Abstract— This paper explores reliability assessment of various Quasi-Resonant (QR) buck DC-DC converters including zero current/voltage switching and half-wave/full-wave topologies. The impacts of output power, input voltage, output voltage, and time duration on the failure rate of each component are investigated, then overall reliability performance of each converter is evaluated. A detailed comparison is performed in which reliability metric of buck soft switching topologies is compared with each other as well as their parent hard switching topology. Eventually, mean time to failure of the converters is analyzed. This approach provides insightful information for selecting the topology or components for the purpose of designing QR converters. To achieve the reliability of these converters, first, the required equations to evaluate the effective factors on the reliability are obtained. Then reliability metric values are calculated for three cases in each of which a key parameter of the converters varies over a specified range.

Keywords—— DC-DC converters, mean time to failure (MTTF), quasi-resonant (QR) converter, reliability assessment.

I. INTRODUCTION

Power electronic converters are an essential part of energy conversion systems and have attracted considerable attention in recent years [1]. DC-DC converters, in particular, are of greatest—significance thanks to their application in renewable energies, electric vehicles, high voltage DC (HVDC) transmission and energy storage systems [2]. However, industrial experiences have shown that power converters are the most vulnerable component in such systems [3], [4]. Therefore, their availability and reliability are highly critical for the whole system to function properly. Quasi-resonant (QR) converters, which are formed by adding resonant components to the basic pulse width modulation (PWM) converters, have the advantage of zero current switching (ZCS) or zero voltage switching (ZVS). Thanks to their inherent soft switching, they have the benefit of higher efficiency and lower electromagnetic interference (EMI) [5], [6].

Generally, reliability analysis in power electronics field is performed from three different perspectives in the literature: component level, converter level and system level.

- **Component level**: From the component perspective, semiconductor devices seem to be the most reliability-critical component of a power converter. Therefore, most studies are focused on reliability assessment of such components. In [7], reliability of power semiconductor devices such as Metal-Oxide Semiconductor Field Effect Transistors (MOSFET), Insulated Gate Bipolar Transistors (IGBT) and diodes are evaluated under power cycling test by applying a periodical current to these devices and monitoring their temperature. A real-time strategy to improve the reliability of IGBT modules by means of collector-emitter voltage monitoring is presented in [8]. The reliability of emerging Silicon-Carbide (SiC) MOSFETs is analyzed in [9], [10], and compared to the conventional silicon-based MOSFETs.

- **Converter level**: From the converter point of view, various analytical frameworks have been proposed to evaluate reliability of power converters in general and DC-DC converters in particular. Such frameworks provide meaningful information for optimum selecting and designing power converters. Reliability-driven optimization of LC output filter of a Buck converter is made in [11]. In [12], reliability of a conventional boost converter is evaluated in which the effect of variation of each component’s characteristics on the overall system’s reliability is investigated. It is shown in [12] that the increase in series resistance of main switch or output capacitance results in degradation of converter’s reliability metrics. In [13], [14], [15], [16], comprehensive analyses for reliability assessment of conventional isolated multi-switch, isolated and non-isolated PWM DC-DC converters are presented, respectively.

- **System level**: Power electronic converters are crucial components in power conversion systems. Therefore, their reliability plays an important role in reliability of the whole power conversion system. Several studies have been done from such point of view in [17], [18], [19].

In addition, some literature focused on fault tolerant strategies. A comprehensive survey of general fault diagnosis and fault tolerant strategies is presented in [20], [21]. In particular, some techniques are introduced in [22], [23] for three-phase voltage source inverters and full bridge DC-DC converter, respectively, which are based on adding extra components or interleaving to improve the reliability of the converter.

In this paper, the effect of using resonant switch in replacement of the PWM switch network on reliability performance of the converters is investigated. In addition, the performance of various QR topologies, in terms of reliability and mean time to failure (MTTF), are compared. In the present study, failure rate of each component is calculated according to [24], [25], and overall reliability performance of the various topologies of QR buck converter is evaluated. For this purpose, the effects of various parameters such as the output power ($P_o$), the input voltage ($V_i$), the output voltage ($V_o$), and time duration ($t$) on the reliability and MTTF of these converters is investigated.
Such analysis provide insight for designers to select the best topology that suits the requirements of their design.

This paper is organized as follows: In section II, operation principles of all four possible configurations of the QR Buck converter is discussed. Then, failure rate of each component and total failure rate of the converter are evaluated in sections III and IV, respectively. Finally, numerical results are presented in section V.

II. OPERATION PRINCIPLES

In this paper, among manifold QR converters, the buck converter is chosen to be analyzed. Depending on the resonant switch network, four different topologies for QR-buck converter is possible: half-wave zero current switching (HW-ZCS), full-wave zero current switching (FW-ZCS), half-wave zero voltage switching (HW-ZVS) and full-wave zero voltage switching (FW-ZVS) [26]. Such circuits are illustrated in Fig. 1.

Fig. 1. Various QR buck converter topologies: (a) HW-ZCS, (b) FW-ZCS, (c) HW-ZVS, (d) FW-ZVS.

Based on analytical principles, the mathematical representation and the tank state plane trajectories are simplified considerably when the waveforms are normalized using the base values as expressed in Table I. The normalized switching frequency, output current and output voltage are defined as $F = \frac{f_{SW}}{f_0}$, $M = \frac{V_o}{V_b}$ and $J_T = \frac{I_o}{I_b}$, respectively, where base values are defined in Table I.

<table>
<thead>
<tr>
<th>Base Parameter</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base impedance $R_b$</td>
<td>$R_0 = \sqrt{L_r/C_r}$</td>
</tr>
<tr>
<td>Base voltage $V_b$</td>
<td>$V_0$</td>
</tr>
<tr>
<td>Base current $I_b$</td>
<td>$I_0 = \frac{V_b}{R_b}$</td>
</tr>
<tr>
<td>Resonance frequency $f_0$</td>
<td>$f_0 = \frac{1}{2\pi\sqrt{L_rC_r}}$</td>
</tr>
</tbody>
</table>

The typical waveforms of the QR-Buck converter resonant tank are illustrated in Fig. 2.

Fig. 2. Typical waveforms of QR buck converter: (a) HW-ZCS, (b) FW-ZCS, (c) HW-ZVS, (d) FW-ZVS.
Depending on $Q_1$ and $D_2$ ON or OFF state, four modes are possible for each of QR buck topologies and the angular lengths of the corresponding subintervals are called $\alpha, \beta, \delta$ and $\xi$ which can be expressed as a function of the normalized output current ($f_p$) in Table II [27].

### Table II. The duration of each subinterval for all QR buck converters

<table>
<thead>
<tr>
<th></th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\delta$</th>
<th>$\xi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HW-ZCS</td>
<td>$f_r$</td>
<td>$\pi + \sin^{-1} f_r$</td>
<td>$\frac{1}{f_r} \left[1 \left(1 - \frac{1}{1 - j f_r^2}\right) \right]$</td>
<td>$\frac{F}{\pi} \left(\alpha + \beta + \delta\right)$</td>
</tr>
<tr>
<td>FW-ZCS</td>
<td>$f_r$</td>
<td>$2\pi - \sin^{-1} f_r$</td>
<td>$\frac{1}{f_r} \left[1 \left(1 - \frac{1}{1 - j f_r^2}\right) \right]$</td>
<td>$\frac{F}{\pi} \left(\alpha + \beta + \delta\right)$</td>
</tr>
<tr>
<td>HW-ZVS</td>
<td>$\frac{1}{f_r}$</td>
<td>$\pi + \sin^{-1} \frac{1}{f_r}$</td>
<td>$\frac{j_f r}{1 + \left(1 - \frac{j_f r^2}{1 - j f_r^2}\right)}$</td>
<td>$\frac{F}{\pi} \left(\alpha + \beta + \delta\right)$</td>
</tr>
<tr>
<td>FW-ZVS</td>
<td>$\frac{1}{f_r}$</td>
<td>$2\pi - \sin^{-1} \frac{1}{f_r}$</td>
<td>$\frac{j_f r}{1 + \left(1 - \frac{j_f r^2}{1 - j f_r^2}\right)}$</td>
<td>$\frac{F}{\pi} \left(\alpha + \beta + \delta\right)$</td>
</tr>
</tbody>
</table>

III. FAILURE RATE CALCULATION

Failure rate of a component during its life cycle typically follows the well-known bath-tub curve in which failure rate is constant during useful life time [28]. With this in mind, failure rate of a component depends on several factors such as material, environmental conditions, quality of manufacturing, operating temperature, voltage stress, etc. which are presented in [24], [25]. In the present paper, such formulas are employed to calculate failure rate of each component. Accordingly, failure rate of each component is evaluated as follows:

$$\lambda_{\text{component}} = \lambda_b \prod_{i=1}^{n} \pi_i \left(10^6 \frac{\text{failures}}{\text{hour}}\right)$$  \hspace{1cm} (1)

where, $\lambda_b$ is the base value of failure rate, and $\pi_i$ are factors that influence failure rates including temperature factor ($\pi_T$), stress factor ($\pi_S$), capacitance factor ($\pi_CV$), application factor ($\pi_A$), quality factor ($\pi_Q$), environment factor ($\pi_E$) and contact construction factor ($\pi_C$). In the following section, failure rate of each type of components is calculated in details.

A. Semiconductor switch

According to [24], failure rate of a MOSFET is evaluated as (2), where $\lambda_b = 0.0012$, $\pi_A = 8$, $\pi_Q = 8$ and $\pi_E = 1$. In addition, temperature factor is calculated as (3), where $T_{J,Q}$ is junction temperature of MOSFET, $T_a$ is ambient temperature, $R_{\theta JC}$ and $R_{\theta CA}$ are thermal resistance of junction to case and case to ambient of the switch, respectively. $P_{\text{loss}}$ is total loss of MOSFET which is the summation of conducted and switching ($P_{\text{sw,Q}}$) losses. The switching loss of a MOSFET for ZCS, ZVS and hard switching configurations can be evaluated as (6), (7) and (8), respectively. In these equations, $R_{\text{DS,on}}$ is the drain-source ON resistance, $t_{on}$ is turn-on delay, $t_{off}$ is turn-off delay, and $C_{\text{oss}}$ is the output capacitance of MOSFET. Moreover, $D$ is the duty cycle of hard switching buck converter. $I_{\text{rms,Q}}$ represents root mean square (RMS) value of switch current which is expressed in Table III.

$$\lambda_{\text{switch}} = \lambda_b \pi_T \pi_A \pi_Q \pi_E$$  \hspace{1cm} (2)

$$\pi_T = \exp \left(-1525 \left(\frac{1}{T_{J,Q} + 273} - \frac{1}{298}\right)\right)$$  \hspace{1cm} (3)

$$T_{J,Q} = T_a + (R_{\theta JC} + R_{\theta CA}) P_{\text{loss}}$$  \hspace{1cm} (4)

$$P_{\text{loss}} = R_{\text{DS,on}} I_{\text{rms,Q}}^2 + P_{\text{sw,Q}}$$  \hspace{1cm} (5)

$$P_{\text{sw,Q}(ZCS)} = \frac{1}{2} f_{sw} V_d^2 \frac{t_{on}}{C_v} + C_{\text{oss}} V_d^2$$  \hspace{1cm} (6)

$$P_{\text{sw,Q}(ZVS)} = \frac{1}{2} f_{sw} I_a^2 \frac{t_{off}}{C_v}$$  \hspace{1cm} (7)

$$P_{\text{sw,Q}(Hard)} = \frac{1}{2} f_{sw} V_d I_a (t_{on} + t_{off}) + C_{\text{oss}} V_d^2$$  \hspace{1cm} (8)

B. Diode

According to [24], failure rate of a diode is calculated as (9); where, $\lambda_b = 0.0038$, $\pi_C = 1$, $\pi_Q = 8$ and $\pi_E = 1$. Temperature factor is calculated as (10), where $T_{J,D}$ is junction temperature of a diode. $T_a$ is ambient temperature, $R_{\theta JC}$ and $R_{\theta CA}$ are thermal resistance of junction to case and case to ambient, respectively. $V_d$ is the stress factor which is defined as the ratio of applied voltage to rated voltage of a diode. Power loss of a diode can be evaluated as (13). $I_{\text{avg,D}}$ and $I_{\text{rms,D}}$ represent average and RMS value of a diode current, respectively, which are defined in Table III. Forward voltage and resistance of a diode in conducting mode is denoted as $V_F$ and $R_F$, respectively.

$$\lambda_{\text{diode}} = \lambda_b \pi_T \pi_S \pi_Q \pi_E$$  \hspace{1cm} (9)

$$\pi_T = \exp \left(-3095 \left(\frac{1}{T_{J,D} + 273} - \frac{1}{298}\right)\right)$$  \hspace{1cm} (10)

$$\pi_S = V_d^{0.43}$$  \hspace{1cm} (11)

$$T_{J,D} = T_a + (R_{\theta JC} + R_{\theta CA}) P_{\text{loss}}$$  \hspace{1cm} (12)

$$P_{\text{loss}} = V_F I_{\text{avg,D}} + R_F I_{\text{rms,D}}^2$$  \hspace{1cm} (13)

C. Resonant & filter capacitor

Based on [24], failure rate of a capacitor is evaluated as (14), where $\pi_Q = 7$ and $\pi_E = 1$. The base value of failure rate can be calculated as (15) and (16) for resonant and filter capacitor respectively, where $C$ is the stress factor and is defined as the ratio of applied voltage to the rated voltage of capacitor. Furthermore, $\pi_{CV}$ is the capacitance factor where $C$ is the capacitance in $\mu F$.

$$\lambda_{\text{capacitor}} = \lambda_b \pi_{CV} \pi_Q \pi_E$$  \hspace{1cm} (14)

$$\lambda_{b-CV} = 0.0086 \left(\frac{S}{0.4}\right)^5 + 1 \exp(2.5 \left(\frac{T_a + 273}{358}\right)^{18})$$  \hspace{1cm} (15)

$$\lambda_{b-CF} = 0.0254 \left(\frac{S}{0.5}\right)^3 + 1 \exp(5.09 \left(\frac{T_a + 273}{358}\right)^5)$$  \hspace{1cm} (16)

$$\pi_{CV-CF} = 1.2 C^{0.095}$$  \hspace{1cm} (17)

$$\pi_{CV-CF} = 0.34 C^{0.18}$$  \hspace{1cm} (18)
TABLE III AVERAGE AND RMS VALUES OF CURRENT FOR RELIABILITY-CRITICAL COMPONENTS OF QR-CONVERTER

<table>
<thead>
<tr>
<th>Converter</th>
<th>$I_{\text{rms},Q1}$</th>
<th>$I_{\text{avg},D1}$</th>
<th>$I_{\text{avg},D2}$</th>
<th>$I_{\text{rms},D2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HW-ZCS</td>
<td>$\frac{2}{\pi}I_0\left(\frac{\pi}{2} + \beta_1 + \frac{\pi}{2} + \frac{\sin\beta_1}{4} - \frac{\sin\beta_1}{4} + 2J_2(1 - \cos\beta_1)\right)$</td>
<td>$\frac{2}{\pi}I_0\left(\frac{\pi}{2} + \beta_1 + 1 - \cos\beta_1\right)$</td>
<td>$\frac{2}{\pi}I_0\left(\frac{\pi}{2} + \beta_1 + 1 - \cos\beta_1\right)$</td>
<td>$\frac{2}{\pi}I_0\left(\frac{\pi}{2} + \beta_1 + 1 - \cos\beta_1\right)$</td>
</tr>
<tr>
<td>FW-ZCS</td>
<td>$\frac{2}{\pi}I_0\left(\frac{\pi}{2} + \beta_1 + \frac{\pi}{2} + \frac{\sin\beta_1}{2} + \frac{\sin\beta_1}{2} + 2J_2(1 - \cos\beta_1)\right)$</td>
<td>$\frac{2}{\pi}I_0\left(\frac{\pi}{2} + \beta_1 + 1 - \cos\beta_1\right)$</td>
<td>$\frac{2}{\pi}I_0\left(\frac{\pi}{2} + \beta_1 + 1 - \cos\beta_1\right)$</td>
<td>$\frac{2}{\pi}I_0\left(\frac{\pi}{2} + \beta_1 + 1 - \cos\beta_1\right)$</td>
</tr>
<tr>
<td>HW-ZVS</td>
<td>$\frac{2}{\pi}I_0\left(\frac{\pi}{2} + \beta_1 + \frac{\pi}{3} + \frac{\pi}{3}\right)$</td>
<td>$\frac{2}{\pi}I_0\left(\frac{\pi}{2} + \beta_1 + \frac{\pi}{3} + \frac{\pi}{3}\right)$</td>
<td>$\frac{2}{\pi}I_0\left(\frac{\pi}{2} + \beta_1 + \frac{\pi}{3} + \frac{\pi}{3}\right)$</td>
<td>$\frac{2}{\pi}I_0\left(\frac{\pi}{2} + \beta_1 + \frac{\pi}{3} + \frac{\pi}{3}\right)$</td>
</tr>
<tr>
<td>FW-ZVS</td>
<td>$\frac{2}{\pi}I_0\left(\frac{\pi}{2} + \beta_1 + \frac{\pi}{3} + \frac{\pi}{3}\right)$</td>
<td>$\frac{2}{\pi}I_0\left(\frac{\pi}{2} + \beta_1 + \frac{\pi}{3} + \frac{\pi}{3}\right)$</td>
<td>$\frac{2}{\pi}I_0\left(\frac{\pi}{2} + \beta_1 + \frac{\pi}{3} + \frac{\pi}{3}\right)$</td>
<td>$\frac{2}{\pi}I_0\left(\frac{\pi}{2} + \beta_1 + \frac{\pi}{3} + \frac{\pi}{3}\right)$</td>
</tr>
</tbody>
</table>

IV. RELIABILITY EVALUATION

Since failure rate of each component in QR buck converter leads to total failure of the system, failure rate of the converter is obtained by adding up the failure rates of components. Hence, considering constant failure rates, failure rate of the converter can be expressed as (19). It is worth mentioning that the case of failure of the inductor is neglected, since the inductor is the component with the lowest failure rate compared to other components. For the power semiconductors, both failure mechanisms, i.e., open circuit and short circuit, result in failure of total converter.

$$\lambda_{\text{total}} = \lambda_{Q1} + \lambda_{D1} + \lambda_{D2} + \lambda_{cr} + \lambda_{cf}$$  \hspace{1cm} (19)

The reliability of the converter can be defined as (20), where $R(t)$ is the probability that the converter will not fail at time $t$.

$$R(t) = \exp(-\lambda_{\text{total}}t)$$  \hspace{1cm} (20)

Furthermore, MTTF metric of the converter is defined as (21), based on [28].

$$\text{MTTF} = \int_{0}^{\infty} R(t) dt = \frac{1}{\lambda_{\text{total}}}$$  \hspace{1cm} (21)

V. NUMERICAL RESULTS

In this section, effects of variation in several parameters on the reliability of each converter is analyzed. These parameters include output power, input voltage and output voltage. To obtain numerical results, a QR buck converter with input voltage of 50 V, output voltage of 24 V and output current of 2 A is considered. Design parameters of both topologies are as follow: $L_f = 0.5$ mH, $C_f = 47$ µF, $L_r = 2$ µH and $C_r = 75$ nF for ZCS, and $L_r = 200$ µH and $C_r = 82$ nF for ZVS configurations, respectively. The MOSFET is IXFH60N60X3 with $R_{DS,on} = 50$ mΩ. Other parameters of the semiconductors are as follow: $V_{F,D1} = 0.9$ V, $V_{F,D2} = 0.7$ V, $R_D = 25$ mΩ, $t_{on} = 20$ ns, $t_{off} = 100$ ns and $C_{oss} = 1000$ pF.

A. Variation of output power

The output voltage and the input voltage of the converter is assumed to be constant, while the load is variable. Since the converter operates in a closed-loop manner, the switching frequency changes to ensure a constant output voltage in the entire range of output power. In the case study, the output current changes from 1 A to 10 A, hence the output power varies from 24 W to 240 W. The effect of the output power variation on the reliability at the time $t = 0.5 \times 10^6$ hours and MTTF metrics of all QR converters along with their hard switching parent is depicted in Fig. 3. It is worth mentioning that both ZVS and ZCS operation for the entire range of the output power is guaranteed.

![Fig. 3. Comparison of hard switching with QR converter with respect to the output power: (a) reliability, (b) MTTF metric.](image-url)

As it is evident, the reliability and MTTF of the hard switching is less than all of other QR topologies. Therefore, it is inferred that employing soft switching is an effective solution to enhance the reliability of a converter. The most vulnerable component of a switching converter is the semiconductor switch. As stated in Table III, the RMS of currents in HW-ZCS and FW-ZVS converters are the same. As a result, their power loss and reliability performance are approximately equal. It is obvious from Fig. 2 that, in the ZCS configuration, the peak of switch current and the angular lengths of conducting periods ($\alpha$ and $\beta$) are considerably greater than those of the ZVS-type converter. Therefore, the thermal stress generated by the power loss of ZVS-type converters is greater than the ZVS-type, resulting in better reliability performance of ZVS configurations. To investigate the effect of time duration in this case, a three-
dimensional plot of reliability vs. output power and operation time for HW-ZCS & HW-ZVS converter are illustrated in Fig. 4. One can see that, at any given output power, the reliability decreases as time duration increases.

In this case, the reliability of hard switching converter is almost independent of input voltage, since the thermal stress for this converter only depends on the output current which is constant in this case. On the other hand, to ensure a constant output voltage, the switching frequency increases as the input voltage goes up resulting in decreased reliability of the converter. Three-dimensional plot of reliability vs. input voltage and operation time for HW-ZCS & HW-ZVS converter are depicted in Fig. 6.

**B. Variation of input voltage**

In this section, effect of variation of the input voltage on the reliability and MTTF of QR converter is investigated. The output voltage and the output current are considered constant, and the input voltage varies from 30 V to 100 V. It should be noted that the ZVS and the ZCS are achieved within the entire range of the input voltage. The reliability at the time $t = 0.5 \times 10^6$ hours and MTTF of each converter with respect to the input voltage is shown in Fig. 5.

In this case, the reliability of hard switching converter is almost independent of input voltage, since the thermal stress for this converter only depends on the output current which is constant in this case. On the other hand, to ensure a constant output voltage, the switching frequency increases as the input voltage goes up resulting in decreased reliability of the converter. Three-dimensional plot of reliability vs. input voltage and operation time for HW-ZCS & HW-ZVS converter are depicted in Fig. 6.

**C. Variation of output voltage**

In this section, effect of variation of the output voltage on the overall reliability and MTTF of QR converter is analyzed. Input voltage and load resistance is considered constant (50 V and 12 Ω), and the output voltage varies from 12 V to 50 V. Therefore, the output current is variable. In this case, ZVS and ZCS operation is also achieved within the entire range of the output voltage. The reliability at time $t = 0.5 \times 10^6$ hours and MTTF metric of hard switching and soft-switching buck converter is shown in Fig. 7. Similar to the section V, part A, the thermal stress caused by power loss on the MOSFET rises as the output voltage increases. Hence, the same implications as section V, part A can be made to compare the reliability of hard and soft switching converter, as well as comparison of various soft switching configurations.


