Helpful Hints to Enhance Reliability of dc-dc Converters in Hybrid Electric Vehicle Applications

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Abstract**—**This paper presents a new method for reliability assessment of bi-directional dc-dc converters which are used in electric and hybrid electric vehicles (EV/HEV). The proposed technique takes into account random modes of operation dictated by the driving scenarios. In order to consider the stochastic nature of the driving, Federal Test Procedure (FTP-75) driving cycle is selected as the reference. A bench mark bi-directional dc-dc converter circuit along with a Hybrid Energy Storage System (HESS) is selected as the typical HEV DC-DC converter. The new method for reliability assessment of HEV DC-DC converters under random behavior of driver is presented using Monte Carlo simulation and part stress method.

I. INTRODUCTION

Bi-directional multi-input dc-dc converters form an integral part of the electrical storage system in modern electric and hybrid electric vehicles. In active hybrid vehicles, the power converter is controlled to regulate the power sharing between the ultra capacitor and the battery in order to maximize the energy harvest and extend the life time of the battery while accommodating the basic needs of the electric power train[1]. Benefits related to the combined use of different storage devices are attributed to their synergic action and their complementary use. The power flows into and from each storage device, has to be executed accurately and controlled to achieve global energy management optimization. This has to be designed and implemented with the aim of optimizing the energy efficiency and with the promise that a regular working condition would reduce the life of the components [2].

To accommodate multi-source energy storage platform, a multi-input dc-dc power convertor is needed. An ideal multi-input power supply could accommodate a variety of sources and combine their advantages. With multiple inputs, the energy source is diversified to increase reliability and utilization of sustainable sources [3]. As a result, Hybrid Energy Storage Systems (HESS) have opened a major research area in electric, hybrid electric and plug-in hybrid electric vehicles (EVs, HEVs, and PHEVs). In [4], a control algorithm was proposed for the power flow management, which achieved optimal mode of operation of energy sources on the basis of their peculiar characteristics. A three port galvanically isolated topology was developed in [5]. This was accomplished using full bridge converters with bidirectional energy flow capability. Such a configuration facilitated the matching of different voltage levels in the overall system. In [6], a new HESS design was proposed. Compared to the conventional HESS, the new design had a lower cost and extended the battery life. Among different points associated with the DC-DC converters compatible with HEV applications, presented in [7], reliability is a missing criterion that has not been investigated properly. Reliability is a key necessity in power electronic devices using which the life time, number of failures and associated cost are estimated. If a system is acceptable from technical point of view but has a low reliability, it would not be practical to use it. Reliability assessment of power electronic devices were presented in [8-10]. In [9], Power Factor Correction (PFC) converters were discussed and compared from reliability point of view. In order to perform this comparative study, a fly-back converter as a single-stage PFC and a boost-forward converter as a two stage PFC were constructed. Using experimental results, reliability of the two prototypes were calculated based on MIL-HDBK standard. Using reliability calculation results, it was shown that the single-stage PFC is superior to the two-stage PFC from reliability point of view. In [10], the paralleling of IGBTs was discussed from the reliability point of view. To show the effect of paralleling on the reliability of DC-DC converters, a 4kW boost converter had been constructed. Two cases were compared with each other. In the first case, 5 paralleled IGBTs were used in the converter. In the second case, the Integrated Power Module (IPM) was used. It was shown that the paralleling of IGBTs can extremely decrease the reliability of the converter.

In previous works, the inputs to the converters were deterministic since they were connected either to the grid or to another converter. However, in EV/HEV applications, since the dc-dc converter is subjected to the random behavior of the driver a stochastic formulation deems necessary. In this study the operational modes of the multi-input dc-dc converter is partitioned into four categories namely, low power, high power, acceleration and regenerative breaking. Therefore, the input/output of the HEV dc-dc converter is not deterministic and rather stochastic. In the presence of stochastic input to the converter, the reliability of the converter could not be evaluated using previous methods mentioned in [8-10] and the use of a Monte-Carlo simulation will be necessary. In this

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paper, first a brief summary of different topologies used as the HEV DC-DC converters along with their design considerations will be presented. Then, definition of reliability along with the new method to evaluate reliability of such DC-DC converter under random behavior will be discussed. Finally, for the proof of concept, the typical HESS presented in [6] will be simulated under the aforementioned four operating modes and its reliability will be calculated using the new method.

II. BATTERY AND SCAP BEHAVIORS IN HEV APPLICATIONS

In order to optimally manage the available energy supply from the sources and power required by the load, combined energy sources including battery/ultra capacitors are utilized in EV/HEV applications. However, the working principles of these two storage systems are different. In advanced automotive applications, because the load profile varies rapidly according to the road conditions and the driver's behavior, the energy storage system suffers form random charges (regenerative breaking) and discharges (acceleration command), which have a negative impact on the life of the battery [11], [12]. It has been shown that the battery life, given by the number of charge and discharge cycles, is improved when current carried out by batteries never exceed weighting values given by the manufacturer [13]. Balancing of cells in a battery system is another challenge that needs to be solved to improve the life of the battery. This is primarily because, with out the balancing system, the individual cell voltages will drift apart over time. The capacity of the total pack will decrease more quickly during operation which might result in the failure of the entire battery system.

In the other hand, super capacitors have much greater advantage over batteries when capturing and supplying short bursts of power due to their higher power density limits, and ability to charge and discharge very quickly. Consequently adding a super capacitor bank will assist the battery during vehicle acceleration and hill climbing, and with its quick recharge capability it will assist the battery in capturing the regenerative banking energy [14]. Super capacitors have a power density that is 10-100 times larger than that of batteries, but they exhibit a much smaller energy density when compared with the electrochemical batteries. Thus, super capacitors follow the evolution of the future energy need for vehicles and find their place in being a complement of or a replacement for batteries. It is true that super capacitors have smaller inner resistance than electro chemical batteries, but the voltage is quickly decreasing when they supply energy. Therefore they appear to be practically unessential if they are directly connected in parallel to an electro chemical battery. To solve this problem of battery and super capacitor hybridization, there must be good energy management between these devices which enables the reduction of the battery size and improves its life span.

III. Hybrid Electric Vehicle DC-DC Power Conversion

To solve the problems listed above, the bidirectional dc-dc converter with proper charging-discharging profile is required to transfer energy between the battery/ultra capacitor and the electric traction system [15].

The basic idea of using a multiple-input bidirectional dc-dc converter is to combine ultra-capacitors (UC) and batteries to achieve a better overall performance. In other expression, the power converter is required to balance the power flow between the ultra capacitor and battery to satisfy the load power requirements while ensuring that the operation is within the limitations of the electrochemical components, such as battery overcharge/discharge, ultra capacitor voltage, etc. To ensure that the dynamic exchange of energy between the super capacitor modules and the batteries are accommodated, various converter topologies and their control have been presented in [16].

Various topologies of dc-dc converters along with effective methodologies of electric power management in hybrid vehicles were presented in [17]. Among different HEV DC/DC topologies presented before, the battery/ultra capacitor hybrid energy storage DC-DC converter presented in [6] is selected in this paper for reliability assessment. The proposed DC-DC converter is shown in Fig. 1. The same method presented here can be applied to other circuit topologies.

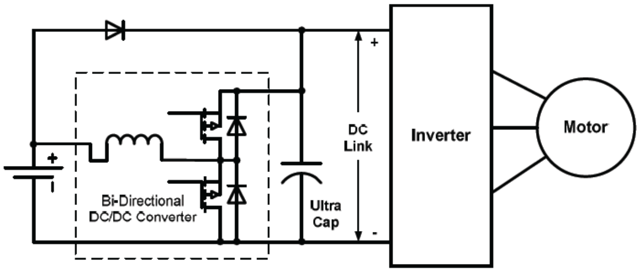

Fig. 1. Selected HEV DC-DC converter

As shown in figure 1, a higher voltage ultra capacitor bank is always connected to the dc bus so as to provide peak power demand where as a lower voltage battery is connected to the dc bus via a power diode. A bidirectional dc-dc converter is normally controlled to maintain the voltage of the ultra-capacitor higher than that of the battery. Therefore, in most cases, the diode is reverse biased [6]. The operation of the HESS can be separated into four modes of operation: low-power mode, high power mode, regenerative breaking mode, and acceleration mode. A more detailed analysis of the operation of this converter under the four operating modes is presented in [6].

IV. RELIABILITY ASSESSMENT OF HEV DC-DC CONVERTERS

A. Definition of reliability

The probability of proper function of a system after a time interval is referred to as its reliability, which is dependent on the type and quality of the parts and materials used in the device, tension each part endures, the ambient conditions in which the device is working and etc. There are two major methods of reliability predictions; "part stress analysis" and "part count" [18]. The parts count method is applicable during bid proposal and early design phase when insufficient information is available. The parts count method requires less information, generally part quantities, quality level and the application environment. In general, the parts count method will usually result in a more conservative estimate (i.e., higher failure rate) than the part stress method. The part stress method has been studied in this paper, to have more reliable results based on the measurements.

Considering deterministic input/output, the failure rate in most of electronic systems is constant and is expressed by λ. The reliability is expressed by;

$$R(t) = e^{-\lambda t} \tag{1}$$

The mathematical mean of *R(t)* occurs at:

$$t = \frac{1}{\lambda} \tag{2}$$

Which is the amount of time that should elapse until the first failure occurs. This is called the Mean Time To Failure (MTTF). The Mean Time To Repair (MTTR) of the system is negligible compared to MTTF, so the Mean Time Between Failure (MTBF) of a system is expressed as:

$$MTBF = MTTF + MTTR = \frac{1}{\lambda} \tag{3}$$

The total rate of the system failure is sum of the failure rate of all parts of the system:

$$\lambda_{system} = \sum_{n=1}^{N} \lambda_{part} \tag{4}$$

Hence the reliability of the system will be the product of all the system component's reliabilities [15]:

$$R_{system} = \prod_{n=1}^{N} \prod R_{part} \tag{5}$$

The failure rate of each part itself is the product of some factors. The failure rate of each part in the proposed converter is expressed as (6) to (9).

$$\lambda_{P(S)} = \lambda_{b_{(S)}} \times \pi_Q \times \pi_A \times \pi_E \times \pi_T \tag{6}$$

$$\lambda_{P(D)} = \lambda_{b_{(D)}} \times \pi_Q \times \pi_E \times \pi_C \times \pi_S \times \pi_T \tag{7}$$

$$\lambda_{p(L)} = \lambda_{b_{(L)}} \times \pi_C \times \pi_E \times \pi_Q \tag{8}$$

$$\lambda_{p(C)} = \lambda_{b_{(C)}} \times \pi_{CV} \times \pi_Q \times \pi_E \tag{9}$$

The parameters of these equations will be defined in the following text.

In equations (6) and (7), the base failure rate (λ_b) of the switch and diode are constant and equal to 0.012 and 0.064, respectively [18]. The base failure rate of the inductor and capacitor ($\lambda_{P_{(L)}}$ and $\lambda_{P_{(C)}}$) are determined by using equations (10) and (12), respectively [18].

$$\lambda_b = 0.00035 \times \exp\left(\frac{T_{HS} + 273}{329}\right)^{15.6} \tag{10}$$

where T_{HS} is the hot spot temperature of the inductor (^{0}C) and can be calculated, as follows:

$$T_{HS} = T_a + 1.1 \times \Delta T \tag{11}$$

where T_A is the device ambient operating temperature (℃) and ΔT is the average temperature rise above ambient (℃).

By the equation (12), λ_b of capacitor can be calculated:

$$\lambda_b = 0.00254\left[\left(\frac{S}{0.5}\right)^3 + 1\right]\exp\left[5.09 \times \left(\frac{T_A + 273}{378}\right)^5\right] \tag{12}$$

where *S* is the ratio of operating voltage to the rated voltage.

In equations (6) and (7), π_T is the temperature factor and is calculated by using equations (13) and (14) for the switch and diode, respectively.

$$\pi_{T(S)} = \exp(-1925 \times (\frac{1}{T_j + 273} - \frac{1}{298})) \tag{13}$$

$$\pi_{T(D)} = \exp(-1925 \times (\frac{1}{T_j + 273} - \frac{1}{293})) \tag{14}$$

where T_j is the junction temperature and can be determined by the equation (15), as follows:

$$T_j = T_C + \theta_{jc} \times P_{loss} \tag{15}$$

where, T_C is the heat sink temperature, θ_{jc} is the thermal resistance of the switch or diode and P_{Loss} is the total loss of switch or diode.

In equations (7) and (8), the stress factor (π_S) and the capacitance factor (π_{CV}) can be determined by equations (16) and (20), respectively.

$$\pi_S = V_S^{2.43} \tag{16}$$

where V_s is the ratio of the operating voltage to the rated voltage and

$$\pi_{CV} = 0.34 \times C^{0.12} \tag{17}$$

where *C* is the capacitance in μF.

The quality factor (π_Q), environment factor (π_E), application factor (π_A) and contact construction factor (π_C) of different elements are constant factors. They are presented in tables in [18] and can be determined considering the specific elements used in the converter structure.

B. Reliability assessment in power electronic systems with stochastic inputs/outputs

As mentioned in the last part, when the input/output of the power electronic system is deterministic, the reliability of the system can be expressed by the MTBF value. However, since in some applications such as HEV or plug-in HEV, the input/output of the system is stochastic, there will be different operating modes such as low power, high power, acceleration and regenerative breaking for the system. That is why the MTBF value of the system will change according to the random behavior of the driver. In this case, Monte Carlo simulation method seems to be a powerful tool that combined with the conventional method of reliability assessment of power electronic systems, can present an appropriate method for evaluating the reliability of power electronic systems under stochastic inputs/outputs.

In this method, the system must be simulated under its different operating modes, according to different inputs/outputs. Then the failure rate of each element in the system, in each operating mode, is calculated using part stress method which has been discussed in the previous part. Based on the part stress analysis results, the system will be modeled in the reliability domain. In this model, there will be a range for the failure rate of each element and consequently for the MTBF value of the system. The range for the total failure rate value corresponds to the range of inputs/outputs. Now, with good approximation, it can be concluded that the actual value of the MTBF of the total system, will be between a minimum and a maximum value. In this step, the Monte Carlo simulation method can be used to evaluate the actual value of the MTBF. This method will be presented in detail in part V.

V. SIMULATION RESUTS

In order to show the effectiveness of the proposed method in reliability evaluation of HEV DC-DC converters, the typical HESS presented in [6] is considered and simulated in this paper. The topology of this converter was presented in Fig. 1. As described in [6], there are four operating modes for this converter, including low power, high power, acceleration and regenerative breaking. The Simulation has been done under the four operating modes mentioned above. Fig. 2 to Fig. 4 show the typical simulations results of the selected converter.

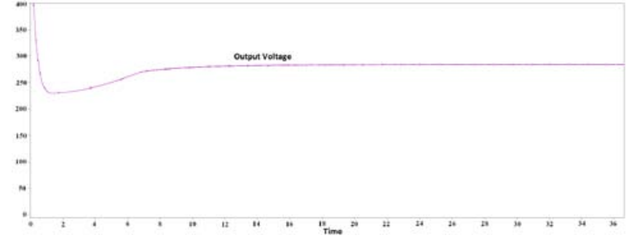

Fig. 2-a)

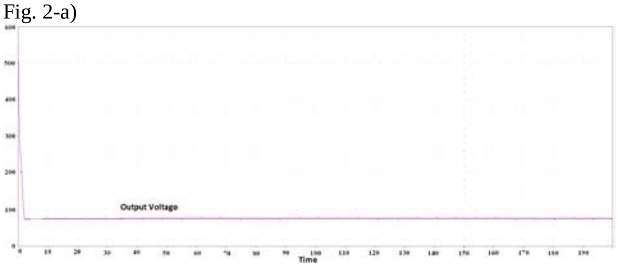

Fig. 2-b)

Fig. 2. Typical output voltage waveforms of the converter in the two operating modes of a) low power and b) acceleration (Volts/ms)

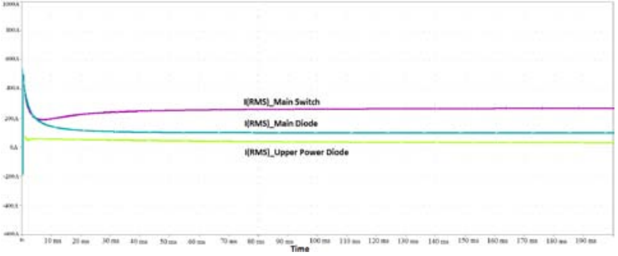

Fig. 3. RMS current of main switch, output diode and the upper power diode in high power mode (A/ms)

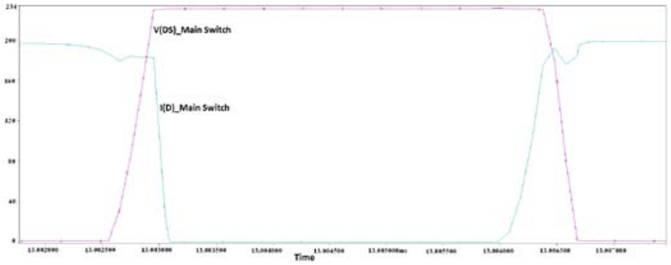

Fig. 4-a)

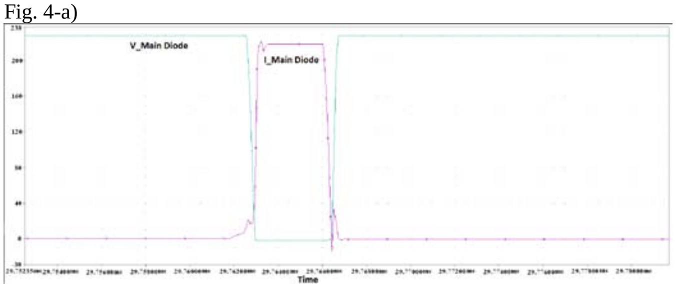

Fig. 4-b)

Fig. 4. Overlap of current and voltage in semiconductors: a) main switch b) main diode (A/ms)

VI. RELIABILITY ASSESSMENT OF THE SELECTED CONVERTER

In order to calculate the reliability of the selected converter, first the failure rate value of each element and consequently the MTBF value of the whole converter has to be determined in each of its four operating modes. The part stress method [20] is used to calculate the MTBF value of the converter shown in Fig. 1. In this approach, first the failure rate of each element in the converter structure is obtained individually and then the value of the converter's MTBF is calculated from equation (4) in which "N" is the number of comprising parts.

To calculate the failure rates, first the dynamic and static losses of semiconductors should be calculated for different operating modes. Considering measurement results, the reverse recovery losses can be neglected in comparison with the static losses of diodes. Dynamic loss of diodes can also be neglected in low power mode. Whereas in acceleration mode, the overlap time of current and voltage waveforms increases as well to the extent that the dynamic loss can not be neglected. However, the dynamic losses of switches are considerable, especially at the turn-off instant. Table 1 summarizes the failure rates and the MTBF calculation results for the selected converter in the four operating modes.

Element	*Failure rate (λ) in each operating mode*			
	Low power	*High power*	*Acceleration*	*Regenerative breaking*
Inductor	2.1	2.3	2.4	2.1
Main Switch	195	198	198	-
Aux. Switch	-	-	-	180
Output diode	0.98	0.2	0.2	-
Upper power diode	-	5.1*10 ^-5	-	-
Output cap.	1.9	1.9	2.07	1.7
Control circuit	0.88	0.88	0.88	0.88
Total system	200.86	203.28	203.55	184.68
MTBF=1/ λ	*4978*	4920	4912	5415

TABLE. 1. RELIABILITY OF THE SELECTED CONVERTER IN THE ACCELERATION MODE

As a discussion of the failure rates and MTBF calculation results in Table 1, the following points are considerable. First, it can be seen that the converter has the lowest reliability in acceleration mode. Of course this point could be anticipated since the dynamic and static losses of semiconductors increase in this mode and the semiconductors sustain much higher stresses in this operating mode.

Second, switches have the highest failure rates among the converter elements in all operating modes. Considering reliability calculation results in the four operating modes, it was seen that approximately 97% of total system failure rates is allocated to the switches in each four operating modes of low power, high power, acceleration and regenerative breaking. During simulation, it was seen that when the converter transitions from low power mode to the acceleration mode, the static and dynamic losses increase significantly and the stresses over the switches become severe. So, it is concluded that in order to increase the reliability of HEV dc-dc converter in the acceleration mode, the amount of power crossing through the switches to the output should be controlled. Instead, the battery/ultra capacitor current must be forced to flow into the load through some different paths other than switches. This point has been partially taken into account in the selected converter using the upper power diode in Fig. 1. The upper power diode in Fig. 1 is forward biased only if the converter works in the acceleration mode, when the output voltage decreases below the battery voltage.

There is an important point that must be taken into consideration according to the converter’s performance. Since the converter's operating mode depends on the random behavior of the driver, so the inputs/outputs of the converter are stochastic.

In order to consider the random behavior of the driver, the FTP-75 driving cycle, shown in figure 5, is used as a reference for this random behavior. As can be seen in this figure, the curve is divided into three phases. The cold phase simulates starting the car and then driving almost immediately onto a highway. While this is feasible for a suburban home, for most city dwellers, one tends to drive out of his/her driveway and into a lot of stationary traffic. The hot phase of the FTP is 10 minutes after the end of the transient phase. This intends to simulate parking a car and then returning to it after a short period of time. It's probably clear that the hot phase is simply a repeat of the cold phase in terms of speed-time [19].

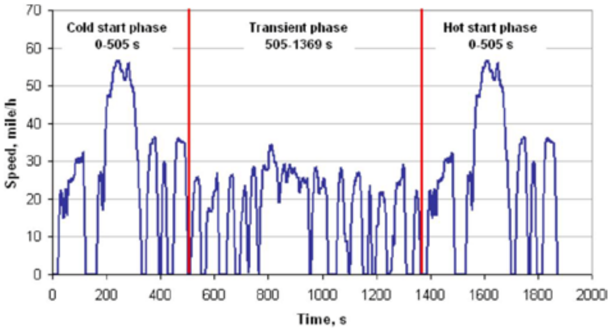

Fig. 5. The FTP-75 curve as a reference for the driver's random behavior

In [20], the FTP-75 driving cycle shown in Fig. 5 was used as a case study for an agent-based power management strategy in hybrid vehicles. Variations of current in terms of time for FTP-75 driving cycle was presented in [20] and is shown in Fig. 7 in this paper.

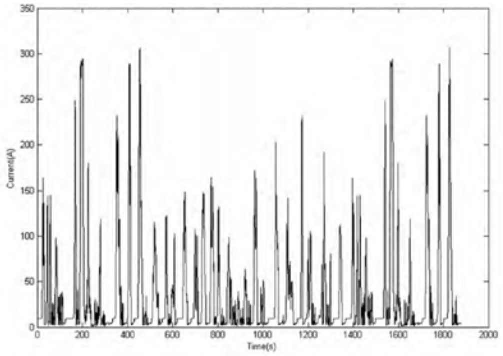

Fig. 6. FTP-75 driving cycle current curve

In order to evaluate the actual reliability of the converter under driver's random behavior, Monte Carlo simulation is implemented based on this curve and the reliability calculation results shown in Table. 1. In this new method for reliability assessment of the converter under stochastic inputs/outputs, first the system is modeled in the reliability domain using the part stress method, as shown in table 1, and then the Monte Carlo simulation is used to involve the effect of randomness in converter's inputs/outputs. The number of iteration in the proposed Monte Carlo simulation used in this paper is 10000 that corresponds to the total error of 0.47%. The value of standard deviation for the random generation in the proposed method is selected based on Fig. 6 to consider the FTP-75 driving cycle as a reference for the driver’s behavior. Figure 7 shows the Probability Density Function (PDF) in terms of failure rates. Based on this figure, the most probable value for the converter’s total failure rate (λ) is 197.68 that corresponds to the MTBF value of 5059 hours.

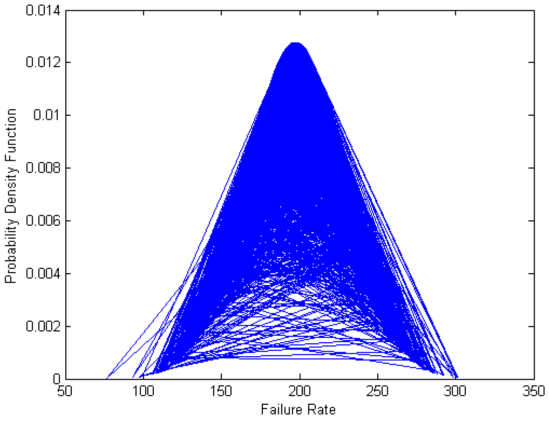

Fig. 7. The curve of PDF in terms of failure rates in the proposed Monte Carlo simulation method

VII. CONCLUSION

In this paper, a new method was presented to evaluate the reliability of HEV dc-dc converters under driver's random behavior. In the new method, first the system was simulated under its different operating modes. Then, using part stress method, the system was modeled in the reliability domain. In this step Monte Carlo simulation method was used to simulate the effect of randomness in inputs/outputs of the converter.

Also, as a case study, a typical DC-DC converter for HEV application was studied in this paper and its reliability was assessed using the new method.

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