

Article

Quasi-Resonant Converter for Electric Vehicle Charging Applications: Analysis, Design, and Markov Model Use for Reliability Estimation

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Abstract: This article presents a quasi-resonant converter (QRC) with multiple sources. A QRC has many benefits, such as high gain, constant current, and nominal voltage stress on MOSFET, with an up to 49% duty cycle with fewer switches. These features of the converter make it suitable for electrical vehicle (EV) off-board charging, which requires significant voltage gain. As the switch operates under soft switching condition, the converter has reduced power loss, improved efficiency, and increased reliability. To reduce grid dependency, the suggested QRC is housed with a grid and PV at the input ports. The proposed converter is modeled using mathematical equations and examined using the MATLAB platform under different operating conditions. In this work, analysis of the steady state, along with components design, estimation of the voltage and current stresses, are addressed. Further, the reliability of the QRC based on the probability of components failure is carried out using the Markov model. The hardware results are observed to validate the design, operation, efficiency, and suitability of the proposed QRC for EV off-board charging applications. A 400-watt test rig is designed to assess the performance of QRC.



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Keywords: battery charging; converter; electric vehicle; Markov model; quasi resonant

1. Introduction

Electric vehicles and charging stations are being developed in many nations due to environmental degradation and resource shortages. As a result, the automobile industry has started developing electric vehicles powered by clean and renewable sources as an alternative to fossil fuels. Owing to proliferation of electric vehicles (EVs) in large numbers, the charging infrastructure, which plays a critical role in EV system requires further research and development [1–3].

Several configurations have already been suggested for EV charging stations based on factors such as power level, charging time, high gain, and efficiency [4]. An on-board battery charger is extensively used as a charging device in low-voltage home networks and has vehicle-to-vehicle functional ability for roadside charging. Such chargers recharge the EV utilizing low utility power [5–7]. The charging cycle takes around 5 to 10 h, and if the above said chargers which have PV as a secondary source are utilized for charging the battery during daytime hours, the EVs cannot be used on a daily basis. This is a fundamental issue that needs attention when developing charging infrastructure. It is necessary to design appropriate chargers that can speed up charging, while adhering grid regulations. Currently, 400 kW and above off-board DC charging stations are the most common type of fast charging stations [8,9]. Power electronic converters support the main functionalities in such EV charging stations.

Based on the topology converters can be characterized as isolated [10] or non-isolated [11]. Some applications need isolation as part of the safety measures. Transformers are incorporated

to isolate the input and output ports. The voltage gain in isolated converters can be tuned by adjusting the transformer turn ratio [12]. Huge component counts, energy losses, and transformer saturation can degrade the performance of isolated converters. If isolation is not required, a non-isolated single-circuit chopper transfers energy between the source and the load side ports. Conventional transformer-less converters are cheaper, smaller, and more effective than isolated circuits. They have minimal voltage gain. Non-isolated converters with minimum voltage gain have been reexamined in the literature using various developing approaches. A switched inductor [13,14], a switched capacitor [15], interleaved topologies (IL) [16], and lift voltage [17] techniques are commonly utilized to increase converter voltage gain. Resonant converters (RC) [18] have high gain at minimal duty cycle, minimum voltage stress, fewer components, and high efficiency. Figure 1 illustrates the schematic of a multisource non-isolated quasi-resonant converter (QRC). It has two sources, like the grid as the primary source and the PV as the secondary source. From the grid, AC power is converted into DC power by a rectifier and the rectified power is connected to the DC bus. And the secondary source PV is connected to the DC bus through a chopper. The QRC has several fundamental elements, such as inductors, capacitors, a diode, and a MOSFET.

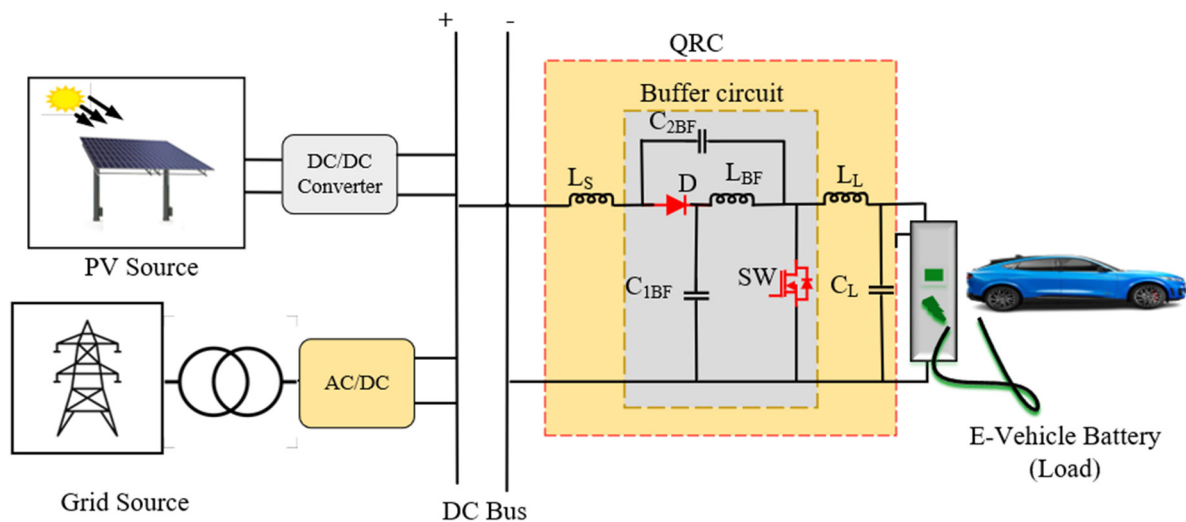


Figure 1. Schematic structure of a QRC.

Several methodologies have been suggested to mitigate the voltage and current stress on the components, as well as to minimize switching losses in converters [18–20]. Paper [21] describes a boost (BoC) converter with a switched inductor that has limited voltage gain, minimal current stress across the inductors, and significant switching stress. To overcome the reduced voltage gain, the paper [22] presents a voltage-lift (VL) switched-inductor dual-leg converter, with continuous current at the output and high gain voltage at a 40% duty ratio for the first and second switches and a 50% duty ratio for the third switch. Comparing the control complexity of proposed converter in [23], which has one switch, to the converter in [24] that has two identical switches having similar duty cycles and a third switch with a different duty cycle, is more complex. Table 1 shows the comparative analysis of the non-isolated converters present in the literature. From the analysis, it can be inferred that the suggested QRC has high gain and minimum components. Therefore, the QRC is suitable for EV charging. The voltage, current, thermal stresses in the MOSFET and the diodes, during the transition from ON and OFF states, damage the devices and shorten their lifespans [25]. This increases the device failure rate, the disaster rate, and requires earlier replacement of converter's internal parts. The bathtub model [26], in Figure 2, is suitable for assessing component failure rates in various applications. Three intermittent zones exist based on the component lifespan in the bathtub curve. These zones contain infant mortality, continual failure, and wear-out. Early device failure is extremely high, resulting in lower

device reliability due to faulty installation, application, or design. Device analysis assumes a constant failure rate during a continual failure period. After a predefined life period, thermal and electrical stresses cause the device to reach the wear-out phase, increasing the failure rate.

Table 1. Comparative analysis of converters.

Converter Topology	Component Count	Specification		Expected Cost
		Frequency	Transformer	Low
BoC [21]	4	10 kHz	No	Moderate
IL [24]	10	20 kHz	No	Low
IL [16]	10	20 kHz	No	Moderate
Suggested QRC	10	20 kHz	No	Moderate

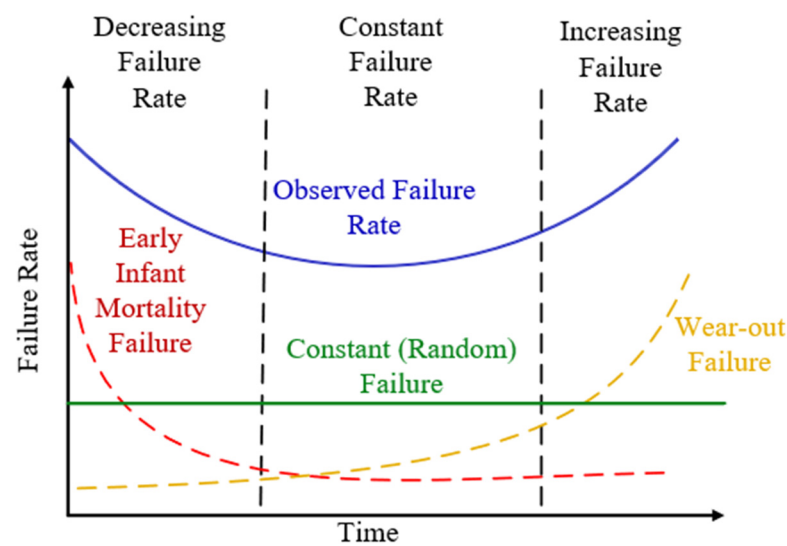


Figure 2. Bathtub curve.

An evaluation of reliability is a type of method that describes the capacity of a component or a system to carry out its intended purpose, in accordance with a predetermined set of conditions over a period. The Markov model and fault traversal algorithm [27] are examples of different probability models that are frequently utilized. The Markov model accurately explains a stochastic process based on the state transition, making it an important tool for reliability analysis of a system that needs to be repaired. It is extensively employed to evaluate and predict system safety [28], and it has a considerable influence on the decision-making process for protecting a piece of equipment's health status. Markov models are incorporated as a key strategy for addressing general probabilistic issues [29] and the reliability assessment of power electronic converters [30–32]. The methods of solving the Markov model include the Markov process and the semi-Markov process. This paper is organized as follows: the operating modes of the QRC, along with the mathematical modeling of converter, are presented in Section 2. Section 3 provides the parametric design details for the proposed QRC. Pulse generation using Xilinx for the prototype QRC is described in Section 4. Power loss analysis and the Markov model of the QRC are evaluated in Sections 5 and 6. The results obtained from the Simulink platform and the low power QRC test rig are illustrated in Section 7. Finally, the inferences from the analysis carried out in Sections 2–8 are consolidated as the conclusions in Section 9.

2. Description, Operating Principle, and Modes of Operation of the QRC

Figure 3 depicts the designed power circuit of the QRC. This circuit contains one power-controlled switch (SW), three capacitors (C_{1BF} , C_{2BF} , and C_L), and three inductors (L_S , L_{BF} , and L_L), in addition to one uncontrolled switch (D). The controlled power switch, SW, transfers power from the grid (primary source) and PV (secondary source) to load (battery) based on the power demand. Consequently, the grid and PV are regarded as input ports, whereas the EV battery is coupled at the output port.

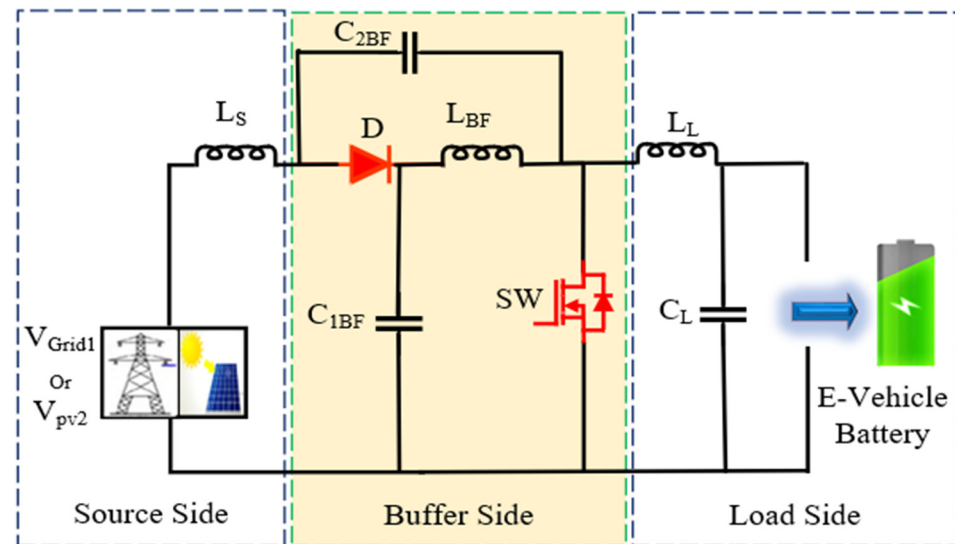


Figure 3. Suggested QRC.

Figure 4 depicts different operating modes and the equivalent circuits for each interval in the operating period of the QRC. Table 2 describes the power transfer in the QRC during various modes of operation. The switch, diodes, capacitors, and inductors are assumed to be lossless components.

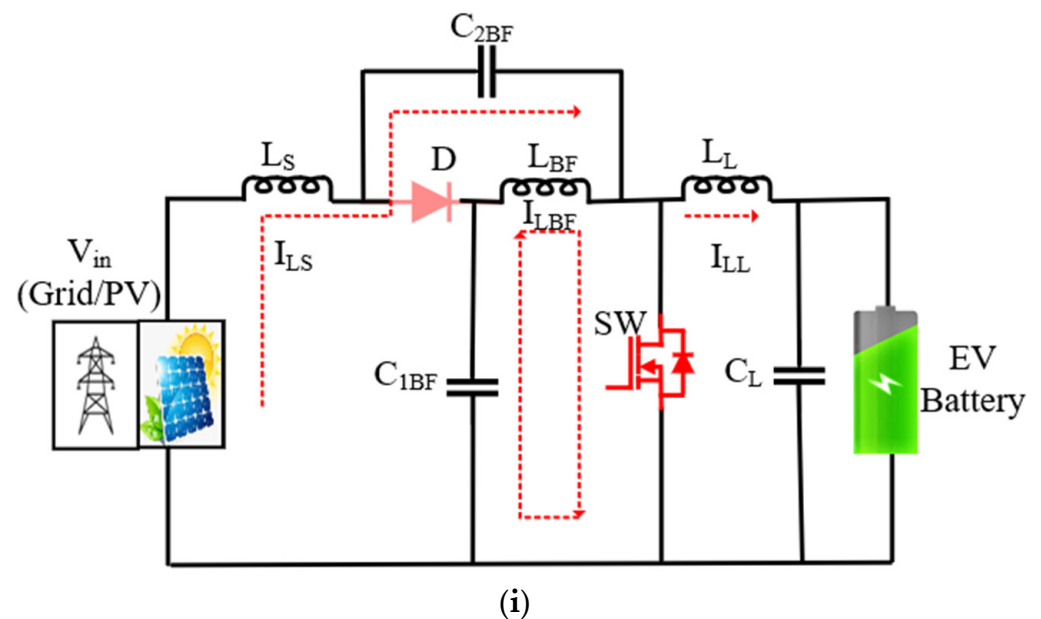
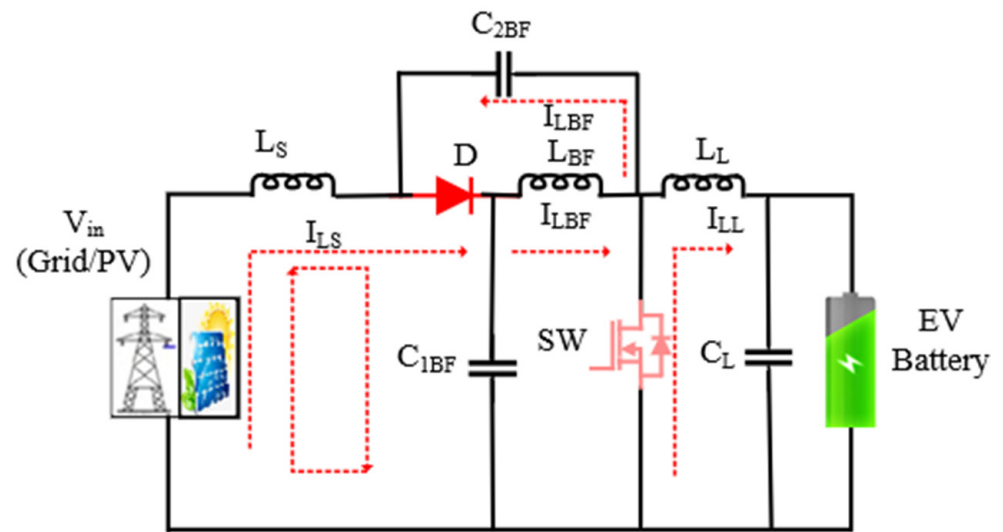
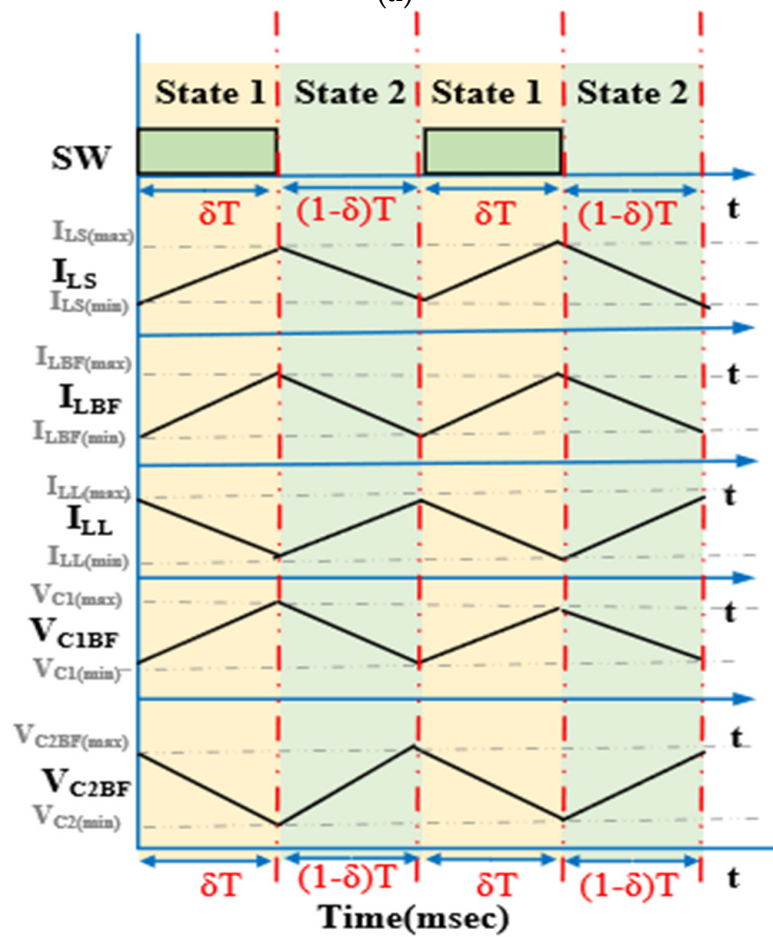


Figure 4. Cont.



(ii)

(a)

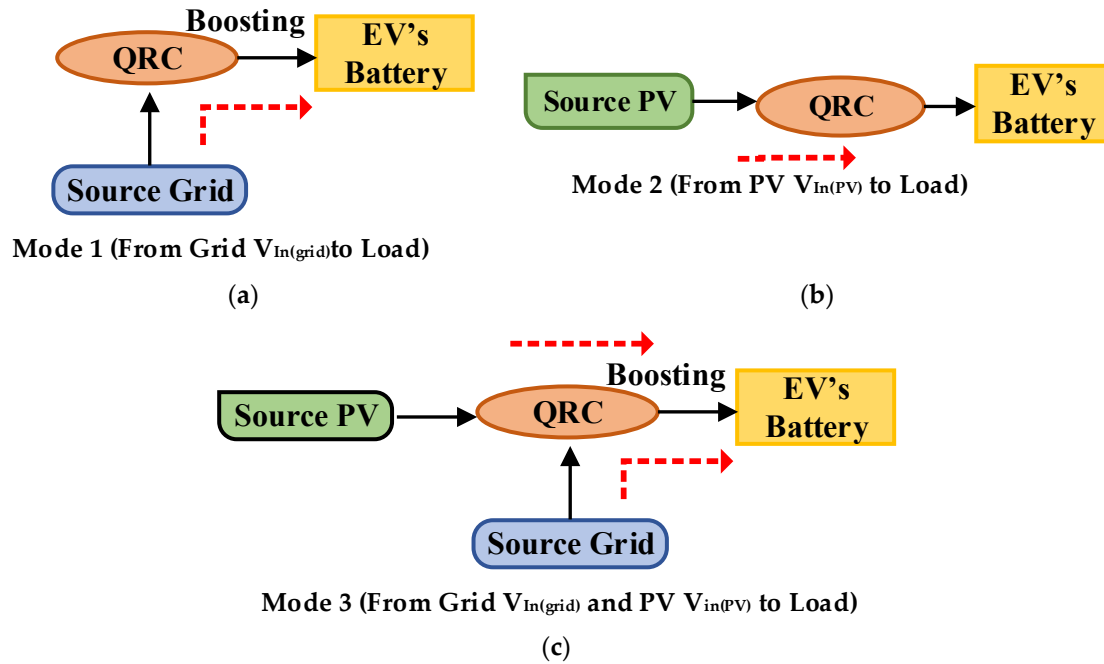


(b)

Figure 4. Operation of the QRC: (a) equivalent circuit diagram, (i) when (Switch S = ON), (ii) when (Switch S = OFF); (b) characteristic waveform.

Table 2. Various operating modes of the QRC.

Mode	Power Flow	Constraints
Mode 1	Figure 5a. Grid to load battery	Grid power is sufficient ($P_{\text{grid}} > P_{\text{bat}}$)
Mode 2	Figure 5b. PV panel to load battery	PV power is sufficient ($P_{\text{PV}} > P_{\text{bat}}$)
Mode 3	Figure 5c. Grid and PV to load battery	PV and grid are sufficient ($P_{\text{grid}} + P_{\text{PV}} > P_{\text{bat}}$)

**Figure 5.** Mode of power transfer operation of the QRC (a) Mode 1 (b) Mode 2 (c) mode 3.

2.1. Operating Principle

State 1: ($0 < T < \delta T$), the switch SW is turned on as depicted in Figure 4a. The current I_{LS} through the inductor L_{S} increases, with a positive slope. The discharging capacitor $C_{2\text{BF}}$ magnetizes the inductor L_{BF} and charges the capacitor $C_{1\text{BF}}$. As a result, inductor L_{L} and capacitor C_{F} are discharging. Equations (1)–(5) represent the operation in state 1.

$$V_{\text{in}} = V_{\text{LS}} - V_{\text{C2BF}} \quad (1)$$

$$V_{\text{LS}} = V_{\text{in}} + V_{\text{C2BF}} \quad (2)$$

$$V_{\text{L2BF}} = V_{\text{C1BF}} \quad (3)$$

$$V_{\text{LL}} = -V_{\text{CL}} \quad (4)$$

$$V_{\text{CL}} = V_{\text{O}} \quad (5)$$

State 2: ($\delta T < T < T$), the switch SW is in the off state as illustrated in Figure 4b. As a result, there is a dip in the inductor current I_{LS} , with a negative slope. The inductor L_{BF} demagnetizes and the capacitor $C_{1\text{BF}}$ discharges. L_{L} and $C_{2\text{BF}}$ charge. The steady state condition of the QRC during state 2 is discussed using Equations (6)–(10).

$$V_{\text{in}} = V_{\text{LS}} + V_{\text{C1BF}} \quad (6)$$

$$V_{\text{LS}} = V_{\text{in}} - V_{\text{C1BF}} \quad (7)$$

$$V_{\text{LBF}} = -V_{\text{C2BF}} \quad (8)$$

$$V_{C1BF} - V_{LBF} - V_{LL} - V_{CL} = 0 \quad (9)$$

$$V_{CL} = V_{CS} - V_{LBF} - V_{LL} \quad (10)$$

The volt-second balance Equations (1)–(10) with respect to the inductor current and the charge-second balance equations with respect to the capacitor voltage are used to calculate the capacitor's voltages and voltage gain (11)–(14).

$$V_{C1BF} = \frac{(1 - \delta)V_{in}}{(1 - 2\delta)} \quad (11)$$

$$V_{C2BF} = \frac{\delta V_{in}}{(1 - 2\delta)} \quad (12)$$

$$\text{Gain } G = \frac{(1 - \delta)}{(1 - 2\delta)} \quad (13)$$

$$V_{bat} = \frac{(1 - \delta)V_{in}}{(1 - 2\delta)} \quad (14)$$

2.2. Modes of Operation

Mode 1—($V_{in(grid)} > V_{in(PV)}$) single input, single output: ($P_{grid} > P_{EV'S Battery}$) Figure 5a depicts the equivalent circuit of the QRC, as well as the power flow schematic while the converter is operating in mode 1. During such conditions, the grid delivers energy individually to charge the EV battery.

Mode 2—($V_{in(PV)} > V_{in(grid)}$): single input, single output: ($P_{PV} > P_{EV'S Battery}$). During the daytime, the PV provides sufficient power to cater to the load demand. This mode delivers energy from PV to the EV battery individually, as depicted in Figure 5b.

Mode 3—($V_{in(PV)} = V_{in(grid)}$): (P_{grid} and $P_{PV} > P_{EV'S Battery}$). When the demand for EV battery power is significant, the grid and PV provide the required energy to meet the EV demand. As depicted in Figure 5c, both the PV and the grid provide energy to the battery in this scenario. During this state, the switch 'SW' is activated.

3. Parametric Design of the Proposed QRC

3.1. Choice of Switches and Diode

The QRC operates under various modes of operation. The power, voltage, and current handling capacities under each operating mode determine which semiconductor switch and diode need to be employed. The power management capability of each mode, namely the peak reverse blocking voltage and peak current, are considered when selecting a MOSFET switch SW with a body diode D for the proposed architecture. Using maximum battery voltage ($V_S = \max(|V_s|, |V_b|)$), the peak voltage rating for the SW is calculated. The peak current rating of the SW is regulated by the peak battery current.

3.2. Inductor

The inductor current ripple is essential for the inductor design. Equation (15) represents the current ripple after taking the voltage across the inductor ' L_S ' into account.

$$\Delta I_{LS} = \frac{V_{in}(1 - \delta)}{(1 - 2\delta)f_{sw}L_S} \quad (15)$$

Inductors are designed to limit twice the magnitude of the ripple current differential. The inductor current I_{LS} should oscillate within 20% of the average current. Equation (16) helps to design inductors L_S by utilizing the appropriate current ripple and volt-sec balancing.

$$L_S = \frac{R(1 - 2\delta)}{X_{LS}\%f_{sw}\delta} \quad (16)$$

where $f_{(sw)}$ represents the switching frequency.

Also, the value of the inductor L_{BF} and L_L are estimated as mentioned by Equation (17).

$$L_{BF} \text{ or } L_L = \frac{R(1-2\delta)}{x_{LBF,L} \% f_{sw} \delta} \quad (17)$$

3.3. Capacitor

The capacitors are considered to limit the change in voltage (ΔV_C), as mentioned by Equation (18). According to an assumption, the permissible value of ΔV_{C1BF} is 20% of the designed average capacitor voltage (V_{C1BF}).

$$\Delta V_{C1BF} = \frac{V_{in}(1-\delta)\delta}{R(1-2\delta)^2 f_s C_1} \quad (18)$$

Using the capacitor charge–sec balance and voltage ripple, the capacitor C_{1BF} is designed. C_{2BF} and C_L capacitor values are designed in a similar way using Equation (19).

$$C_{1BF} = \frac{\delta}{x_{C1BF,C2BF} \% R(1-2\delta) f_{sw} \delta} \quad (19)$$

4. Code Generation Using Xilinx ISE (VHDL)

As shown in Figure 6, with the assistance of FPGA and VHDL coding, Xilinx ISE 14.7 generates the pulse for the QRC. Xilinx ISE 14.7 is suitable for writing VHDL code and feeding it into the FPGA processor. Table 3 provide the parameter details of QRC for both simulation and experimental.

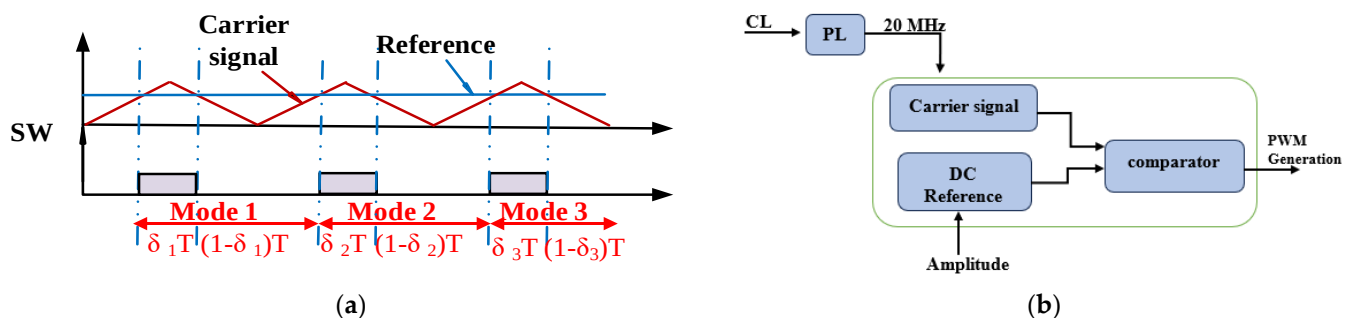


Figure 6. (a) Generation of the pulse at the 0.4 duty cycle. (b) Block diagram of the PWM generation in the FPGA.

Table 3. Parameter details of the QRC.

Parameter Used	Input Voltage V_{in}	Inductors $L_S = L_{BF} = L_L$	Capacitor C_{1BF}, C_{2BF}, C_L	Rating of Load (Battery)	Switching Frequency (fsw)
Simulation	Mode 1—12 V (V_{in1}) Mode 2—12 V (V_{in2}) Mode 3—10 V (V_{in1}) and 10 V (V_{in2})	100 μ H	10 μ F	24.8 V, 8 Ah	20 kHz
Experimental	Mode 1—12 V (V_{in1}) Mode 2—12 V (V_{in2}) Mode 3—10 V (V_{in1}) and 10 V (V_{in2})	122 μ H	12 μ F	24.8 V, 8 Ah	20 kHz

Coding

Figure 7 illustrates the generation of the switching pulse with the 0.4 duty ratio, using VHDL code. The generated switching pulse pattern for the 0.4 duty cycle using PWM techniques in the Xilinx platform is shown in Figure 8.


```

entity pwm is
  Port ( CLK : in STD_LOGIC;
        PWM : out STD_LOGIC);
end pwm;
architecture Behavioral of pwm is
  SIGNAL SA:INTEGER:=0;
  SIGNAL TEMP:STD_LOGIC='0';
begin
  PROCESS (CLK)
  BEGIN
    IF RISING_EDGE (CLK) THEN
      -- no of samples=sampling freq/required freq;
      SA<=SA+1;
      IF SA>=800 THEN --for 0.4 duty cycle
        TEMP<= NOT TEMP;
        SA<=0;
      END IF;
    END PROCESS;
  end Behavioral;

```

Figure 7. Switching pulse using VHDL code.

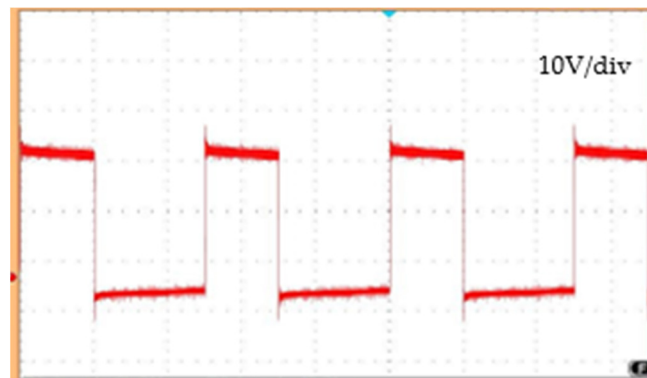


Figure 8. Pulse generated using VHDL code.

5. Analysis and Comparison of the QRC

Power Loss

The following parasitic parameters were evaluated to study the QRC efficiency and reliability: Switch ON—state resistance $R_{DS(ON)}$, r_{FD} —forward resistance (MOSFET), V_T —threshold voltage, I_S —switch current.

The total power loss of the MOSFET SW can be determined by Equation (20).

$$P_{SWMOSFET} = P_{rsL} + \frac{P_{SL}}{2} \quad (20)$$

Equation (21) depicts the formula to evaluate the switch conduction loss (P_{rsL}):

$$P_{rsL} = R_{DS} I_S^2 = R_{DS} \left(\frac{\delta I_o}{(1 - 2\delta)} \right)^2 \quad (21)$$

The QRC switch output current and duty cycle are ' I_o ' and ' δ ', respectively. Equation (22) is used to estimate the MOSFET switching loss (P_{SL}).

$$P_{SL} = f_{sw} C_S \left(\frac{V_{in}}{(1-\delta)} \right)^2 \quad (22)$$

V_{in} , C_S , and f_s are the input voltage, snubber capacitor, and switching frequency respectively. Equations (21) and (22) are substituted into Equation (20) to derive MOSFET power losses is depicted in Equation (23).

$$P_{MOSFET} = 1.02 \text{ W (for } \delta = 40\%, V_{in} = 10 \text{ V)} \quad (23)$$

Table 4 shows the switch's total power loss (P_{MOSFET}) for a constant voltage of 10 V and a variable duty cycle.

The total diode D (P_D) power loss can be determined by Equation (24).

$$P_D = P_{FR} + P_{FV} \quad (24)$$

The diode's 'D' forward resistance loss (P_{FR}) can be calculated by Equations (23) and (24).

$$P_{FR} = r_D I_D^2 = r_D \left(\frac{I_o}{(1-\delta)} \right)^2 \quad (25)$$

where r_D and I_D are the diode resistance and current, respectively.

The forward voltage loss of the diode (P_{FV}) can be computed using Equation (26).

$$P_{FV} = V_D I_D \quad (26)$$

Substituting Equations (25) and (26) into Equation (24), the total power loss of the diode is evaluated using Equation (27).

$$P_D = 0.508 \text{ W (for } D = 40\%, V_{in} = 10 \text{ V)} \quad (27)$$

Table 4. Analysis of the QRC for various duty cycles.

Duty (δ)	Gain	Operating Time	Power Loss
0.1	1.125	0.5×10^{-5}	0.0066
0.2	1.33	1×10^{-5}	0.0342
0.3	1.75	1.5×10^{-5}	0.944
0.4	3	2×10^{-5}	1.022
0.45	5.5	2.25×10^{-5}	2.712

6. Comparative Analysis of Converters

Figure 9 provides the comparative analysis of conventional converters with the QRC, based on the efficiency and duty ratio. Various DC/DC converters' switches, transformers, diodes, capacitors, and inductors need to be considered while designing a charging system. QRC topologies are inexpensive, as they have fewer components than conventional boost converters. BC [27], IBC [30], and ZVS [12] converters are uneconomical because of their high component count and HFT or the need to use many inductors. Voltage gain is also significant in system design. A boost converter is exclusive in that it only needs a conventional control system. The fundamental circuitry is simple and cost effective, but more capacitors increase its size, making it inappropriate for high-power conversion. IBC can provide maximum efficiency at 91% full load and less current ripples, but with high

losses. Also, IBC requires EMI suppression. Table 5 summarizes the comparison of the QRC with various DC/DC converters.

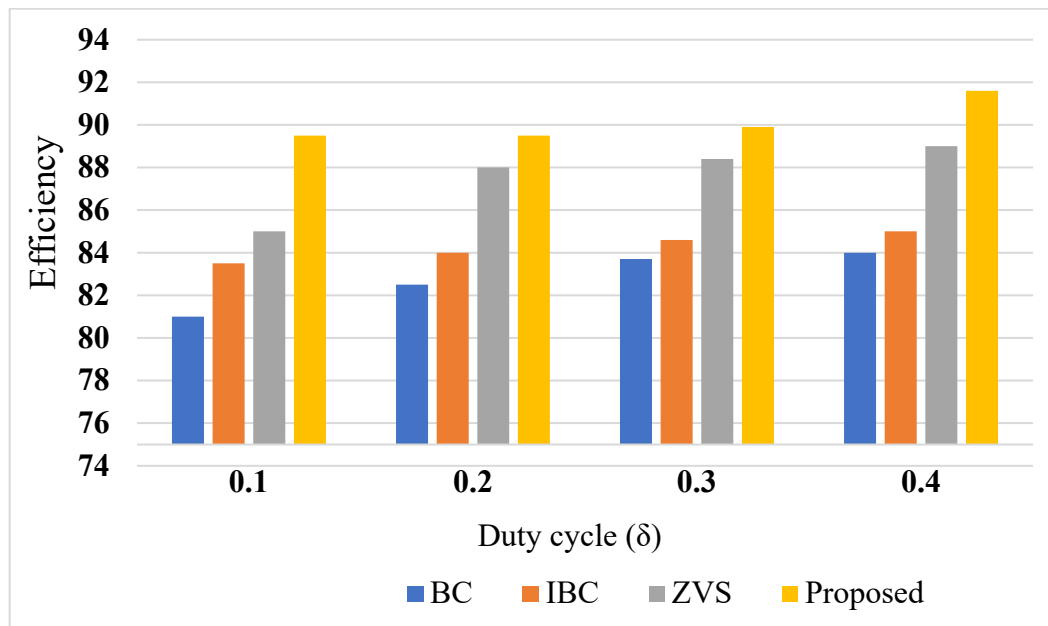


Figure 9. Comparative analysis of the converters.

Table 5. Comparison summary of the QRC with various DC/DC converters.

	Ref [12]	Ref [21]	Ref [24]	QRC
Gain (Voltage)	$\frac{2n}{1-3\delta}$	$\frac{1}{(1-\delta)}$	$\frac{\delta}{(2-\delta)}$	$\frac{(1-\delta)}{(1-2\delta)}$
Voltage stress on MOSFET	$\frac{GV_{in}}{n} \& \frac{GV_{in}}{2n}$	V_o	$\frac{V_{in}}{(2-\delta)}$	$\frac{V_{in}}{(1-2\delta)}$
Stress on diode voltage	$\frac{GV_{in}}{n} \& \frac{GV_{in}}{2n}$	V_o	$\frac{V_{in}}{(1-2\delta)}$	$\frac{V_{in}}{(1-2\delta)}$
Stress on MOSFET current	$\frac{GI_o}{n}$	$\frac{2I_o}{(1-\delta)}$	$\frac{I_o\sqrt{\delta}}{(2-\delta)}$	$\frac{I_o}{(1-2\delta)}$
Stress on diode current	$\frac{GI_o}{n}$	$\frac{I_o}{(1-\delta)}$	$\frac{I_o}{(2-\delta)}$	$\frac{I_o}{(1-2\delta)}$
Isolation	Yes	No	No	No

7. Markov Model for the QRC

The Markov approach is one of the analytical methods for assessing system reliability that has gained acceptance in recent years. The Markov reliability model consists of state-dependent failure rates. In this article, the continuous Markov model is used to determine the reliability performance of the QRC. Figure 10 depicts the corresponding Markov model based on the operation of the QRC under various faults, where the conditions of the QRC are characterized by four operating states. State 1 is a healthy state, state 2 and 3 are derated states, and state 4 is the failure condition of the QRC. The initial and final states represent the healthy and absorbing states, while the middle states represent the derated states. The failure rate of the QRC from state 1 to 2 and 4 are defined in Table 6. In Table 6, λ_{MOSFET} , λ_D , λ_L , and λ_C denote the failure rates of the MOSFET, diode, inductor, and capacitors which are elucidated from the power loss calculations and the MIL-HDBK-217F failure rate equations [30]. In addition, the probabilities of short circuit (SC) failures in each semiconductor MOSFET switch and diode are assumed as α_{SW} (the SC probability of the SW) and α_D (the SC probability of the D), respectively. Based on the research conducted, it is understood that the chance of an SC liability in power electronic semiconductor devices is significantly larger than the probability of an OC fault [23]. As a result, if a switch

or a diode experiences a defect, the probability of having an SC fault or an OC fault are 75 percent and 25 percent, respectively. In addition, components are only susceptible to SC faults because of the operating characteristics, and these assumptions are enforced as λ_{ijs} . Moreover, λ_{ijs} is the failure rate of the QRC in various conditions and states.

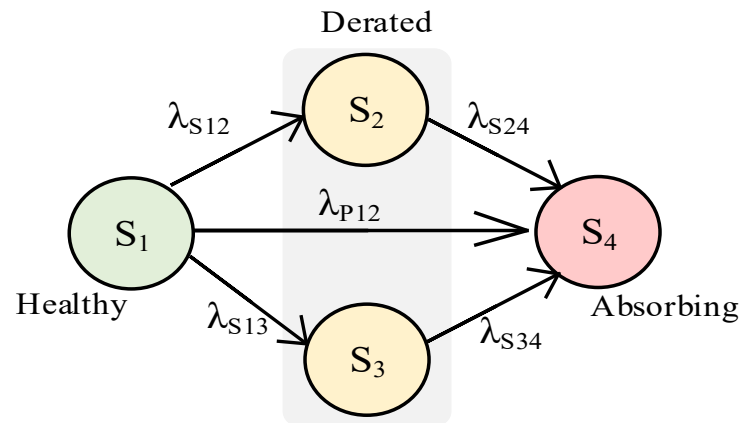


Figure 10. Markov model for the QRC.

Table 6. QRC transition failure rates.

Converter	Failure Rate	Equation	Transition
QRC	λ_{S12}	$(1 + 2\alpha_S)\lambda_{\text{MOSFET}}$	State 1 to 2
	λ_{S13}	$(1 + 2\alpha_D)\lambda_{\text{DIODE}}$	State 1 to 3
	λ_{S14}	$\lambda_{\text{MOSFET}} + \lambda_{\text{CAP}} + \lambda_{\text{DIODE}} + \lambda_{\text{Inductor}}$	State 1 to 4
	λ_{S24}	$\lambda_{\text{CAP}} + \lambda_{\text{DIODE}} + \lambda_{\text{Inductor}} + (1 + 2\alpha_S)\lambda_{\text{MOSFET}}$	State 2 to 4
	λ_{S34}	$(1 + 2\alpha_S)\lambda_{\text{MOSFET}} + \lambda_{\text{CAP}} + \lambda_{\text{Inductor}} +$	State 3 to 4

In accordance with the Markov model in Figure 10, the QRC's reliability performance is equivalent to:

$$R(t) = \sum_{x=1}^S P_x(t) \quad (28)$$

where $P_x(t)$ represents the chance of operating state 1 at time t , and s represents the total number of operating states, which can include both healthy and derated states. To get the value of $P_x(t)$, the equation for a state-space matrix must be taken into consideration:

$$\frac{d}{dt}[P_1(t) \dots P_{S+1}(t)] = [P_1(t) \dots P_{S+1}(t) \times A]$$

$$A = \begin{bmatrix} \lambda_{S11} & \lambda_{S12} & \lambda_{S13} & \lambda_{S14} \\ 0 & \lambda_{S22} & 0 & \lambda_{S24} \\ 0 & 0 & \lambda_{S33} & \lambda_{S34} \\ 0 & 0 & 0 & \lambda_{S44} \end{bmatrix}$$

where λ_{Sxy} ($x \neq y$) is the failure rate from state x to y . Moreover, λ_{Sxy} is defined as the negative sum of the failure rates in row x , and the sum of each row's elements must be equal to zero [28]. The failure probability of each transition is shown in Table 6.

8. Result Analysis for the QRC

8.1. Simulation Results

Simulations were carried out with the help of MATLAB/Simulink. An input voltage of 12 V is considered for the entire period of QRC operation. For the simulation, as depicted in Figure 11a, the grid, PV voltage, and current are $V_g = 12$ V, $V_{PV} = 12$, V and $I_g = 6.8$ A,

$I_{PV} = 6.7$ A. The battery voltage and current are $V_b = 24.8$, V and $I_b = 3.2$ A, respectively. The gate signal and the inductor currents are assumed to be I_{LS} , I_{LBF} , and I_{LL} . The average current through inductors I_{LSavg} , I_{LBFavg} , and I_{LLavg} are 6.8 A, 6.8 A, and 4.2 A, respectively. The capacitor voltages are C_{1BF} and C_{2BF} at a duty cycle of $d = 0.4$.

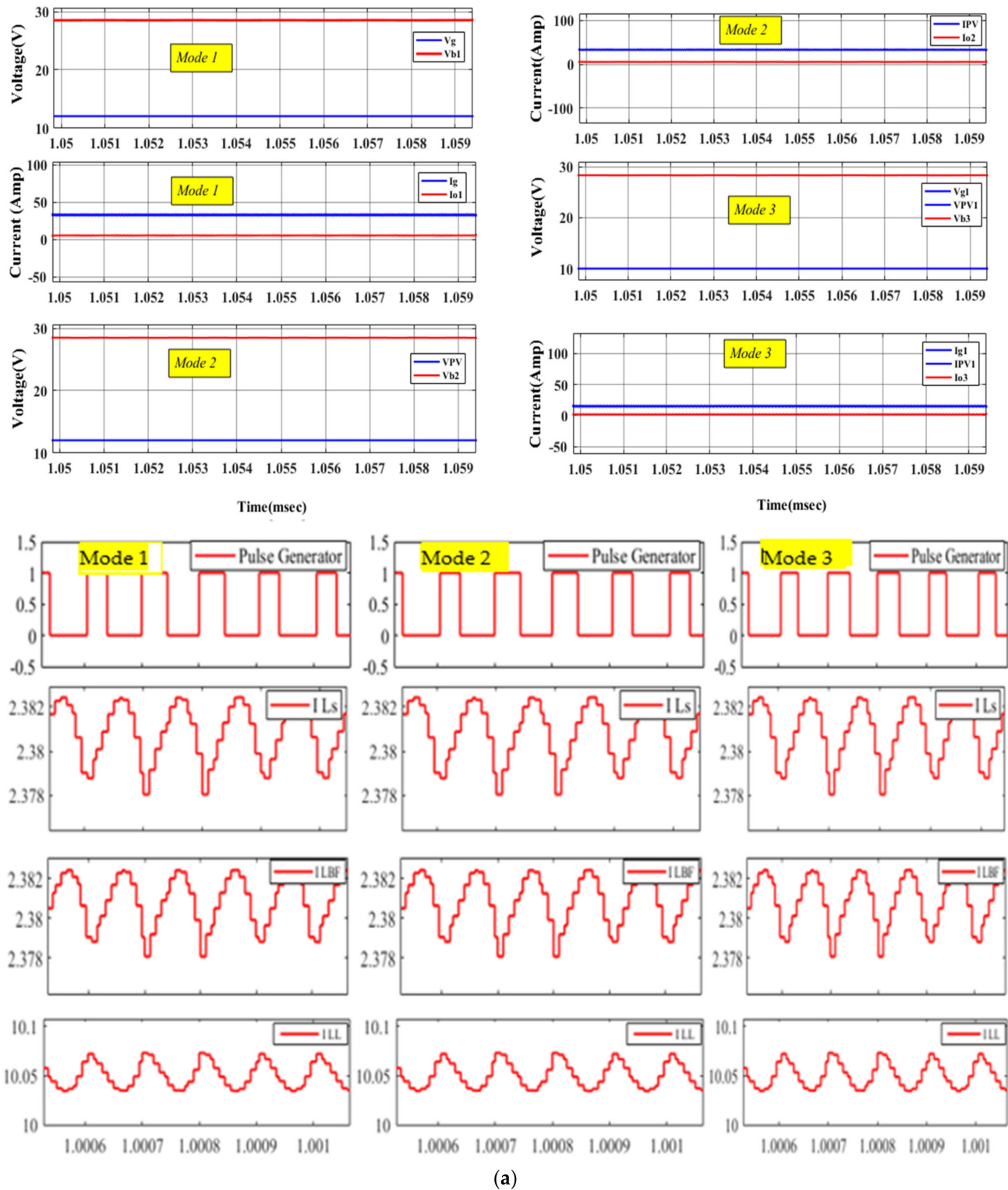
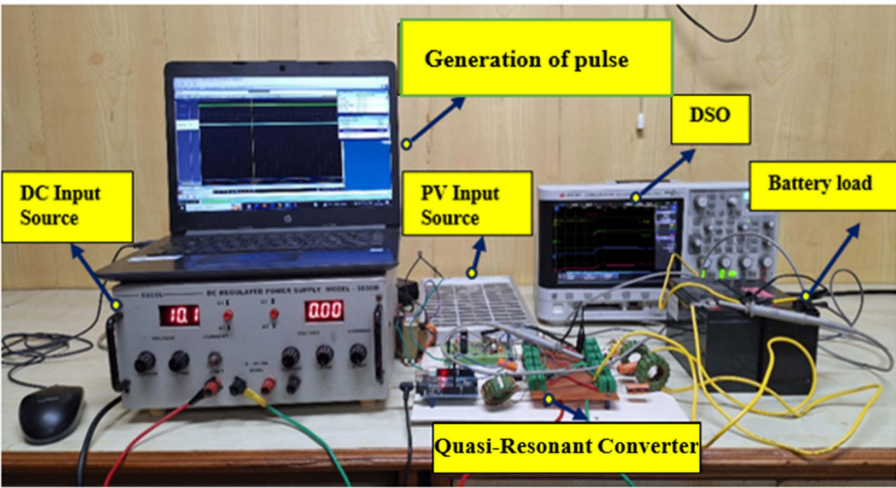


Figure 11. Cont.



(b)

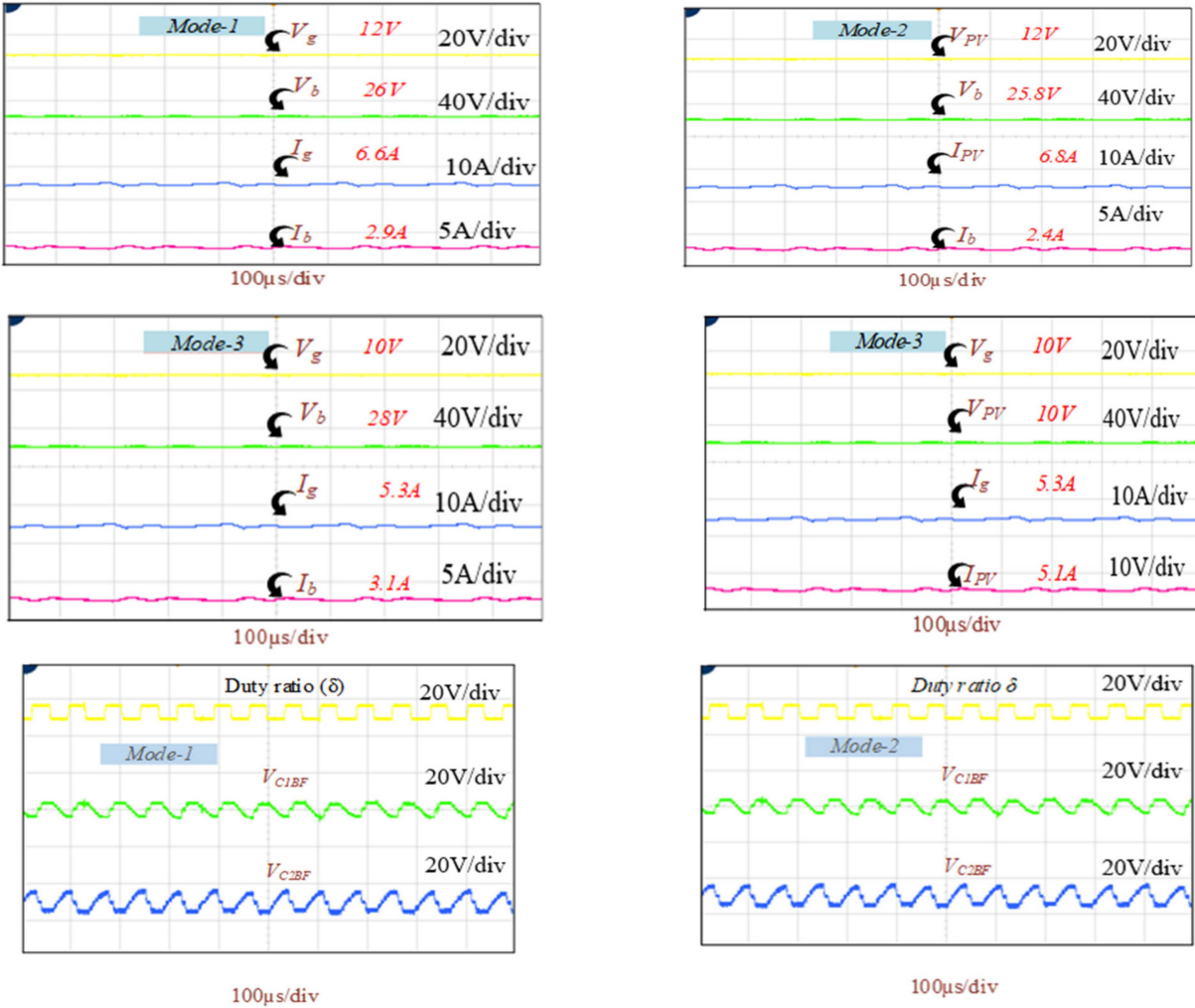


Figure 11. Cont.

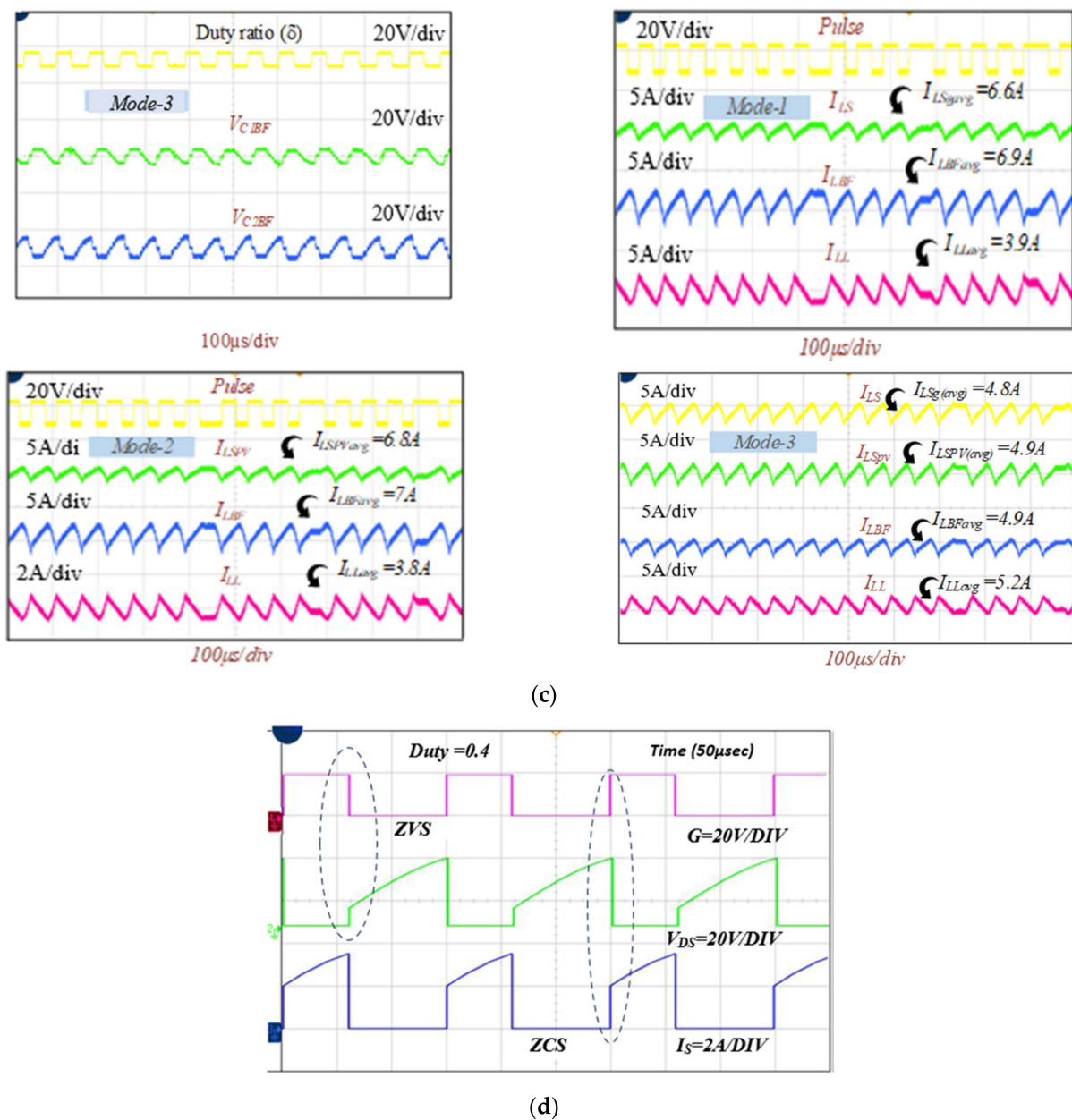


Figure 11. Output voltage of the QRC: (a) simulation, (b) test rig of the QRC, (c) experimental, (d) experimental result for the switch current and voltage.

8.2. Experiment Results

The test rig, shown in Figure 11b, consists of the QRC converter with a PV and a DC supply, along with a battery as the load component. The proposed converter is analyzed under various testing conditions, with an input voltage of 12 V, and the experimental results are presented in Figure 11c.

As depicted in Figure 11c, the grid, PV voltage, and current are $V_g = 12$ V, $V_{PV} = 12$ V and $I_g = 6.6$ A, $I_{PV} = 6.8$ A. The battery voltage and current are $V_b = 24.8$ V and $I_b = 2.9$ A, respectively. The gate signal and the inductor currents are I_{LS} , I_{LBF} , and I_{LL} . The average current of the inductors I_{LSavg} , I_{LBFavg} , and I_{LLavg} are 6.6 A, 6.9 A, and 3.9 A, respectively. The capacitor voltages are C_{1BF} and C_{2BF} at a duty cycle of $d = 0.4$. From Figure 11c, it can be understood that the experimental results are in coherence with the simulation results. However, when the converter operates beyond 0.38, the real-time losses that occur are significant and contribute to the variations in the converter gain. Figure 11d shows the

attainment of ZVS and ZCS of the MOSFET SW. The distribution of the losses in QRC is depicted in Figure 12.

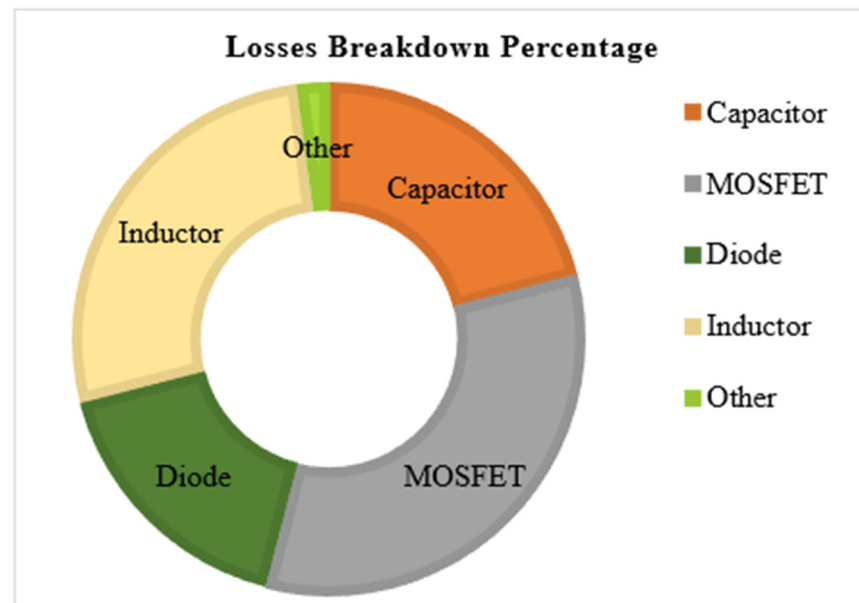


Figure 12. Distribution of the losses (QRC).

9. Conclusions

A quasi-resonant converter is designed and implemented for an off-board charging station to operate with high gain at a low duty cycle and significantly reduce the charging time. The proposed QRC can operate under various operating conditions by utilizing the available sources during charging of the EV battery. Implementation of soft switching to the MOSFET, using the recommended converter, aids in reducing the switching losses. Also, a Markov model has been derived for the purpose of determining the failure rate possibilities of the QRC system. The simulation results in the MATLAB/Simulink platform and test rig results validate the viability of proposed EV off-board charger. A comparison of the QRC with conventional converters demonstrates its efficacy. The analysis of the proposed converter can be extended in future with the execution of the following work:

1. Development of an optimized control strategy (CC-CV) for monitoring EV battery charging;
2. Determination of component failure and reliability of the QRC using the MIL-HDBK-217F military handbook.

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