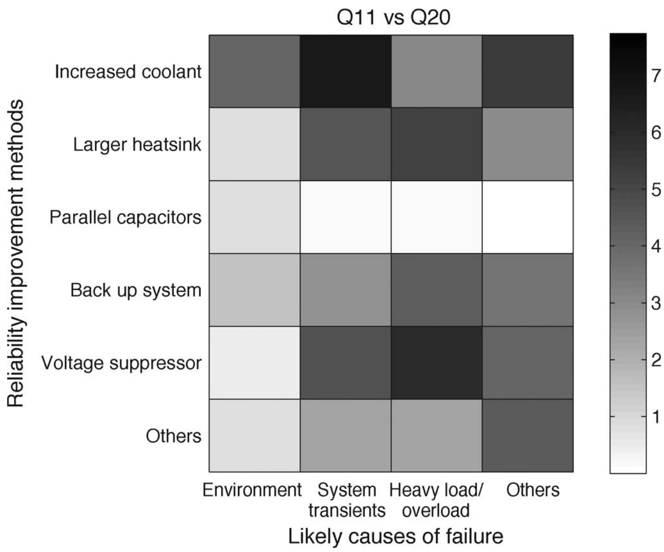

Fig. 22. Correlation between failure causes and measures to improve reliability.

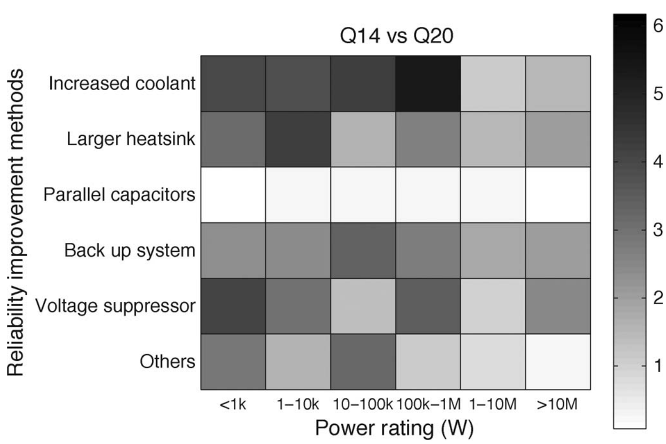

Fig. 23. Correlation between power rating and measures to improve reliability.

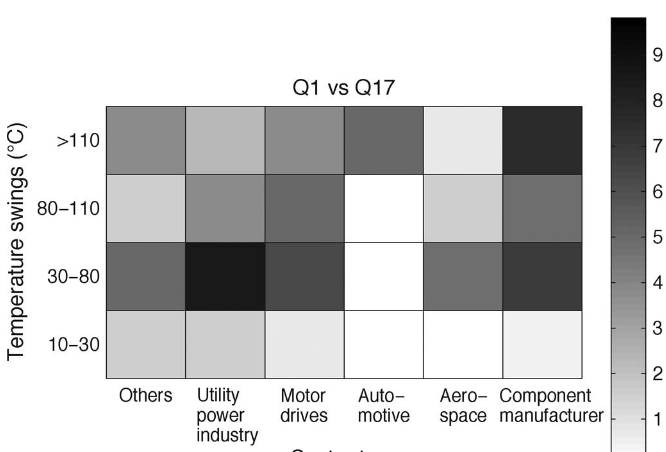

Fig. 24. Correlation between responder sectors and temperature swing.

It should be noted that, although there are low response numbers for Figs. 15–17, the results are still valid since they show that the distributions are category dependent.

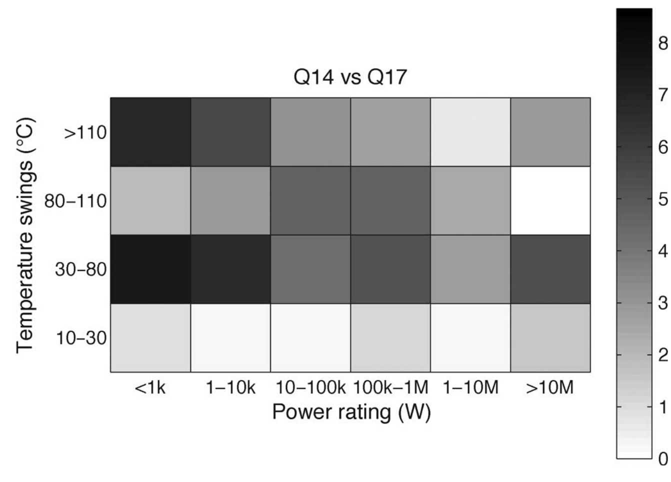

Fig. 25. Correlation between power rating and temperature swing.

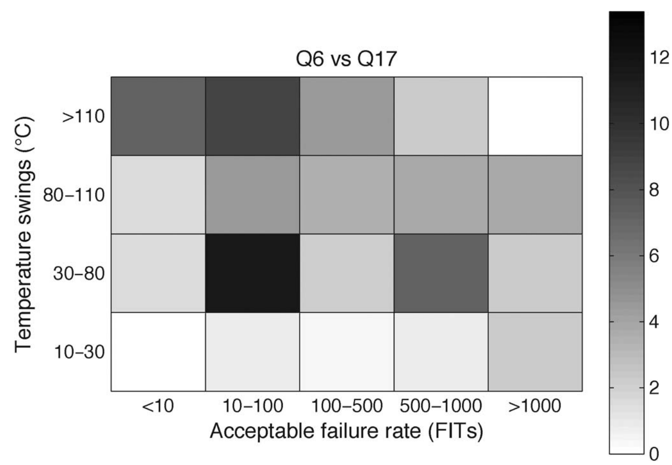

Fig. 26. Correlation between acceptable failure rate and temperature swing.

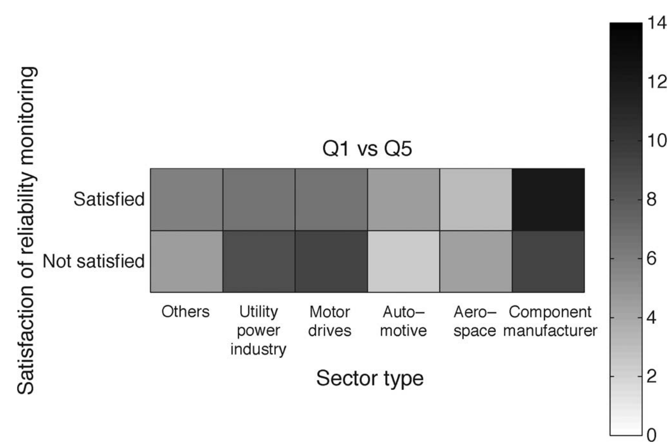

Fig. 27. Correlation between responder sectors and satisfaction of reliability monitoring.

B. Existing Measures to Improve Reliability

Fig. 19 shows the measures used to improve the reliability. Two ways to achieve this are to increase the coolant flow rate and increase the size of the heat sink. Both effectively reduce the thermal resistance to the dissipated power and decrease the junction temperature. From the results, it appears that this is a method strongly favored by the respondents, particularly for

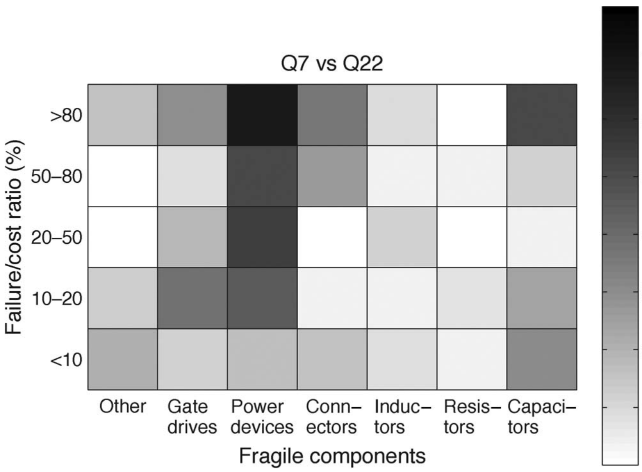

Fig. 28. Correlation between fragile components and failure/cost ratio.

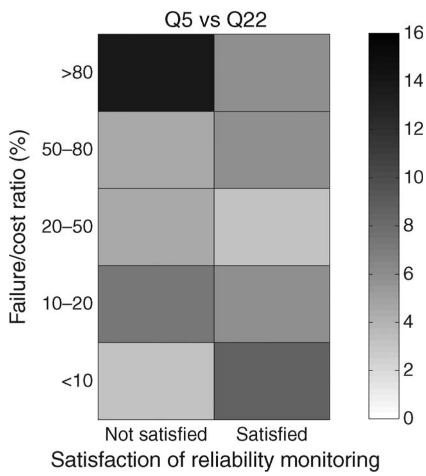

Fig. 29. Correlation between satisfaction of reliability monitoring and failure/cost ratio.

low FIT rates (high reliability) of less than 100 FITs. Backup systems also appear to be more favored at higher FIT rates; this could be necessary to cope with the higher FIT rates. The system that is chosen would also depend on the industry sector; for example, high efficiency would allow a larger heat sink while high density would not. Increasing the coolant flow by using a fan also brings its own reliability impact, as some of the responders noted. Fig. 20 shows the dependence on industry sector; in particular, motor drive manufacturers prefer increased coolant to larger heat sinks because of power density requirements, while component manufacturers—with different priorities—recommend larger heat sinks and voltage suppressors.

Fig. 21 shows these measures against the fragile components. Devices would appear to prefer increased coolant or a larger heat sink (reduced thermal resistance, i.e., lower temperatures). Capacitors would not appear to benefit from more in parallel; however, capacitor aging may, to a larger extent, be regarded as due to environmental impact, e.g., elevated ambient temperature.

In Fig. 22, these measures are shown against likely reasons for failure. Increased coolant is required for heavy load/overload or environmental triggers. Coolant reduces the thermal resistance, i.e., reducing the long-term temperature rise.

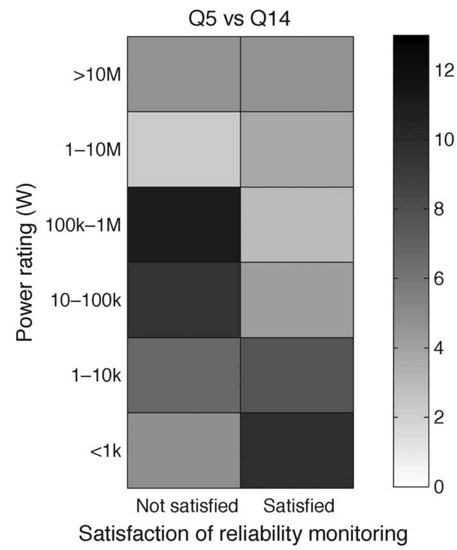

Fig. 30. Correlation between satisfaction of reliability monitoring and power rating.

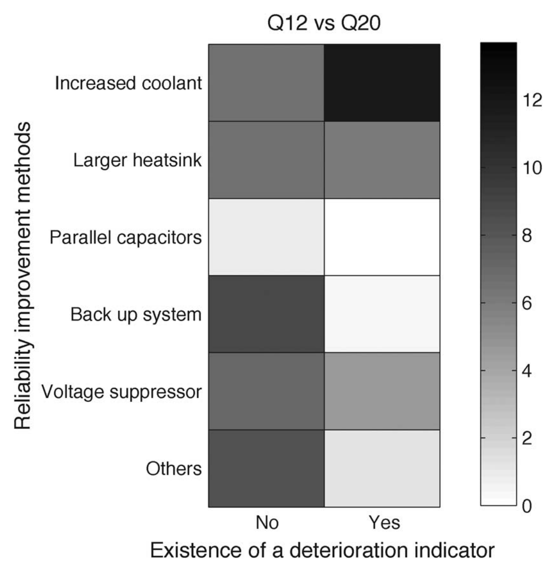

Fig. 31. Correlation between existence of deterioration indicator and reliability improvement methods.

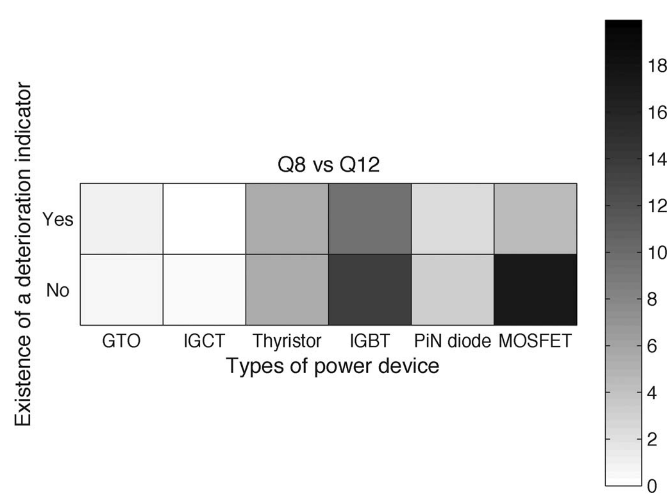

Fig. 32. Correlation between type of power device and existence of a deterioration indicator.

In both these cases, the overload condition or environmental change is likely to last for long enough that the steady-state thermal resistance is important, requiring an increased coolant rate. However, while a larger heat sink may contribute to reducing the thermal resistance, it also heavily affects or increases the thermal capacitance. Therefore, system transients, such as load current or power surges, may be safely ridden through if the thermal capacitance is high enough, as indicated in the figure. The power rating of the converter may also have an influence; from Fig. 23, it appears that increased coolant is preferred for higher power levels, suggesting either that the thermal capacitance is already high enough or that coolant-based systems are simply more widely used at these power levels.

C. Temperatures Experienced in Power Converters

The temperature swings experienced in converters strongly affect the reliability through the device packaging structure. Fig. 24 shows that the temperature swings depend strongly on the industry sector. The utility power industry has particularly low temperature swings of 30 °C–80 °C, while motor drives have much higher swings of 30 °C–110 °C. Automotive has particularly high swings of 110 °C and above, although this may be related more to traction converters and not to low-voltage automotive power devices. The component manufacturers' figures may be misleading, however, since the swings quoted may be those that the device can withstand rather than those actually experienced in the converter operation. Fig. 25 shows these effects in a slightly different way, with temperature swing decreasing slightly with increased power rating. This may be indicative of larger converters having steadier loads or longer thermal time constants to reduce the temperature swings.

Fig. 26 shows that there is a weak correlation between the temperature swing and FIT rate, albeit in the opposite direction from that expected since the acceptable FIT rate decreases as the temperature swing increases. This suggests that applications which demand low FIT rates also subject the converters to large temperature swings, making the design of reliable converters doubly challenging. Applications such as traction and wind power, where there are large transients and the thermal cycling issues are severe, are examples of this. It also suggests that greater reliability is being designed into applications with large temperature swings in order to give suitably low failure rates. It is not clear, however, what extra cost or size/mass is incurred in order to achieve this. However, examining the failure costs stated in the responses gives more insights into this tradeoff. After checking the responses, it has been found that failure costs caused by "power devices" are very application dependent.

1) Failure costs in utility power industries and consumer electronics are not high perhaps because such failures do not cause very dangerous consequences or because there is sufficient redundancy.
2) Failure costs in transport applications, military, aerospace, and some motor drives are very high because such failures can cause catastrophic results and unrecoverable effects.

For the latter applications, power device reliability is clearly a critical issue.

D. Importance of Condition Monitoring in Power Electronics

Having discussed the importance of reliability and examined the converter temperatures and methods used to improve reliability, there remains the question of condition monitoring. Condition monitoring could potentially improve reliability by measuring or estimating the health of the converter to predict when to perform maintenance on the converter. Fig. 27 shows that opinions on reliability-monitoring methods are split between different industry sectors. Component manufacturers are generally satisfied with reliability-monitoring methods, which may be expected since they are considering the components themselves and not the final converters. However, the other sectors are generally not satisfied with the reliability-monitoring methods, indicating that when it comes to monitoring converter reliability there is room for improvement.

A significant motivation for monitoring reliability is the cost. Therefore, the failure/cost ratio (failure cost divided by original system cost) for a converter is important in determining the motivation for monitoring reliability. Fig. 28 shows that the number of failure/cost ratio responses in the 80%–100% region is particularly high for power devices. However, a significant proportion of responses indicating that power devices are fragile reported that the failure/cost ratio is lower (10%–80%), although this is likely to be application dependent. Capacitors also had a generally high failure/cost ratio.

Fig. 29 shows the satisfaction with reliability monitoring when related to the failure/cost ratio. Responders who were satisfied with reliability monitoring indicated that the failure/cost ratio is low ($< 10\%$), suggesting that, if failure is likely, then its impact is reduced by a low failure/cost ratio. However, those who were not satisfied with reliability monitoring had a high failure/cost ratio (80%–100%), suggesting that there is a strong demand for better reliability- or condition-monitoring systems for power conversion systems where failure costs are high. The satisfaction of reliability monitoring also follows power levels; Fig. 30 shows that the dissatisfaction increases with power level, perhaps indicating the more critical nature of higher power converter systems.

In condition monitoring, the existence of a deterioration indicator is key. Fig. 31 shows that, if such an indicator is not known, then a range of methods is applied to improve the reliability, from increased coolant flow and heat sink size to including backup systems. However, if an indicator is known, the most popular solution is increased coolant flow. Fig. 32 shows the existence of deterioration indicators against the device type. Thyristors have an equal chance of having an indicator or not, while IGBTs and MOSFETs are much more likely not to have indicators. Given that the latter is more common in power converters, it is therefore important to determine which indicators may be used for condition monitoring in power converters.

V. Discussion

The questionnaire suggests that power electronic converter reliability is indeed an area of concern. The most fragile components in converters are the power semiconductor devices and capacitors, which is consistent to some extent with a survey result for electronic products in [16], although, there, capacitors were regarded as the most fragile. The key difference here is that this survey examines power electronic converters in general, rather than just printed-circuit-board-based microelectronic circuits. The power devices are clearly considered to be the most fragile power components. This correlates with the importance placed by the responses on methods to improve reliability, such as improved cooling.

According to the survey, the reliability concern is application dependent. The aerospace sector considers itself to face higher risks than other sectors, and its failure costs are much higher; this is expected given the nature of aviation. The utility power industries have much longer lifetimes, and their duty times are often 365 d and 24 h, which suggests a need for a very high reliability level. However, the failure costs are not high probably because a failure does not necessarily cause danger to life and there is adequate designed redundancy in such converters and the utility power network. This is a principal reason behind the ability of this sector to tolerate a FIT rate in excess of 500, as noted in Section III-B. The sectors able to tolerate high FIT rates were motor drives industries—where fault tolerant control may have been applied—and lighting and consumer electronics, where the replacement cost is not very high and manufacturers would give customers a new replacement. However, it should be noted that, despite the ability of utility power converters such as static synchronous compensators to tolerate high failure rates due to redundancy, they are often unable to compete with passive solutions such as filters and capacitor banks.

The main stresses come from system transients and overload conditions, with the most significant being external or environmental conditions, for example, ambient temperature extremes, mechanical vibration, and moisture. The effects of these conditions cannot be determined during the converter design. The ability of the converter to withstand these conditions depends upon the margins inherent in the converter, which may lead to rather conservative converter designs. Ultimately, this is a tradeoff between the extra cost and size or mass of the converter and the reduced cost and impact of reliability in the face of unexpected conditions. One aspect of stress which was not investigated here and warrants further investigation is that of voltage stress; indeed, the dc link voltage of a converter has a strong influence on the reliability of power devices.

Component or system design and manufacture have been shown in Fig. 6 to be important, and power cycling has been shown in Fig. 7 to also be important as significant stress sources. However, these can be considered during the converter design only to some extent since detailed knowledge of the expected converter operating conditions, i.e., load cycle or mission profile, is frequently not available. To what extent this is possible depends on the modeling techniques available for which there are currently relatively few in the area of reliability [10], [11], [17], [18]. Indeed, modern power devices are intended to work at high temperatures, and their thermal behavior is the key design and performance issue.

The satisfaction level with reliability-monitoring methods is low at 50%, and the knowledge of an indicator for reliability and deterioration during use is also low at 23%. According to Johnson and Palmer [19], the top three challenging technology areas are as follows: reliability and qualification, packaging and integration, and thermal management. It is expected that these challenges can be partly solved with continuous research efforts and investment until beyond 2025. The results of this suggest that, for the first of these challenges, research effort into the power electronic health management area—such as diagnosis, prognosis, and condition monitoring—is needed. A review of such condition-monitoring approaches is given in [15].

Finally, the validity of the questionnaire should be discussed. It is noted that the survey is neither exhaustive nor definitive. It is inevitably limited by the question quality, the restricted detail of the replies, and, most of all, the restricted sample of the responses. However, the effective response rate was satisfactory at 19% in view of the quality of the industrial partners responding; in future work, they could be widened in number and application area.

VI. Conclusion

A questionnaire survey has been carried out to determine the industrial requirements and expectations of reliability in power electronic converters, systems, and components. Power semiconductor devices were ranked as the devices for which reliability was of most concern. This, and the fact that there is significant need identified by the responders for better reliability-monitoring methods and indicators, suggests that there is significant work to be carried out in this area.

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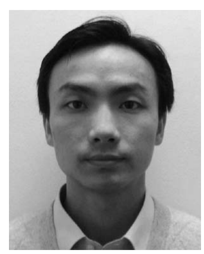

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