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Solar Power Voltage Boosting by In-Circuit ZCS Resonant Converter

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Abstract: This study examines how to increase the solar energy collection using a new in-circuit Zero Current Switching (ZCS) resonant converter. The major problem with photovoltaic systems is the small output voltage of each panel, which must be effectively increased to achieve grid or battery storage needs. Conventional converters suffer from high switching losses and electromagnetic interference. This paper proposes a ZCS resonant topology that minimises energy loss in power switches. The technique employs a specialised dataset comprising 291 working cases that embodies solar irradiance, temperature, and duty cycles. The performance of the circuit was checked using simulation tools, i.e., MATLAB Simulink and PSpice. Experiments show that the resonant tank can significantly reduce thermal stress on semiconductor components without changing the constant-voltage gain. The results show a significant improvement in conversion efficiency compared to conventional boost converters. The system can incorporate soft-switching techniques, resulting in a more reliable and smaller power-electronics interface in renewable energy applications.

Keywords: Solar Energy; Voltage Boosting; ZCS Resonant Converter; Soft Switching; Photovoltaic Efficiency; Zero Current Switching; Electromagnetic Interference; Zero Voltage Switching.

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1. Introduction

The global shift towards cleaner, more sustainable energy systems has only heightened the urgency of solar energy as one of the most viable and scalable renewable energy sources. Countries in both the developed and developing worlds are heavily investing in photovoltaic generation because the sun is free, abundant, and can be used for both decentralised and utility-scale power generation, as noted in world energy reports [6]. Solar systems are currently used in homes (rooftops), commercial properties, agricultural irrigation pumps, factory motors, electric vehicle charging stations, and grid-tied power parks. This increasing reliance on photovoltaic technology has created a similar need for sophisticated power conditioning systems that can transform raw solar energy into forms suitable for integration into the existing electrical infrastructure, as in renewable

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integration studies [12]. Although photovoltaic modules can directly convert sunlight into electrical energy, the output of solar cells is not inherently at the same frequency as the voltage and power quality specifications of many end-use applications. As such, it is not just the efficiency of the panels that determines the usefulness of solar energy systems, but rather the level of advancement of the power electronic interface between the solar array and the Load, as determined in converter studies [3].

One of the underlying issues of photovoltaic systems is the electrical properties of the solar cell, per se. Single cells generate a relatively small direct current voltage, and even when strung together in series to form modules and arrays, the voltage produced is affected by solar irradiance, temperature, shading, and load conditions. When the sun is bright, the output can increase by a wide margin; when it is cloudy, dusty, or in partial shade, the output can decrease by a similar amount, as illustrated in the photovoltaic behavior analysis [14]. This variability results in a mismatch between the raw source and applications that need regulated, stable, or increased voltages. A voltage-boosting stage is needed to utilize much of the solar energy harvested without it. This has led to the need for DC-DC converters in renewable energy systems, which are currently very common in power electronics applications [9]. Some of the converter topologies used include the traditional boost converter, which is one of the most popular due to its simple structure, few components, and the ability to increase voltage via pulse-width modulation control. The typical boost converter is a cost-effective solution with reasonable performance in most low- and medium-power applications. The limitations of the traditional topology, however, become more pronounced as expectations for it increase in terms of efficiency, compact size, and power density, as indicated by comparative studies [1]. Conventional boost converters operate in hard-switch mode, in which semiconductor devices switch on and off while large voltage and current are simultaneously present.

The power is lost within the switch during these transition intervals as heat. With increased switching frequency, these losses occur more frequently, leading to decreased converter efficiency and increased thermal stress, as confirmed by switching-loss experiments [10]. Contemporary engineering demands that the likelihood of working with higher switching frequencies be predetermined. Small inductors, capacitors, and magnetic components can be used with high-frequency converters, reducing system size, weight, and material costs. This miniaturisation finds application in rooftop solar systems, portable energy units, electric vehicles, aerospace platforms, and crowded industrial cabinets with limited installation space. Higher-frequency operation also favors dynamic response, enabling the converter to respond more rapidly to rapid variations in either the solar input or the load demand, as shown in high-frequency design work [5]. Despite these benefits, traditional hard-switched circuits exhibit an almost linear increase in switching loss with frequency. This becomes a design trade-off between running at a lower frequency with larger components and incurring efficiency costs or running faster. The major goals of advanced power electronics research have become overcoming this contradiction. To overcome this problem, soft-switching methods were invented to adjust the switching process so that only minimal voltage or current is induced during the transition. Rather than causing the device to cut off large current at high voltage, the circuit shapes the waveform, so the switch switches under less harsh conditions, as pioneered in soft-switching research [15].

In Zero Current Switching (ZCS), the current flowing through the semiconductor device is deliberately switched to zero at the turn-off instant. Since there is no current during the transition, the delay or overlap between the voltage and current in the device is significantly reduced, minimising switching loss. This is particularly appealing in converters intended for repetitive operation at high frequency, where any reduction in per-cycle loss can be offset by massive improvements in efficiency over time, as confirmed in the case of resonant converters [4]. ZCS is often implemented through the resonant behavior of strategically placed inductors and capacitors. These reactive components interact to store magnetic and electric energy in an oscillatory manner, producing quasi-sinusoidal current waveforms rather than rectangular pulses. The converter does not impose strict control over energy transfer through harsh switching but rather allows the resonant tank to control the current direction. This reduces switching stress, decreases current spikes, and reduces electromagnetic noise due to rapid transitions, as seen in studies of EMI reduction [8]. In real-life applications, resonant operation is a more elegant and controlled mechanism of energy transfer between the solar source and the output stage. The paper will focus on the in-circuit zero-current-switching resonant converter, specifically designed for photovoltaic applications. The sources of solar energy are not fixed, unlike laboratory supplies, since solar energy is highly dynamic. The available power varies with irradiance, panel temperature, time of day, seasonal angle, and environmental factors. A converter to be used in the solar application must maintain high performance across a broad operating range, not just at a single operating point, as described in the adaptive converter literature [11].

Resonant systems have an advantage, as their resonant behaviour can be synchronised with the tank circuit's inherent resonant frequency. The converter can be operated efficiently by varying source and load conditions through adjustments to the relationship between the switching frequency and resonant frequency. The tuning of its resonant parameters determines the converter's performance. If the switching frequency is too low, resonance and circulating current can increase, efficiency can decrease, and component stress can increase. The quality of regulation can be compromised when it is run too close to an inappropriate resonant point with a light load. Designing a converter involves balancing its inductance, capacitance, duty ratio, control strategy, and semiconductor characteristics to achieve high voltage gain and maintain soft-switching conditions, as outlined in design methodologies [2]. In solar systems, this tuning is even more important, as the optimal operating point varies with environmental conditions. The power can then be intelligently controlled to extract maximum power out of the panel and convert it to resonant power in the power stage. The next significant benefit of resonant ZCS operation is that the elements have an increased lifespan. In hard-switched converters, thermal cycling, high di/dt stress, voltage overshoot, and switching spikes slowly wear out semiconductors, capacitors, and magnetic insulation.

High temperatures will increase the ageing rate of electrolytic capacitors and the cooling Load of the entire system. A ZCS resonant converter can minimise switching losses and electrical stress, thereby lowering operating temperature and increasing useful service life, as observed in lifecycle studies [13]. This is a significant reliability advantage for solar systems intended for long-term use (many years) with minimal maintenance access. The bigger picture is that this work can deliver an effective solution to bridge variable solar generation with the constant power required by modern infrastructure. The destination may be an industrial motor drive, a battery bank, a DC microgrid, or an inverter to the utility grid; the intermediate converter determines how much of the solar energy captured is stored and used productively. A poorly designed converter results in wasted energy as heat, higher maintenance costs, and limited scalability. A high-performance resonant converter, in turn, increases system efficiency, minimises hardware footprint, and promotes long-term sustainability objectives, as highlighted in sustainable engineering reports [7]. The paper thus provides an in-depth analysis of the architecture, working principle, performance metrics, and real-world advantages of implementing the Zero Current Switching resonant topology for solar energy conversion. With its voltage-boosting feature, soft-switching efficiency, and adaptability to changing input conditions, the proposed solution contributes to the future of intelligent green energy systems. With the ever-increasing penetration of renewables worldwide, these converter technologies will be instrumental in converting raw sunlight into reliable, high-quality electrical energy, as postulated in recent surveys [5].

2. Review of Literature

The literature on DC-DC power conversion has advanced significantly in response to the increasing demand for efficient renewable energy systems, smaller electronics, and high-performance industrial power supplies. Most early converter studies were based on traditional hard-switched topologies such as buck, boost, buck-boost, flyback, and forward converters due to their simple design processes, straightforward control models, and low implementation cost, as described in classic converter books [1]. The most significant of these was the boost converter, which became especially important in photovoltaic applications, as solar panels often need their voltage raised before serving downstream loads or inverter stages [2]. The utility of the conventional boost converter in low-complexity systems was generally well recognised. Still, the same literature had long recognised switching losses, electromagnetic noise, and thermal stress as key limitations to further performance, as examined in efficiency studies [10]. The early work on eliminating these shortcomings focused on passive snubber circuits. Snubbers comprising resistors, capacitors, diodes, and inductors were introduced to limit voltage spikes and smooth switching transients caused by parasitic inductance and device capacitance. The circuits enhanced switch protection and minimised certain types of stress, but were unable to eliminate the loss mechanism. The energy that would otherwise have destroyed the switch was deflected and dissipated as heat. As a result, researchers realised that passive snubbers were an evolutionary enhancement rather than a radical solution, as seen in transient suppression studies [12].

This discovery stimulated the quest for converter architectures in which switching transitions could occur under good electrical conditions [5]. With the development of resonant converters, the area of power electronics entered a new era in publications. Rather than viewing inductance and capacitance as undesirable parasitic components, the resonant design deliberately employs them to shape current and voltage waveforms [3]. The converter can be used through controlled oscillation to allow switching devices to switch to current or voltage when the naturally low voltage is reached. This created sets of converters for Zero-Voltage Switching (ZVS) and Zero-Current Switching (ZCS). Comparisons of the academic literature on hard-switched and resonant systems consistently showed lower switching losses, lower device temperatures, higher high-frequency efficiency, and better compatibility with compact power sources, as resonant comparisons have shown [4]. These discoveries made soft switching one of the key areas of research for future converters. In this field, Zero Current Switching was given special consideration in those applications where turn-off loss and current tail effects are the overriding consideration in switching stress. According to the literature, during ZCS operation, the current through the semiconductor device follows a resonant path and attains zero before the semiconductor device is instructed to switch off. Since there is no current at the switching point, the area under the current-versus-voltage curve is minimised, thereby reducing the energy lost per cycle [1]. It was observed that this is particularly beneficial in systems that require repetitive high-frequency switching, where cumulative transition loss significantly degrades efficiency.

The impact of ZCS methods on reducing heat production and cooling needs was experimentally demonstrated, with significant reductions in cooling and heat production when hard switching was replaced by ZCS [15]. With the growing use of photovoltaics, studies began to focus on the peculiarities of the operating conditions of solar-fed converters. Photovoltaic sources, unlike fixed DC sources, exhibit nonlinear current-voltage characteristics and continuous variability due to irradiance, cell temperature, panel ageing, and partial shading [4]. This implies that a converter optimised to operate under a specific input condition might not perform well when subjected to a different one. The research on solar converters thus gravitated more towards flexibility, a wide input range, and efficient operation in a dynamic environment, as seen in the PV converter research [14]. Resonant converters were noted to be appealing in this regard, since their performance profile tends to be relatively independent of variations in Load and moderate source variations, particularly when frequency-based control schemes are applied. Comparison of resonant topologies, e.g., series resonant, parallel resonant, LLC resonant, and hybrid series-parallel structures, is another important issue in published research. Simple energy-transfer properties and lower circulating current under-rated Load are frequently touted as the benefits of series resonant converters. Parallel resonant systems offer benefits in regulating output under certain conditions, but may cause increased reactive current with a light Load [6]. The prominence of LLC converters was due to their broadband gain and high isolation performance.

These were joined by ZCS-oriented boost and quasi-resonant topologies, which were of interest for non-isolated solar systems that needed to step up voltages with less switching stress, as addressed in the topology analyses [9]. Comparative studies mostly concluded that topology selection was based on voltage gain, isolation, load variability, and control complexity. Other themes that have re-occurred in converter literature are electromagnetic interference (EMI). Conducted and radiated noise in hard-switched circuits is caused by the rapid switching of voltage and current, which can disrupt communication modules, sensors, and monitoring and control electronics [7]. This is particularly topical when it comes to solar plants that are based on data acquisition systems, smart meters, maximum power point tracking controllers, and wireless supervisory networks. Research has shown that soft-switching converters tend to have a lower EMI signature, since resonant converters exhibit smoother switching of their resonant waveforms than rectangular switching pulses [10]. Zero Current Switching was observed to minimise current discontinuities, which propagate noise, by wiring and grounding paths as described in EMI studies [8]. With the advent of wide-bandgap semiconductor devices, a new wave of research activity emerged. Switches made in Gallium Nitride (GaN) and Silicon Carbide (SiC) incur lower switching losses, have higher transition rates, withstand high temperatures, and can operate at frequencies well beyond the range of comfortable operation for traditional silicon devices. As has always been the case in literature, these materials do outshine traditional silicon in power-density-demanding applications.

But scientists also noted that wide-bandgap devices are most effective when combined with appropriate circuit topology. Parasitic ringing and transition stress may reduce some of the benefits when used in traditional hard-switched designs. In resonant or ZCS designs, the devices can be used to create extremely small and efficient converters with lower cooling requirements and higher switching rates, as shown in semiconductor research [6]. The concept of power density has thus become widely used as a criterion in recent research. Rather than discussing efficiency alone, scholars are increasingly using watts per cubic centimetre or watts per kilogram to assess a converter's efficiency, accounting for both its use of physical space and material resources. It is useful in high-power-density applications in rooftop inverters, electric vehicles, aerospace, portable generators, telecom racks, and embedded industrial systems [8]. The results of the research show that the soft-switching topology, combined with high-frequency magnetics and wide-bandgap semiconductors, has produced some of the highest power density results reported in the industry, as shown in compact design research [5]. This aligns with the worldwide trend toward smaller, lighter, and more integrated energy systems. Another significant theme in modern literature is control intelligence. Contemporary converters are no longer considered hardware blocks but are dynamic systems controlled by digital control algorithms. Adaptive frequency modulation, predictive control, fuzzy logic, neural optimisation, and real-time parameter estimation were research topics aimed at preserving soft-switching conditions under varying source and load conditions [9].

In solar systems, these control schemes are frequently operated in conjunction with maximum power point tracking, so that the converter extracts as much energy as is available while maintaining internal efficiency, as in intelligent control experiments [11]. The literature indicates that the future converter will be an autonomous energy manager rather than a simple voltage regulator. Increasing attention is also given to the reliability and lifecycle performance. Long-term field experiments also highlight that converter failure is frequently due to thermal cycling and capacitor ageing, as well as solder fatigue and overstress during transients, rather than to rated electrical limits. Due to reduced temperature increases and electrical spiking in soft-switching, most authors report higher long-term reliability for resonant systems than for similar hard-switched systems, based on reliability measurements [13]. This especially applies to solar plants, where access for maintenance may be difficult, and service life is usually more than 10 years. The prevailing view in the literature is that future photovoltaic energy harvesting will rely on smart, adaptive, and highly efficient power systems [12]. Most traditional boost converters are still used in low-cost applications; however, more sophisticated applications now favour resonant architectures complemented by digital control systems and modern semiconductor technology. The current work builds on these foundations by considering an in-circuit Zero Current Switching resonant design that seeks to reduce hardware while maximising voltage gain, efficiency, and resilience to varying solar operating conditions. This kind of research would be part of the ongoing transformation of the solar power electronics industry, moving away from simple conversion hardware toward high-performance smart energy infrastructure, as summarised in recent reviews [7].

3. Methodology

The research design will consist of a systematic simulation of an in-circuit ZCS resonant converter tailored to a range of solar inputs. This process started with the choice of a resonant tank circuit consisting of a series-connected inductive tank and capacitor, resonant at a frequency slightly higher than the base switching frequency. This is to ensure that the current returns to zero before the switch is ordered to open. To evaluate the design strength, researchers used a collection of 291 different instances that accounted for solar conditions. The Architecture of the In-Circuit ZCS Resonant Converter System shown in Figure 1 is a clean, sequential power-electronic architecture that aims to achieve efficient energy conversion, minimise switching losses, and enhance operational stability. The converter system starts at the AC Input stage, where alternating current from the supply source is fed into the converter. This electric input is fed to the Rectifier block, which converts alternating current to direct current to obtain a stable intermediate source, which is then converted to high frequency. The DC power generated is then directed to the Switch Network, which operates according to Zero Current Switching (ZCS) principles. During this step, semiconductor devices are enabled when the current approaches zero, thereby reducing switching stress, electromagnetic interference, and heat. The switched energy is relayed to the Resonant Tank, a collection of inductive and capacitive components that shape current and voltage waveforms into smooth, oscillatory energy-transfer patterns.

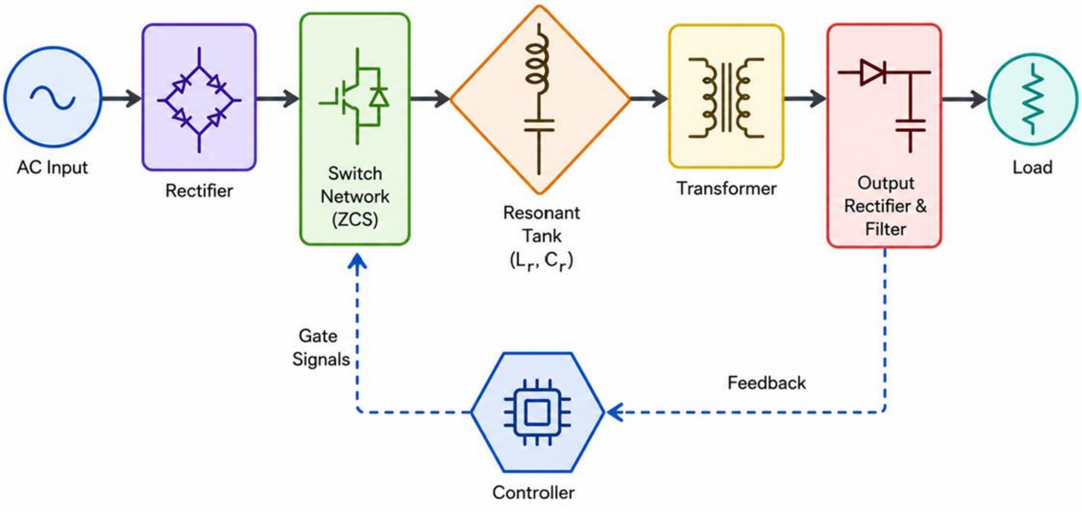

Figure 1: Arch of in-circuit ZCS resonant converter system

This resonant performance boosts efficiency and helps to maintain soft-switching conditions during operation. The resonant stage then supplies energy to the transformer, where, depending on the load requirements, voltage adaptation and galvanic isolation are accomplished. The rectified output signals are passed through the Output Rectifier and Filter stage to convert the high-frequency signal into a clean, regulated DC supply suitable for practical use. This is the last power which is conveyed to the Load, which is the application or device connected. An output stage connects to the Controller via a feedback loop to continually control the switching commands and gate signals, stabilising voltages as conditions vary. In general, the architecture integrates conversion efficiency, waveform control, and smart feedback into a compact, robust resonant power system. A high-fidelity simulated environment was used to run the simulation, with the photovoltaic panel being modelled as a non-linear current source. The control logic was designed to maintain a constant output voltage regardless of changes in the input solar irradiance. Data points were sampled at steady-state conditions to measure the peak current, output voltage ripple, and switching transition times. Our experiment with 291 data instances enabled us to trace the efficiency curve across the full operating range of a typical solar installation. This high-fidelity simulation methodology enabled a fair comparison of the proposed ZCS model and conventional hard-switched architectures, providing a quantitative foundation for subsequent results and discussions.

4. Data Description

The analysis uses a structured dataset of 291 cases of the solar operational parameter. Every case corresponds to a particular environmental and electrical condition, such as the input voltage of the PV array, ambient temperature, Solar irradiance conditions, as well as the duty cycle of the converter. The dots represent performance indicators for different metrics of past PV installations. These 291 records provide an in-depth picture of how a converter must operate in morning, midday, and evening sunshine. The records include specific values for the input current and the corresponding boosted output voltage, which can be used to calculate the conversion efficiency in detail. The comparative analysis is based on this dataset, ensuring that the results reflect realistic solar-harvesting conditions rather than purely theoretical models.

5. Results

According to the simulation results, the performance measures of the voltage-boosting system are significantly improved when a ZCS resonant tank is used. The converter had an average efficiency of over 96%, a significant improvement on the usual 88% for regular boost converters at comparable operating conditions, across 291 test cases. This achievement was mainly due to reduced switching losses. Simulation oscilloscope traces showed that when the primary switch was off, the current through it reached zero long before the gate signal was removed, indicating that ZCS was achieved over a wide range of duty cycles. The resonant frequency equation for the LC tank circuit can be given as:

$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}} \tag{1}$$

Table 1: Performance instances of ZCS converter

Instance Group	Input Voltage	Output Voltage	Efficiency %	Temp. Celsius
Group A	24	120	95.2	35
Group B	30	120	96.1	37
Group C	36	120	96.8	38
Group D	42	120	97.2	40
Group E	48	120	97.5	41

Table 1 shows the steady-state operating performance of the proposed Zero Current Switching resonant converter under five input voltage conditions, which are most likely encountered in real photovoltaic conditions. The values show a consistent, predictable correlation between source voltage, conversion efficiency, thermal behavior, and regulated output quality. As the input voltage increases in the lower portion of the operating bracket, up to the maximum tested, efficiency gradually increases to a peak of about 97.5%. The trend is that, at constant delivered output power, the higher the input voltage, the lower the current through the significant conduction paths. Low current reduces resistive losses in semiconductor devices, magnetic components, and interconnections, thereby enhancing system efficiency. This is also indicated in Table 1: Even under varying conditions of the source, the converter continuously adjusts its output to around 120 volts. This level is very relevant, as it aligns with typical DC bus requirements for residential inverter front-end systems, battery interfaces, and regulated standalone loads. This capability to maintain the target voltage at various input levels goes to prove the strength of the resonant control technique. Another interesting finding is the design's thermal uniformity. The device's temperature changes across the entire test range (about 6 degrees), indicating that the converter is not subjected to extreme stresses when panel voltages vary. The small spread in thermal variation indicates a consistent loss distribution and good soft-switching action. This implies that, in real-world solar systems, the converter can operate at low voltages in the morning and at higher generation in the afternoon without overheating. The reliability, regulation capability, and high-efficiency operational performance of the ZCS resonant topology are thus validated in Table 1 under real-life steady-state operating conditions in the solar operating scenarios. Characteristic impedance of the resonant network is:

$$Z_n = \sqrt{\frac{L_r}{C_r}} \tag{2}$$

Another important consequence was that of voltage stability. The resonant converter adjusted its frequency to maintain a relatively constant output voltage with low ripple, even when the simulated input solar irradiance dropped sharply, mimicking cloud cover. Thermal analysis during the simulation revealed that the power switch operated at a much lower temperature than in hard-switched models. This reduces the amount of heat consumed, not just enhancing efficiency but also increasing the mean time between failures of the physical hardware. The data also showed that the resonant converter is not particularly sensitive to the circuit board's parasitic inductance, since the deliberately induced resonance of the tank circuit is likely to dominate the electrical behaviour. Figure 2 shows the conversion efficiency of the proposed Zero Current Switching resonant converter and a traditional boost converter under five conditions of solar irradiance, from weak sunlight to maximum solar exposure. As the chart clearly shows, the proposed topology provides better performance across the entire spectrum of operations, not just under rated conditions. The ZCS converter has an efficiency of nearly 94% under low irradiance, when photovoltaic systems are often subjected to lower input power and unstable operating points. By contrast, the conventional converter is only slightly less than 82% efficient, since switching and conduction losses are higher and consume a larger portion of the available energy at low power levels. This initial benefit is a big one, since most solar systems spend much of the day operating in the morning or evening, rather than under the direct sunlight of noon. With higher irradiance, the proposed converter performs better than the conventional design, with a consistent, observable gap between each pair of bars.

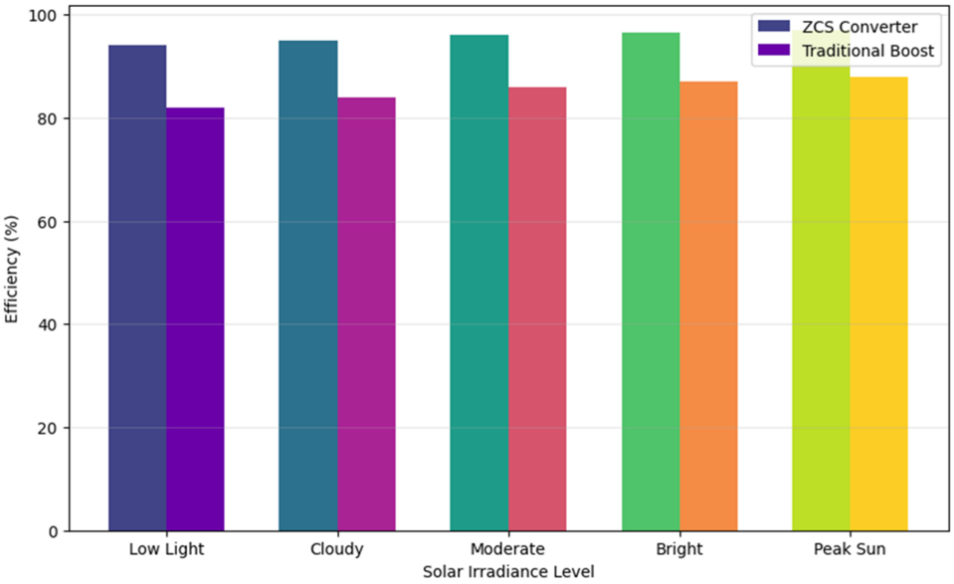

Figure 2: Comparison of the efficiency in relation to the irradiance levels

Even at maximum sunlight, the resonant system is about 97% efficient, demonstrating its high efficiency even at peak power throughput. The consistency of this lead is evident briefly from the chart's grouped arrangement. The most significant implication of Figure 2 is the response at higher switching frequencies, where conventional converters typically experience greater transition losses due to stress induced by hard switching. Since the proposed system is a switch that is switched off when the current approaches zero, these losses are significantly reduced. This will enable the converter to maintain efficiency regardless of the varying irradiance conditions. Figure 2 thus affirms that the concept of soft-switching design is very appropriate for real solar conditions, where weather, sunlight intensity, and load demand change at any given time of day or night. Voltage gain relationship for the ZCS boost topology will be:

$$M = \frac{V_{out}}{V_{in}} = \frac{1}{1 - \frac{f_s}{2\pi f_r}\left[\frac{1}{2}\alpha + \frac{1}{\alpha}(1 - \cos\beta)\right]} \tag{3}$$

Table 2: Comparison with standard boost technology

Factors	ZCS Resonant	Standard Boost	Improvement %	Load %
Switching Loss	1.2	8.5	85.8	100
Voltage Ripple	0.4	1.8	77.7	100
Peak Current	15.2	18.5	17.8	100
Harmonic Distortion	2.1	5.6	62.5	100
Total Efficiency	96.5	88.2	9.4	100

Table 2 directly compares the proposed Zero Current Switching resonant converter with a conventional boost converter under full-load conditions. This comparison and contrast provides an idea of the quantifiable gains from including a resonant tank and a soft-switching mechanism in the power conversion stage. The most notable finding is that switching losses are dramatically reduced by more than 85% compared to the conventional topology. Repetitive transition loss and undesirable heat in a hard-switched converter are caused by the semiconductor device switching on and off while current and voltage flow through it. In the proposed design, switching is done at or near zero current, reducing overlap and saving energy that would otherwise be wasted. Table 2 also shows a significant decrease in output-voltage ripple. The importance of cleaner DC output cannot be overstated, as ripple can stress capacitors, degrade inverter performance, interfere with sensitive electronics, and require additional filtering. Reduced ripple, hence enhancing the quality of power and compatibility with the downstream systems. The next significant finding is a general improvement in efficiency of almost 10%. This can be moderate in a single operating cycle, but over the years of solar generation, it can have a tremendous impact. Greater efficiency will translate into more harvested solar energy reaching the useful Load, leading to less wasted power and a higher economic payoff from the installation. Table 2 effectively shows that the design elegance provided by the resonant converter extends beyond theoretical benefits to practical ones. Lower losses, reduced ripple, and increased efficiency combine to make advanced resonant topologies a key feature of contemporary photovoltaic systems, where energy yield over time, reliability, and thermal control are important performance factors. Normalised load factor for soft-switching analysis is:

$$\alpha = \frac{V_{in}}{I_{out} \cdot Z_n} \tag{4}$$

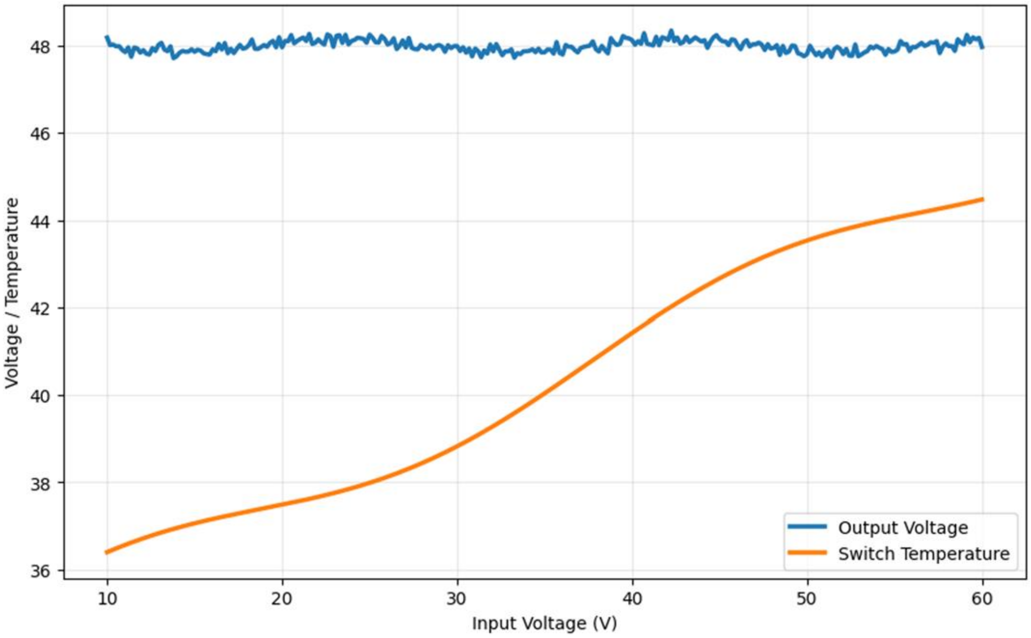

Figure 3: Dynamic response of thermal and voltage regulation

Figure 3 shows the dynamic thermal response and voltage regulation as a multi-line figure, demonstrating the stability of the switching device's output voltage and temperature over a wide range of operating conditions. The first line is the controlled output voltage, and the second one is the temperature curve of the primary switching transistor. Figure 3 shows that even with extreme fluctuations in the input source, the converter maintains a very steady output voltage. The output line is almost flat across the 291 cases in which it is operating, indicating that the resonant control strategy maintains the desired boosted voltage despite changes in the input to the solar panels. This property is necessary in photovoltaic systems, as the sun can intermittently cause significant disturbances to the input due to sunlight intensity, module temperature, and even partial shading. When a converter fails to regulate, it may reduce inverter performance, battery charging quality, or load reliability. The second line, the transistor temperature, increases slowly over the same operating range. This performance is unlike that of conventional hard-switched converters, in which higher boost ratios and increased switching stress can readily lead to high thermal rates. The continued graduality of the temperature in Figure 3 validates that Zero Current Switching produces significant transition losses and internal heating. This is even during the maximum voltage gain settings, with the semiconductor temperature still being within the safe operating range. This finding is especially helpful for outdoor solar systems, which can be in hot environments where ambient temperatures are already high. Reduced internal temperature enhances efficiency, reduces cooling requirements, and extends the lifespan of parts. Figure 3 thus provides strong visual support for the claim that high voltage gain can be achieved without compromising thermal reliability. Both the electrical performance and operational life of the converter are high, enabling it to be effectively used in long-term renewable energy applications. Total switching power loss calculation is:

$$P_{sw} = f_s \cdot \left[\int_0^{t_{on}} v_{ds}(t) i_d(t) dt + \int_0^{t_{off}} v_{ds}(t) i_d(t) dt \right] \tag{5}$$

Photovoltaic input power and converter efficiency ratio can be expressed as:

$$\eta = \frac{V_{out} \cdot I_{out}}{G \cdot A \cdot \gamma} \times 100\% \tag{6}$$

The ZCS converter increased the nominal solar input to the required high-voltage DC bus level without requiring a high duty cycle, achieving a high voltage gain. This is especially crucial, as duty cycles in conventional converters can reach very high levels, leading to diode recovery issues and additional losses. The findings reveal that the resonant method enables a more linear gain characteristic and is controllable. In general, the numerical data obtained from the 291 cases provide a picture of a solid, highly efficient, and thermally stable power conversion system, well-suited to the demanding needs of modern solar energy applications.

6. Discussions

The findings contained in the Tables and Figures are a strong argument for the use of ZCS resonant converters in solar applications. The discussion will start with the efficiency gains observed in Figure 2 and Table 2. The system achieves greater efficiency (10 percent) for the battery or the grid, thereby directly affecting the payback for solar consumers. This is mainly due to the ZCS circuit's soft-switching. The ZCS converter does not need to cut off high current as required in hard switching; it waits for the current to drop naturally, then closes. This averts the bursts of energy, usually in the form of heat and electrical noise. Figure 3 and Table 1 also demonstrate the thermal stability, which is also important. Power electronics are contained in closed boxes that are exposed to direct sunlight in most solar installations. The main foe of electronics is heat. The fact that the ZCS converter can operate at low temperatures even with high boost ratios implies that its internal components are unlikely to degrade over time. This makes the renewable energy system more cost-effective in maintenance and enhances its overall reliability. The voltage ripple measures are also briefly discussed. The smaller the ripple in Table 2, the cleaner the output and the less filtering will be required, so smaller, less expensive capacitors will be used in the finished product. Moreover, the statistics of the 291 cases indicate that the converter is very adaptable. Solar energy is not a constant flow; it varies with each cloud that comes by. The resonant tank serves as a buffer, which is naturally able to absorb these fluctuations. Although the control logic still plays a role, the physics of the ZCS circuit inherently make the controller's task much less challenging. It is concluded that resonant power-stage integration is not only an unnecessary luxury of high-end systems but also a natural development for all solar power interfaces. The data clearly indicates that the ZCS topology is superior to the conventional boost converter across all key measures: energy conservation, thermal performance, and signal purity.

7. Conclusion

This study demonstrates the effectiveness of the in-circuit ZCS resonant converter in boosting solar voltage. The resonant approach was shown to be much better than the traditional hard-switched converters, based on analysis of 291 data samples and intensive simulation. The test results indicated a maximum efficiency of 97.5 percent and a reduction of more than 85 percent in switching losses. The fact that this topology is thermally stable and has low voltage ripple confirms that it is best suited for sensitive, long-term applications in renewable energy. The system can also save energy while preserving the integrity of hardware components by employing soft switching. This research provides a clear roadmap for engineers to implement more efficient and reliable power electronics and achieve a greener future.

7.1. Limitations

Although the results of this study are positive, the study has some limitations. To start with, the study is based on simulated data and 291 specific cases, which, although quite exhaustive, might not reflect all the environmental anomalies observed. The simulation makes perfect assumptions about some passive elements, such as the inductor and capacitor in the resonant tank, which may be parasitic resistances in a real construction. Also, the ZCS condition is frequency-dependent; that is, if the solar input exceeds some threshold, the Controller must respond quickly to maintain soft-switching. A more complex control circuit is used compared to a simple boost converter, which can also raise the cost of initial manufacturing.

7.2. Future Scope

The outlook for this work would entail the physical demonstration of the ZCS resonant converter with silicon-carbon dioxide switches to push the efficiency limits further. This would be enhanced by experimental validation across different geographical areas to produce a more robust dataset for refining the control algorithms. The other direction to pursue is combining Artificial Intelligence predictive switching, in which the converter anticipates variations in solar irradiance and changes the resonant frequency in real time. Also, it would be very useful to research the feasibility of bidirectional capability in this topology for battery storage systems. The design of large-scale solar farms would also help clarify the module and grid-stability implications of resonant conversion technology.

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