Evaluation of Failure Trends on a PID-Controlled Synchronous Buck Converter based Battery Charging Controller

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Abstract— The future trends in renewable energy generation are to select appropriate components and topology for power electronics converters with optimized costs and power density while satisfying the reliability target. This paper evaluates the reliability of a PID-controlled synchronous buck converter-based (SBC) battery charging controller for solar-powered lighting system in a fishing trawler and figure out most failure prone components. This reliability prediction has been developed according to MIL-HDBK-217F(N1/2) handbook models along with performance degradation analysis of individual components. Simulation results have demonstrated that there are two general failure effects of components in the overall circuit, with the MOSFETs being the most failure prone device for a wide range of temperature; however, the overall system can expect an average operational lifetime of between 5 to 11 years before failing, under worst case scenario.

Keywords—Power losses, junction temperature, MTBF, converter, reliability.

I. INTRODUCTION

One of the key challenges for transitioning from a fossil fuel-based energy economy to a renewable energy-based economy is the reliability of the power electronic components involved in the energy extraction and storage process. Power density, efficiency, cost, and reliability are the major concerns when designing any power electronic system [1], especially so in marine systems, where the operating conditions are very harsh. This paper will look at the reliability of the PID controlled SBC-based battery charging controller designed for a solar-power lighting system in a fishing trawler operating in the Bay of Bengal.

Reliability, which is defined as the probability that a product will continue to work for a specified time interval under specific conditions, is a key element of the product life cycle analysis (LCA) [2]. The traditional model to ensure reliability of a product relied on extensive testing of the product during the manufacturing phase (alpha), and on the consumer to find faults within the final product during normal use (beta). Consistent and reproducible faults are then identified and analyzed before a fix or a solution to the fault is released. To a large extent, when the product is a software, that is still the case. While, reliability in modern hardware-based system is ensured with Design for Reliability (DfR), a design process for ensuring that the product performs its specified function, over its expected lifetime, within its use environment [3]. It is an iterative process that typically consists of six stages that span the product’s lifecycle from concept till retirement: requirements definition, risks identification, reliability design, analysis and assessment, verification, validation or demonstration, and monitor or control [4].

This paper presents a model to describe the overall reliability of the SBC system used for the battery charging controller in a fishing trawler. To investigate the reliability of the converter, the components configurations, components ratings and system rating are taken as input for reliability evaluation. The thermal stresses on each component is obtained from electro-thermal model also consider as input. Afterwards the data gathered from the military handbook, MIL-HDBK-217F(N1/2), to identify the component failure rates, which will be used to predict the system level reliability of the SBC as shown in Fig. 1.

The paper is organized as follows: Section II will describe the physics of loss for the system based mainly on the thermal model of the SBC, Section III will perform a reliability analysis of the system, with Section IV analyzing the results, followed by a concluding section.

II. SYSTEM MODELING AND INSTANTANEOUS POWER LOSSES PROFILE

The trawler in question is one of hundreds of medium sized boats that ply the waters off the coast of Chittagong in the Bay of Bengal. These trawlers, which originally had diesel generators to power the electrical system on board the trawler, were modified to incorporate solar energy as the electrical source. Therefore, a 120W solar panel, a 1.2kWh lead acid battery, and a charging unit was incorporated. The charge controller is based on a synchronous buck controller that utilized a PID algorithm (instead of the traditional MPPT algorithm) to charge the battery using maximum available current. While the life cycle analysis (LCA) of the system was performed in [5] and its control structure and performance were extensively evaluated in [6], this paper will conclude the investigation with an analysis of the system reliability.

As reliability of a semiconductor-based system is highly influenced by temperature effects, thermal stress due to instantaneous power losses needs to be analyzed. As per mode operation of SBC, the losses in the SBC’s power switches can be defined as [7, 8]:

\[ P_{\text{loss,semi}} = P_Q + P_{Q2} + P_{BD} \]  

(1)
where \( P_{Q1} \) is the total power losses in upper switch, \( P_{Q2} \) is the total power losses in lower switch, and \( P_{BD} \) is the body diode losses. The total power losses in the upper switch are composed of conduction losses \( (P_{c1}) \), switching power losses \( (P_{sw}) \), and gate drive losses \( (P_{G}) \). Thus, the total losses are:

\[
P_{Q1} = P_{c1} + P_{sw} + P_{G}
\]

(2)

On the other hand, the switching losses for lower switch can be ignored. Typically, the lower side switch is conduction loss dominated with additional diode conduction losses for dead times. Therefore, the total loss in lower switch is comprised of conduction losses \( (P_{c2}) \) and gate drive losses \( (P_{G}) \) [5, 6].

\[
P_{Q2} = P_{c2} + P_{G}
\]

(3)

The conduction losses are:

\[
P_{c1} = (I_{s,rms}D)^2 \times R_{DS(on)}
\]

(4)

\[
P_{c2} = [I_{s,rms}(1 - D)]^2 \times R_{DS(on)}
\]

(5)

The switching losses are:

\[
P_{SW} = \frac{[V_{DS(max)}(t_r + t_f)I_s,_{rms}]f_{sw}}{2}
\]

(6)

The gate-drive losses are:

\[
P_{G} = V_{GS} \cdot \frac{Q_{gs}}{t_{on}} \cdot f_{sw}
\]

(7)

The body diode losses are:

\[
P_{BD} = 2 \cdot V_f \cdot \left( I_0 + \frac{\Delta I_L}{2} \right) \cdot t_d \cdot f_{sw}
\]

(8)

where the MOSFET parameters \( (R_{DS(on)}, V_{DS(max)}, t_r, t_f, V_{GS}, Q_{gs}, t_{on}, V_f \) and \( t_d \)) are taken from the FQP50N60 datasheet. \( I_o, I_s,_{rms}, \) and \( \Delta I_L \) are the output current, switch current, and input current ripples, respectively. The inductor losses are the sum of core losses in the iron-powered toroidal core \( (P_{core}) \) and conducting losses in the windings of the inductor \( (P_{cond}) \) [9].

\[
P_{loss,inductor} = P_{Core} + P_{Cond}
\]

(9)

with

\[
P_{cond} = I_{L,_{rms}}^2 R_L
\]

(10)

\[
P_{core} = W_{t}f_{sw}1.68P_{ac}^{0.99}
\]

(11)

and

\[
B_{ac} = \frac{L \Delta I_L}{N_t}
\]

(12)

where \( B_{ac} \) = magnetic flux density ripple, \( R_L \) = internal resistance of the coil, \( W_{t} \) = weight of the inductor, \( L \) = core-length, and \( N_t \) = number of turns. The ESR losses of DC link capacitor can be calculated as:

\[
P_{loss,C} = I_{C,_{rms}}^2 ESR
\]

(13)
The total losses of the system then are the sum of all losses of all components in the SBC system.

\[
P_{\text{loss, total}} = P_{\text{loss, semi}} + P_{\text{loss, inductor}} + P_{\text{loss, capacitor}}
\]

Based on the power loss model, the RC lumped equations have been developed to predict the junction temperature \(T_j\) and heat sink temperature \(T_H\) as equation (15) and (16) [11].

\[
T_j = T_a + P_{\text{loss, total}}[Z_{th(jc)} + Z_{th(ch)}] + Z_{th(ha)}
\]

\[
T_H = T_a + P_{\text{loss, total}}Z_{th(ha)}
\]

where \(Z_{th(jc)}\) is the junction-to-case thermal impedance \(\text{°C/W}\), \(Z_{th(ch)}\) is the case-to-heatsink thermal impedance \(\text{°C/W}\), \(Z_{th(ha)}\) is the heatsink-to-ambient thermal impedance \(\text{°C/W}\), and \(T_a\) is the ambient temperature.

The maximum \(T_j\) of the SBC during its operation will have a significant impact on selecting the range of operation to find component failure rate and thus will affect the reliability of the system.

III. SYSTEM RELIABILITY EVALUATION

This section seeks to provide a prediction of the system Mean Time Between Failure (MTBF), to evaluate its potential reliability. This will provide information to assist in directing and planning for reliability and related program efforts, and to identify design features which are critical to reliability. The method of reliability prediction used in this analysis is taken from MIL-HDBK-217F(N1/2) [10]. The Mathematical Model used in determining the converter reliability is known as the series model. This model is based on the equation (17).

\[
R(t) = e^{-\lambda t} = e^{-\frac{t}{MTBF}}, \quad \lambda = \frac{1}{MTBF}
\]

where \(R(t)\) is the overall reliability of the converter, \(t\) is the elapsed operation time (hr), and \(\lambda\) is the constant failure rate.

The Reliability model MTBF reflects the reliability of all electrical parts in the topology. The component failure rates can be found using either the parts count method or the parts stress method. The difference between due is that the parts count method relies only on the generic failure rates of components to quickly determine an approximate reliability estimate, while the parts stress method is more operation specific. The part stress prediction model considers the component parameters and the stress factors for the components running and performing their intended function in their considered environment. The part stress prediction model is usually used after the design phase for reliability trade-offs vs part selection and stresses.

The quality of a part, which also play a vital role in its failure rate, for the converter has been selected as MIL Spec quality, but with a lower \(\pi_q\) factor since they are sourced commercially. All part reliability model includes the effects of environment stresses through the environment factors, \(\pi_E\). The overall part failure rate, \(\lambda_p\), of the individual components depends on a combination of various stress factors including \(\lambda_b\) (base failure rate), \(\pi_T\) (temperature factor), \(\pi_Q\) (quality factor), \(\pi_A\) (application factor), \(\pi_E\) (environment factor), \(\pi_P\) (active pin factor), \(\pi_S\) (power stress factor), \(\pi_C\) (capacitance factor), \(\pi_V\) (voltage stress factor), \(\pi_{SR}\) (series resistance factor), \(C_1\) (die complexity failure rate), \(C_2\) (package failure rate), \(\pi_P\) (acceleration voltage breakdown), and \(\pi_L\) (learning factor). The right sign (✓) represents the stress factor applying to the components. The temperature factor, \(\pi_T\), in turn depends on the temperature of the component, \(T_j\), and the temperature coefficient, \(E_a\) based on the Arrhenius equation. The likelihood of systems failing due to failure in passive devices such as inductors, resistors, and capacitors are negligible. Thus, major reliability system models are based on the reliability of the semiconductor components (Diode, MOSFET, Microcontroller).

To calculate the overall reliability of the system, it is necessary to ascertain system functionality in the face of failures to individual or groups of components. Simulations of the system in Simulink were used to investigate how a system reacts to failure in individual components. A component can fail in many ways, but the effect of that failure on an electrical circuit can often be felt as an “open circuit” or a “short circuit” where the component is located. Simulations show that open circuit or short circuit failure in the inductor causes total system failure. Open circuit failure in the capacitor allow the system to operate, albeit with higher THD in the output, whereas short circuit failure of the capacitor cause total system failure. In the SBC, there are two MOSFET/diode components in the circuit, one connected in series, while the other is connected in parallel. Considering the parallel MOSFET/diode component, if the MOSFET or diode suffer an open circuit failure, the other component provides redundancy, and the system operates properly, albeit with low efficiency. On the other hand, if the MOSFET or diode suffers from a short circuit failure, it causes total system failure. Finally, considering the series MOSFET/diode component, if the MOSFET or diode suffers from a short circuit failure or the MOSFET suffers from an open circuit failure, it causes total system failure. However, if the diode suffers from an open circuit failure, it has no effect on the system. The microcontroller unit (MCU) is an interesting case since its failure manifest in the circuit as two invalid control inputs: both control inputs are continuously low or continuously high.
Table 1: Failure rates of the individual components of the Synchronous Buck Converter at 105°C

<table>
<thead>
<tr>
<th>Component Name</th>
<th>Failure rate ($\lambda_p$)</th>
<th>Stress Factors</th>
<th>Quantity (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistor</td>
<td>$8.72 \times 10^{-2}$</td>
<td>$\lambda_p = \lambda_{p_a} \pi_{p_r} \pi_{p_s} \pi_{c_r} \pi_{c_s}$</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>where $\lambda_{p_a} = 0.0024$, $\pi_{p_r} = 0.58$, $\pi_{p_s} = 10$, $\pi_{c_r} = 1$, and $\pi_{c_s} = 4$</td>
<td></td>
</tr>
<tr>
<td>Inductor</td>
<td>$1.337 \times 10^{-3}$</td>
<td>$\lambda_p = \lambda_{p_a} \pi_{p_r} \pi_{p_s} \pi_{c_r} \pi_{c_s}$</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>where $\lambda_{p_a} = 0.0003$, $\pi_{p_r} = 2$, and $\pi_{c_s} = 6$</td>
<td></td>
</tr>
<tr>
<td>MOSFET</td>
<td>16.5</td>
<td>$\lambda_p = \lambda_{p_a} \pi_{p_r} \pi_{c_r} \pi_{c_s}$</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>where $\lambda_{p_a} = 0.012$, $\pi_{p_r} = 0.58$, $\pi_{c_r} = 0.5$, $\pi_{c_s} = 8$, and $\pi_{c_r} = 1.33$</td>
<td></td>
</tr>
<tr>
<td>MCU</td>
<td>2.776</td>
<td>$\lambda_p = \lambda_{p_a} \pi_{p_r} \pi_{c_r} \pi_{c_s}$</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>where $\lambda_{p_a} = 0.00037$, $\pi_{p_r} = 0.58$, $\pi_{c_r} = 0.5$, and $\pi_{c_s} = 1$</td>
<td></td>
</tr>
<tr>
<td>Capacitor</td>
<td>1.258</td>
<td>$\lambda_p = \lambda_{p_a} \pi_{p_r} \pi_{c_r} \pi_{c_s}$</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>where $\lambda_{p_a} = 0.00037$, $\pi_{p_r} = 0.58$, $\pi_{c_r} = 0.5$, and $\pi_{c_s} = 1$</td>
<td></td>
</tr>
<tr>
<td>Diode</td>
<td>1.778</td>
<td>$\lambda_p = \lambda_{p_a} \pi_{p_r} \pi_{c_r} \pi_{c_s}$</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>where $\lambda_{p_a} = 0.00037$, $\pi_{p_r} = 0.58$, $\pi_{c_r} = 0.5$, and $\pi_{c_s} = 1$</td>
<td></td>
</tr>
<tr>
<td>Connectors and sockets</td>
<td>$5.669 \times 10^{-2}$</td>
<td>$\lambda_p = \lambda_{p_a} \pi_{p_r} \pi_{c_r} \pi_{c_s}$</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>where $\lambda_{p_a} = 0.00037$, $\pi_{p_r} = 0.58$, $\pi_{c_r} = 0.5$, and $\pi_{c_s} = 1$</td>
<td></td>
</tr>
<tr>
<td>Fuse</td>
<td>$2 \times 10^{-2}$</td>
<td>$\lambda_p = \lambda_{p_a}$</td>
<td>1</td>
</tr>
</tbody>
</table>

where $\pi_{p_r} = e^{-\frac{k}{T}} \left(\frac{1}{k} - \frac{1}{m}\right)$ and $k = 8.6173303 \times 10^{-5}$. The other factors are constants specific to the component.

Both MCU failure combinations of the control inputs cause system failure. To summarize, the following causes total system failure: any type of failure in the inductor, short circuit failure of the capacitor, short circuit failure of the parallel connected MOSFET or Diode, any type of failure in the series connected MOSFET, short circuit failure in the series connected Diode, and any type of failure of the MCU control inputs. For all components, half of the value of the failure rate from Table 1 is used for calculations, assuming every component has equal chance to fail as either a short circuit or an open circuit. Moreover, two different reliability scenarios will be investigated, one where the components fail as a short circuit, and the other when they fail as an open circuit. Based on the methodology described in [11] and [12], the parallel connected MOSFET/diode components are modelled as parallel association if they fail as an open circuit, because the system fails only if both devices fail, while they are modelled as a series association if they fail as a short circuit, because the system will fail if any of the components fails. The remaining components of the SBC are modelled as series association, but in the case of open circuit failure, the capacitor and the series diode are not considered as their failure do not affect the system.
Reliability calculation for Series Association is given as follows:

\[ R(t) = \prod_{i=1}^{n} R(t)_i = e^{-n \lambda t} \quad (18) \]

\[ \lambda = \sum_{i=1}^{n} \lambda_i \quad (19) \]

\[ MTBF = \frac{1}{\lambda} \sum_{i=1}^{n} \frac{1}{i} \quad (20) \]

Reliability calculation for Parallel Association can be expressed as:

\[ (1 - R(t)) = \prod_{i=1}^{n} (1 - R(t)_i) \quad (21) \]

\[ R(t) = 1 - (1 - e^{-\lambda t})^n \quad (22) \]

\[ MTBF = \frac{1}{\lambda} \sum_{i=1}^{n} \frac{1}{i} \quad (23) \]

Based on (18) and (21), and the description given above, the equations for the two types of failure scenarios are given as:

\[ R_{SC}(t) = e^{-\frac{8.252}{10^6} \cdot e^{-\frac{0.889}{10^6}} \cdot e^{-\frac{1.388}{10^6}}} \cdot e^{-\frac{0.629}{10^6}} \cdot e^{-\frac{20.299}{10^6}} \cdot e^{-\frac{0.006666}{10^6}} = e^{-\frac{10.529}{10^6}} \quad (24) \]

\[ R_{OC}(t) = \left[ 1 - \left( 1 - e^{-\frac{8.252}{10^6} \cdot e^{-\frac{0.889}{10^6}} \cdot e^{-\frac{1.388}{10^6}}} \right) \right] \cdot e^{-\frac{8.252}{10^6} \cdot e^{-\frac{0.889}{10^6}} \cdot e^{-\frac{1.388}{10^6}}} \cdot e^{-\frac{10.529}{10^6}} \quad (25) \]
where 't' is the time in hours. Reliability coefficients are given for \( T_j = 105^\circ C \). As can be seen, the system is twice more reliable (in the log scale) when experiencing open circuit failure than when experiencing short circuit failure. Also, the contribution of capacitor to the failure of the system disappears, while the contribution of the MCU doubles, but contributions of MOSFETS and Diodes remains unchanged.

IV. RESULTS AND DISCUSSION

Fig. 4 represents the percentage of contributions of each component in MTBF and as expected MOSFET is the most failure prone component and contributes 81.3% of the failure rate for the Short Circuit failure scenario and 78.4% of the failure rate for the Open Circuit failure scenario.

Result 1 (worst case scenario): When operated at 105°C, the MTBF for the system is found to be between 5.62 to 10.84 years based on (24) and (25), and Fig. 3 shows that the system is mostly reliable for 3.88 to 7.42 years.

Result 2 (average case scenario): As comparison, the simulation was also run for operating temperature of 75°C, which is the junction temperature common in industrial applications. For the short circuit failure case, the system failure rate was found to be approximately 13 failures for every million hours of operation, which corresponds to a MTBF of 8.79 years, and the MOSFET was found to contribute to 81.92% of the failure. For the open circuit failure case, the system failure rate was found to be approximately 7 failures for every million hours of operation, which corresponds to a MTBF of 16.36 years, and the MOSFET was found to contribute to 76.23% of the failure. From this it can be concluded that the contribution of the MOSFET to the overall failure of the system remain steadily high despite changes in the operating temperature.

Recommendation: It should be noted that failure of the MOSFETs account for more than three quarters of the failure of the SBC system regardless of which type of failure scenario is being investigated. According to [13], the main reason MOSFETs fail is due to Electrical Overstress (EOS) which includes Unclamped Inductive Switching (UIS), linear mode operation during switching, and over current. A common outcome is the melting of the die and metal due to burning. To improve the reliability of the system it is essential to design circuits that protect the MOSFET, including using Schottky diode in series with the MOSFET and a fast recovery diode in parallel, and improving switching control by making use of dead time between switching transitions. However, adding lots of protective and redundant features into a PCB leads to cost increases, that must be balanced against application requirements. The field test of the SBC during sea trials remarkably shows no failures to date. However, not enough time has elapsed to make a valid judgement for system reliability. Furthermore, the system was operated in ambient temperatures below 45°C, thus it has better reliability practically than in simulation. In the absence of testbeds that can conduct accelerated stress tests, years of sea trials will be needed before a judgement can be made as to whether the SBC components tend towards short or open circuit failure.

V. CONCLUSION

This paper has presented a model to describe the overall reliability of the SBC system used for the battery charging controller in a fishing trawler. The reliability model has been developed for two common types of component failure categories using series and parallel association. Simulation results have demonstrated that the studied system has a MTBF of between 5 to 11 years under the worst-case scenario; however, practical data is not enough yet to compare with simulation data and determine whether the SBC components tend to fail as open circuit or short circuit conditions.

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