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TOPICAL REVIEW

Enhancement of RF-DC Converters Efficiency by Input Impedance Optimization

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ABSTRACT The Internet of Things has transformed modern technology relying on sensors powered by batteries. However, the environmental impact of batteries is a significant concern. This paper explores wireless power transfer as a viable solution to this problem. This study focuses on improving the antenna impedance to maximize the performance of the diode on the WPT receiver. The study was made with a numerical and theoretical analysis, simulations, and experimental validations. Moreover, it was demonstrated that the optimum input impedance is high impedance, approaching an open circuit. The paper concludes that designing RF-DC converters with high source impedance leads to an improvement on the rectifying efficiency.

INDEX TERMS Diode, high impedance, load-pull, rectenna, rectifier, RF-DC converter, source-pull, WPT.

I. INTRODUCTION

The Internet of Things (IoT) has revolutionized the industry of new technologies. Enabling the interaction between machines that rely mainly on sensor data. These sensors are powered by batteries, which are essential for their operation [1], [2]. However, according to [3], in 2050, it is provisioned to consume more than 19 to 50 metric tonnes of batteries per year. This brings an environmental sustainability problem due to the limited and non-renewable nature of the resources and their long decomposition periods, leading to a serious environmental problem [4], [5]. There are already many solutions to this, the reduction of the battery size is one example [6]. However, this approach alone is insufficient. So, a more reliable strategy involves the increase of periodicity and speed of charge to the power unit, with wireless power transfer (WPT) as the most viable solution. Even though WPT is not the fastest charging method, it grants the possibility of eliminating the need for a direct connection to a power outlet, thus improving the portability of the device and enabling continuous charging.

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A WPT system typically consists of a transmitter and a receiver, with the microwave beam between them, as illustrated by Figure 1. The DC-DC efficiency of the overall system depends on the efficiency of each component. Thus, it is very important to maximize the efficiency on every part since the slightest decrease in efficiency in a block can significantly impact the overall system.

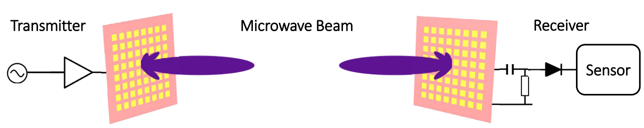

FIGURE 1. WPT's block diagram.

The receiver block is composed of an antenna and a rectifier, also known as a rectenna, which is a concept proposed in 1960 by William C. Brown [7]. Numerous studies are focused on improving the efficiency of the rectifier, For instance, in 2021, N. Shinohara demonstrated that achieving 91 % efficiency in the rectifier was possible by changing the composition of the diode and matching it very carefully to the input impedance [8]. So, the diode is the most critical component in rectennas. An RF-DC converter comprises a matching impedance network, a diode or other rectifier component, and an RC low pass filter with a load. Since the diode is a non-linear component designing a circuit with it is complex. In [9], Z. Popovic analyzed methods to eliminate the harmonics generated by the diode, thereby improving the rectifier's efficiency. Nevertheless, the most important part is the matching impedance network. Depending on the matched impedance at the source, the diode's performance varies significantly.

Designing the matching impedance network often involves simulations to compute the refined stub lengths or component values. Other research suggests using the complex conjugate to match impedance in both sides of the rectifier for the improved efficiency point.

Even though RF circuits typically use the complex conjugate to optimize the performance of non-linear devices, as it is possible to analyze in papers such as [10], [11], and [12], the design of RF-DC converters with diodes requires a different approach. The most common method found in newer studies is to use a source pull simulation to find the best source impedance for the diode used in each RF-DC converter or rectenna. Through the analysis of some papers it is possible to conclude that depending on the diode's configuration, the source impedance should be designed differently. For example, a bridge or shunt configuration performs best with high input impedance, as it is possible to see in some studies, such as [13], [14], [15], [16], [17], and [18], in which the source impedance exceeds 100 Ω. On the other hand, a voltage doubler requires a high input reactance as demonstrated in [19] and [20]. A brief overview of these conclusions can be found in Table 1. Despite the prevalent use of source-pull methods, there remains a need to explain why high impedance or reactance is necessary to achieve the best diode's performance. So, this work presents a study on the impacts of the source impedance on the diode's performance in a single shunt configuration. Moreover, when analyzing this paper, it is important to take into account that the work is focused on low input power. This is due to the diode requiring different impedance values for high power, a study on this can be found in [21].

TABLE 1. Brief overview on the input impedance used in RF-DC converters and rectennas when a source pull method is applied.

Rectifier's configuration	Frequency	Impedance	Efficiency	ref
Single Shunt	915 MHz	$0.94/9°$	40.7 %	[13]
Single Shunt	2.45 GHz	$0.94/24°$	56.2 %	[13]
Single Shunt	900 MHz%	$181 + j375\ \Omega$	70.6 %	[14]
Single Shunt	1.85 GHz	$325 - j57\ \Omega$	65 %	[15]
Single Shunt	1.85 GHz	$349 - j166\ \Omega$	70 %	[15]
Single Shunt	2.4 GHz	$80\ \Omega$	75 %	[17]
Bridge	5.8 GHz	$580\ \Omega$	90 %	[16]
Bridge	2.4 GHz	$670\ \Omega$	81 %	[18]
Voltage Doubler	930 MHz	$20 + j280\ \Omega$	70 %	[19]
Voltage Doubler	860 MHz	$25 + j340\ \Omega$	83 %	[20]

This paper builds on concepts initially introduced in a book chapter from [22], where the basic principles of RF-DC converter design were explored. While the chapter provided an overview of early theoretical analysis and experimental setups, this manuscript follows that work by refining input impedance to improve RF-DC converter efficiency. In this study, new simulations, such as source-pull and load-pull analyses, are applied and experimentally validated. These contributions, which include refined designs and practical implementations, offer novel insights and experimental validation.

This study aims to understand how the source impedance affects the diode's performance, providing a theoretical and experimental analysis on the rectifier's behavior. For this, the diode will be tested in a load/source-pull simulation, in which the source and load impedances will be changed to find the maximum efficiency point. To verify the simulation results, two circuits will be designed and compared: one using the complex conjugate to match the impedance $\Gamma_l = \Gamma_s^*$ and the other using the impedance found theoretically.

This paper is sectioned into five parts. Section II provides the theoretical simulations and studies, including the source/load-pull simulation. Section III presents the designing procedures of a matched impedance and the proposed high impedance converts. Section IV presents the experimental results of the designed circuits and an analysis of the results. Finally, Section V provides some conclusions to this work.

II. RF-DC CONVERTERS DESIGN THEORY

As discussed in the previous section, it is crucial to understand what impacts the diode's behavior. One of the most important design aspects is the matching impedance network or the antenna's output impedance. Some articles suggest the use of the complex conjugate, others rely on the optimization tools available on the simulator, and a few use a source pull method to determine the best impedances.

Nevertheless, none of these methods provide a definitive rule or equation to find the best performance impedance for a given diode. So, this section is dedicated to understanding the best method to design an RF-DC converter. The following subsection is dedicated to understanding the theoretical foundations of rectenna design.

A. CIRCUIT LEVEL DESIGN THEORY: USING IDEAL COMPONENTS

A rectenna is an antenna with rectifying capabilities, comprising an antenna and an RF-DC converter. The performance of the latter is mainly dependent on the diode's behavior.

Diodes are commonly used for rectification due to their minimal amount of parasitic elements, which means, lower losses when compared to other components like transistors. Nevertheless, there are some disadvantages to consider, the main one is the interconnection between its two ports, so changes at one port affect the behavior at the other. So, if the antenna is directly connected to the diode, the antenna must be designed to improve the diode's performance.

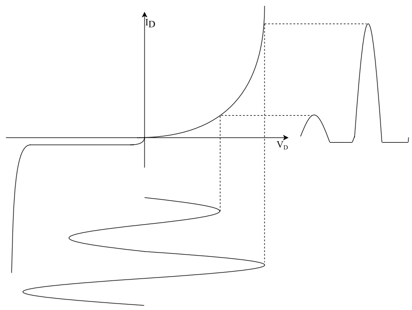

FIGURE 2. Typical diode I-V curve.

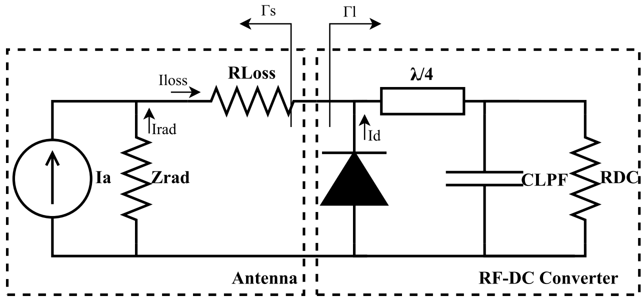

FIGURE 3. Rectenna's circuit schematic.

According to Equation 1, the characteristic curve of an ideal diode is exponential, thus, even a small change in the diode's voltage leads to a significant variation in the current, as illustrated in Figure 2. This characteristic can be used to improve the rectenna's performance in low-power scenarios, providing that the input signal amplitude from the antenna does not reach the diode's breakdown voltage.

$$I_d = I_S(e^{\frac{V_d}{nV_T}} - 1) \quad (1)$$

The basic principle of an antenna, represented as the first block in Figure 3, involves converting an electromagnetic wave into an electric signal. Through the circuit from Figure 3, it is possible to perform a theoretical analysis of how the radiative impedance from the antenna influences the RF-DC converter's efficiency. The rectenna's efficiency dependence on the radiative impedance can be computed by examining a rectenna with a single shunt rectifier configuration and applying equation 2 - 6. As demonstrated in Figure 4, as the antenna's radiative impedance increases, the efficiency also increases, tending to 45 % for 10 dBm input power, given the diode's parameters from Table 2.

$$V_d = V_T * log(\frac{I_d}{Is} + 1) \quad (2)$$

$$I_d(\omega) = I_a(\omega) - I_{rad}(\omega) \quad (3)$$

$$= I_a(\omega) - \frac{P_{in}\sqrt{2}}{I_a(\omega)Z_{rad}}, \; if \; R_{loss} \approx 0 \quad (4)$$

$$P_{diode}(\omega) = V_d(\omega) * I_d(\omega) \quad (5)$$

$$\eta(\%) = 100 * \frac{P_{diode}}{P_{in}} \quad (6)$$

As can be seen from the previous equations, the current and voltage at the diode have a hard non-linear behavior. So, it is expected that the optimum load changes depending on the input signal amplitude. If a pure continuous wave (CW) is applied, a constant load should be used for each input power. However, if the signal is not CW, as shown in Figure 2 the input impedance can also change over time.

To complete this study, the load was also analyzed. This analysis confirms, as expected, that both load and source impedances are interconnected, and changes in one's characteristics affect the other. The study in [23] highlights the importance of finding the best load value in an RF-DC

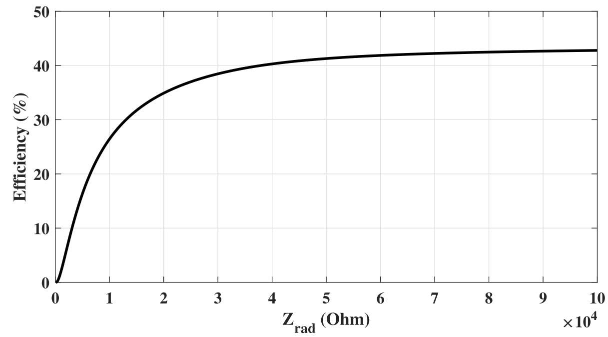

FIGURE 4. Rectenna's efficiency with the antenna's impedance variation. (R_{DC} = 1800 Ω due to the results from Figure 5).

converter, so in this case, and for a 4 $k\Omega$ radiative impedance, the best load value would be 8 $k\Omega$ as shown in Figure 5. Figure 6 illustrates the impacts of the impedance on both ports of the rectifier.

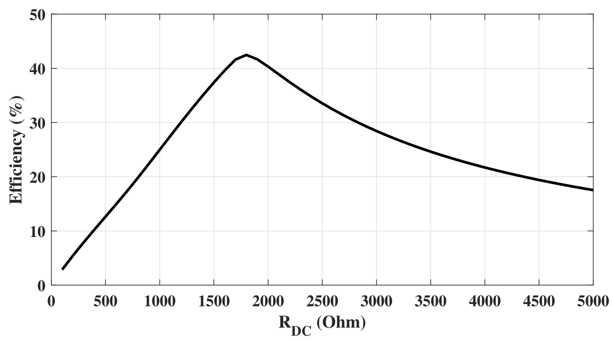

FIGURE 5. Rectenna's efficiency for several values of DC resistor.(Z_{rad} = 4 $k\Omega$).

This theoretical study concludes that for an input power of 10 dBm and shunt rectifier configuration, the best source or antenna impedance is a high impedance with values above 4 $k\Omega$. Regarding the load impedance, a load-pull simulation is always required to achieve the best performance from the diode.

B. DEVICE LEVEL THEORETICAL CONSIDERATIONS - LOAD/SOURCE PULL SIMULATION

This subsection presents a detailed simulation analysis based on the theoretical study from the previous subsection.

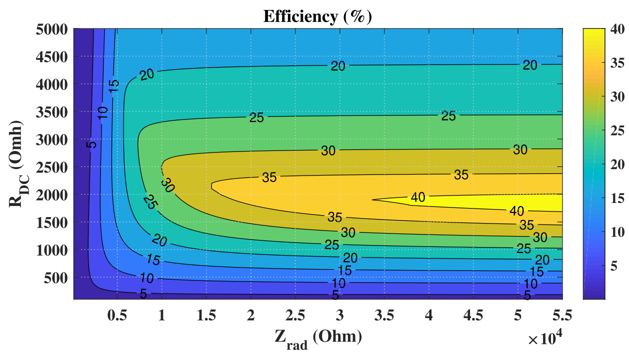

FIGURE 6. Rectenna's efficiency dependency with impedance.

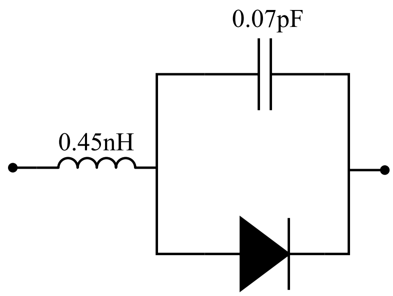

FIGURE 7. Diode SMS7630 electrical model with parasitic elements [25].

Moreover, the advantages of the source-pull / load-pull analysis will be highlighted.

A source-pull / load-pull simulation consists of varying the impedance seen by a component or network while computing the desired output results. These results are compared to find the optimal source and load impedances.

As the main objective of this work is to determine the correlation between the antenna impedance and the rectifier's performance, a source-pull simulation is the most suitable approach.

For a comprehensive analysis, the Skyworks SMS7630-040LF Schottky diode was chosen since it has a fast recovery time, low power consumption, and widespread use in the literature. Table 2 and Figure 7 present the parameters and parasitic components used to model the diode in the chosen simulator, with the intention of having the most reliable results possible.

TABLE 2. Diode SMS7630 Spice parameters [25].

Parameter	Value
Is	5 uA
Rs	20 Ω
N	1.05
Tt	1E-11 s
Cjo	0.14 pF
Vj	0.34 V
M	0.4
Fc	0.5
Bv	2 V
Ibv	1E-4 A
Xti	2
Eg	0.69

To perform an accurate simulation and analysis, Keysight's Advanced Design System (ADS) was used due to its advanced simulation tools and reconfigurable components. As shown in Figure 8, the diode included into an RF-DC converter with input and output impedance blocks (*SnP_Eqn* blocks in ADS) which varied the impedances in fundamental frequency (2.4 *GHz*) and its first three harmonics (4.8 *GHz*, 7.2 *GHz* and 9.6 *GHz*). A Harmonic Balance simulation was used alongside the Parameter Sweep tool to calculate the output efficiency of the overall converter for the various impedance combinations. The impedances Γ_s and Γ_l were obtained through a Large Signal S-Parameters simulation. Figures 9 - 11 show the results of this analysis.

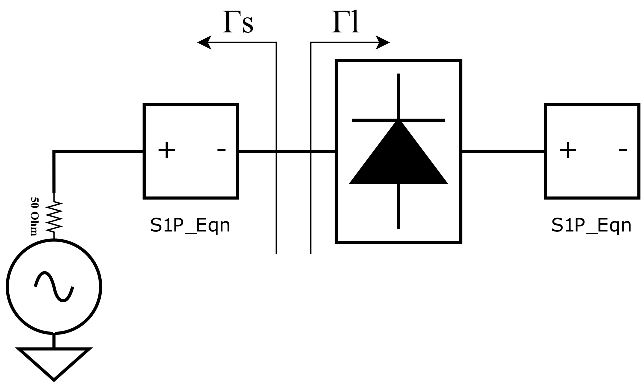

FIGURE 8. Schematic of the load/source pull simulation.

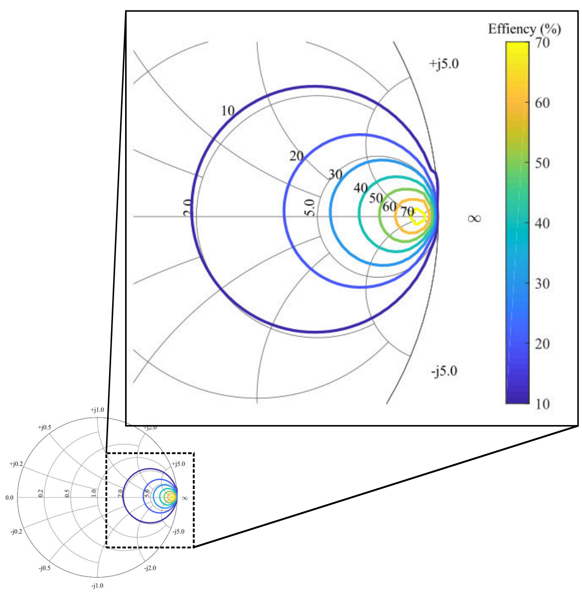

FIGURE 9. Source-pull simulation results for 2.45 *GHz*.

As it is possible to observe in Figure 9, the diode's rectifying behavior improves when the source impedance at the fundamental frequency is as high as possible, approaching an open circuit behavior ($1861.7 + j204.70$), which is in

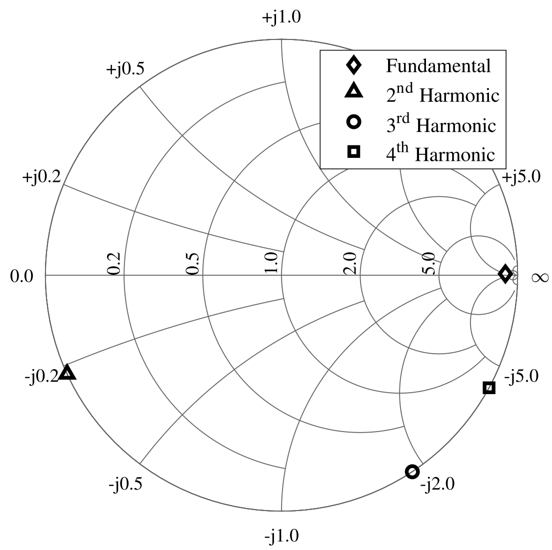

FIGURE 10. Source-pull harmonic simulation results for −5 *dBm*.

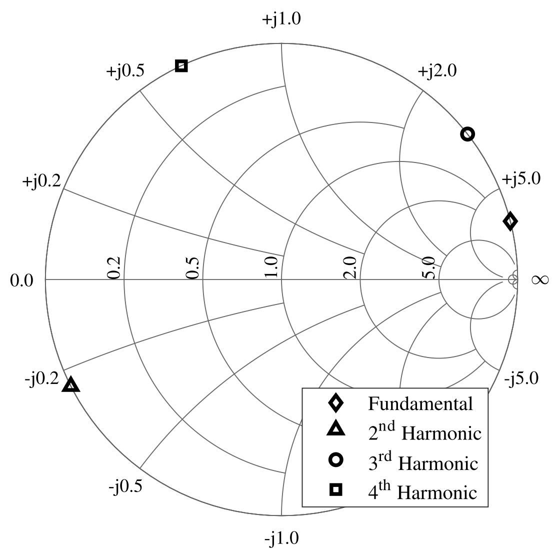

FIGURE 11. Load-pull simulation results for −5 *dBm*.

agreement with what was concluded in subsection II-A. For optimal efficiency, harmonic values should cancel out the intrinsic harmonic content of the diode [24]. In our case, this led us to set the second harmonic to $2.62 \times 10^{-3} - j11$ and the third harmonic to $11.2 \times 10^{-3} - j93.50$, as illustrated in Figure 10. The impact of the harmonics' impedance can be studied in future work since it is also important to understand their impact [24].

On the load side, the refined impedance is $0.15+j397.90$ at the fundamental frequency, as demonstrated in Figure 11. The impedances for the harmonic frequencies can be found in the Smith Chart.

Through the analysis of the source-pull simulation, it is possible to conclude that the diode achieves its peak performance with very high source impedance. This validates that the values and graphs computed in subsection II-A are correct, following the simulations performed with ADS. The next section will extend this analysis to different diodes and will validate this with real design procedures.

III. DESIGNING PROCEDURES

The previous section presented a theoretical and numerical demonstration of determining the improved antenna's impedance. This section applies the theoretical study to a real design procedure for its validation.

To achieve this, the diodes from Table 3 were used to design two circuits at a frequency of 2.4 *GHz* for each diode. One circuit follows the complex conjugate method used in [10], [11], and [12] works. The other circuit implements the impedances computed theoretically in the section II. All RF-DC converters designed in this work follow the block diagram from Figure 12, which includes: a DC pass filter, consisting of a simple RC filter; a single shunt diode converter, chosen for its simplicity; and a matching impedance network to mimic the antenna impedance, which is either employing the complex conjugate or a high-impedance. Due to the purpose of this study being to determine how input impedance affects the diode's behavior, no other improvements to the converter were made through harmonic canceling or other methods.

TABLE 3. List of diodes used in this work.

Diode	Ref
SMS7630	[25]
BAT24	[26]
MACOM MA4E1317	[27]
NSVR201MX	[28]

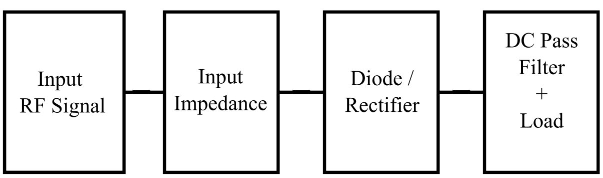

FIGURE 12. RF-DC converter's block diagram.

The SMS7630 diode is used to illustrate the design process of a matching impedance network based on the complex conjugate method, in subsection III-A; and the high input impedance approach, in subsection III-B. The design techniques from these subsections are then extended to other diodes in subsection III-C. Each RF-DC converter is designed using the same process to compare and validate the effectiveness of each design method across different diodes. Subsection III-C ensures a robust validation of the theoretical findings presented in section II.

A. COMPLEX CONJUGATE APPROACH

In the first design, an RF-DC converter was designed with the complex conjugate impedance on either side of the diode. To produce the best results possible the goals implemented in the design were to obtain the best match for the complex conjugate while achieving the best efficiency possible.

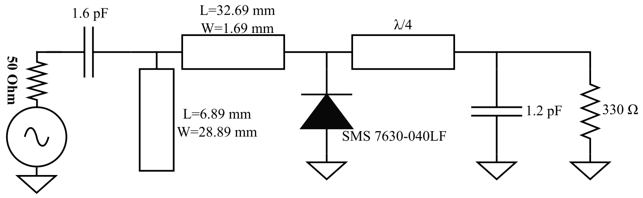

FIGURE 13. Complex conjugate impedance RF-DC converter schematic.

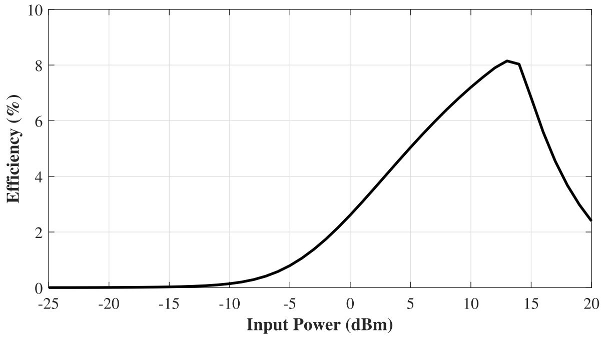

FIGURE 14. Complex conjugate impedance RF-DC converter simulated efficiency.

The designed circuit can be found in Figure 13. To reach the imposed goals the length and width values of the matching impedance network stubs, capacitors, and resistor values were adjusted. The final design is illustrated in Figure 13, with an efficiency of 5% at 5 *dBm* and a peak efficiency of 8.1% at 13 *dBm* (Figure 14). The source impedance is the complex conjugate of the load impedance seen by the diode at 10 *dBm*, as illustrated in Figure 15.

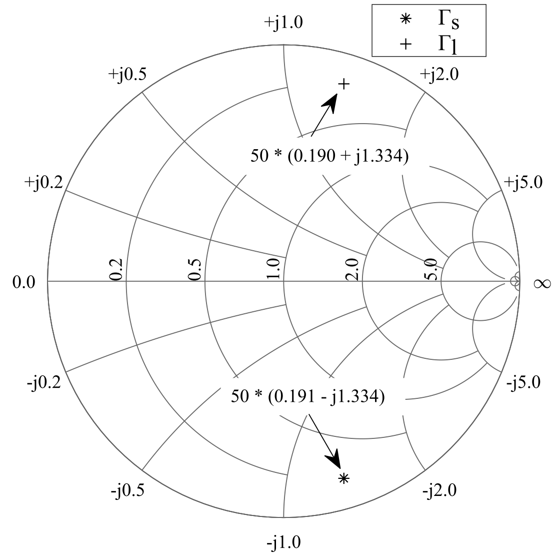

FIGURE 15. Simulated source and load impedance of the diode. (Pin=10 *dBm*).

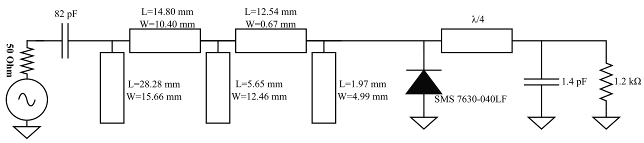

FIGURE 16. High input impedance RF-DC converter schematic.

B. HIGH IMPEDANCE APPROACH

Through the analysis from section II, the antenna needs a high impedance to improve its efficiency. The circuit follows the same structure as Figure 12, however, the matching impedance network transforms the source impedance in the impedance obtained in section II-B.

Using the same approach as in section III-A, an RF-DC converter was designed with the same input impedance as the one obtained in the source pull simulation from section II-B. The main goals of this design were to have the input impedance in the fundamental frequency equal to the one obtained in the source pull simulation and to maximize the circuit's efficiency.

To achieve the imposed goals, the length and width values of the matching impedance network's stubs were adjusted along with the capacitors and resistor values. The designed circuit, illustrated in Figure 16, achieves an efficiency of 35.6% at 0 *dBm* and 21.3% at 5 *dBm* (Figure 17). Moreover, the antenna's impedance is nearly an open circuit at the fundamental frequency (Figure 18), which is very close to the values obtained in the source pull simulation. However, the efficiency obtained did not reach the expectation from the source pull due to the inability to achieve as high an impedance and the fact that the components used in the source pull simulation are ideal, whereas the practical design accounted for losses and parasitic. Nevertheless, this circuit had better results than the complex conjugate approach.

When comparing the simulation results, it is evident that the high-impedance method outperforms the complex conjugate technique. In this case, the high-impedance circuit results are more than four times higher, with the peak efficiency occurring at a much lower input power for an improved performance.

Moreover, when comparing the results from subsection II-A, II-B and III-B, it is evident that the diode performs best with high input impedance, confirming the theoretical analysis that an antenna with high impedance is necessary for peak performance.

C. VALIDATION WITH DIFFERENT DIODES

To complete this analysis, coherence in the results with other diodes has to be established. Figures 19 and 20 present the efficiency of the RF-DC converters designed with diodes from Table 3 and following the design process from subsections III-A and III-B.

The results consistently show that the antenna impedance should be high impedance when using a shunt diode configuration, reinforcing the study from the previous sections.

IV. RESULTS

To experimentally test the simulated circuits and confirm their results, the Isola Astra 3 subtract with a thickness of 0.762mm, a dielectric constant of 3, and a dissipation factor

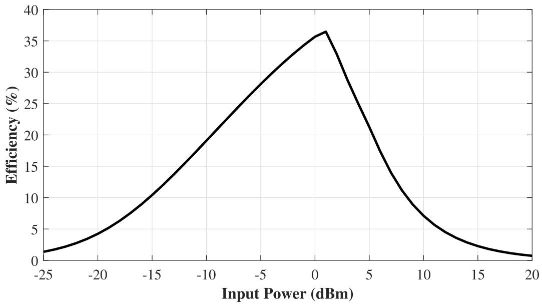

FIGURE 17. High input impedance RF-DC converter simulated efficiency.

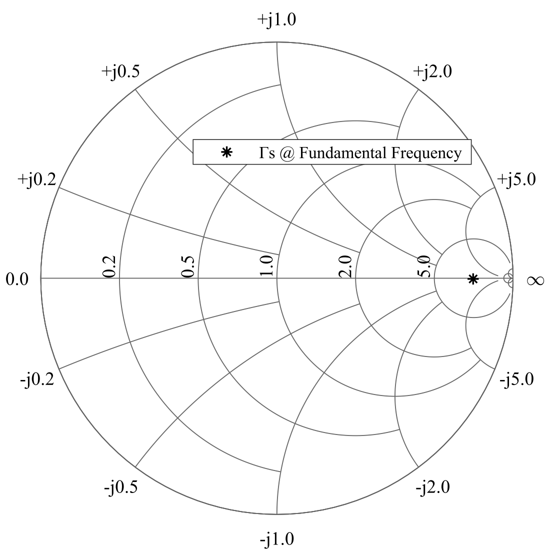

FIGURE 18. Simulated source impedance of the diode.

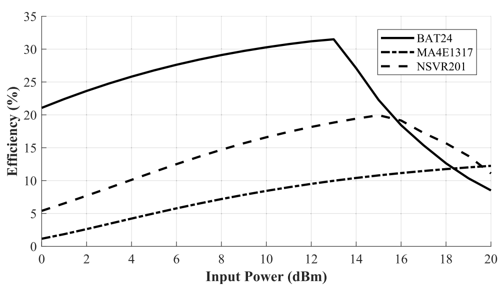

FIGURE 19. Validation of the complex conjugate method through different diodes.

of 0.0017 was chosen. Figure 21 and Figure 22 show the manufactured printed circuit board (PCB) for the complex conjugate converter and high input impedance converters, respectively, for the SMS7630 diode.

The setup (Figure 23) for measuring the output results from the built PCB includes Keysight's PSG vector signal generator E8267D to supply the input signal to the converters, and the multimeter 34461A, also from Keysight, to measure the output voltage. The input signal consisted of an RF CW that varied the power from $-20\,dBm$ up to $20\,dBm$ at $2.4\,GHz$. This range was chosen to analyze the behavior of the converters at both low and high input power.

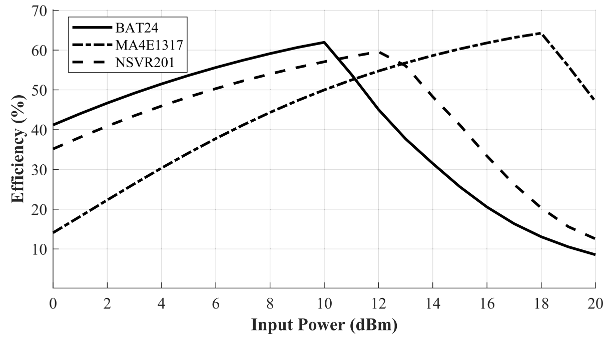

FIGURE 20. Validation of the high input impedance method through different diodes.

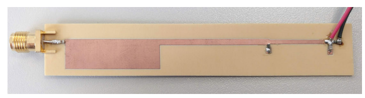

FIGURE 21. Manufactured PCB of the matching impedance converter.

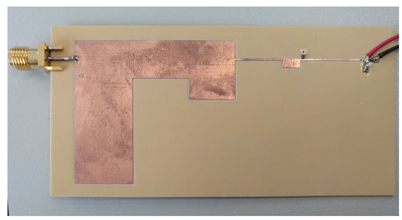

FIGURE 22. Manufactured PCB of the high impedance converter.

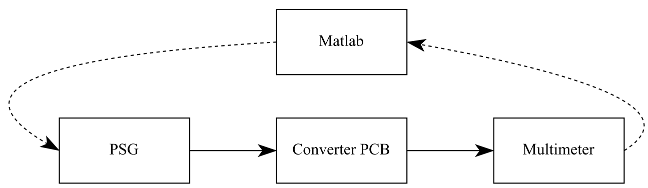

FIGURE 23. Experimental setup.

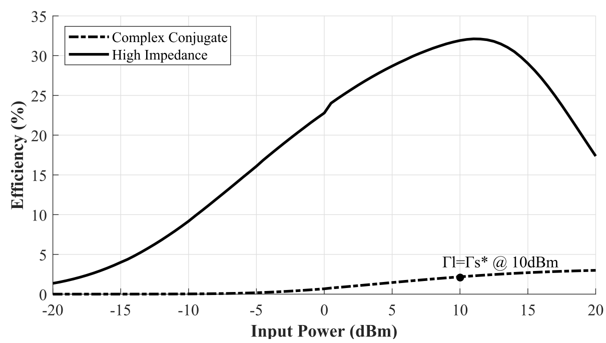

FIGURE 24. Comparison of the efficiency between the two produced circuits.

Figure 24 presents the efficiency of both manufactured rectifiers. The complex conjugate rectifier has an efficiency of 3%, while the high-impedance converter has an efficiency of 33% at $11\,dBm$. These results suggest that the high-impedance method can significantly enhance the rectifying performance of a diode. As explained in section II-A, increasing the impedance of the antenna for a given current results in a higher voltage. Moreover, due to the characteristic curve of the diode, a slight increase in the diode's voltage leads to a significant increase in the current.

Figure 25 shows the manufactured converters designed in subsection III-C. Figure 26 shows the efficiency of all rectifiers. The results validate the study made in this work, showing higher efficiency for RF-DC converters with high impedance at the source.

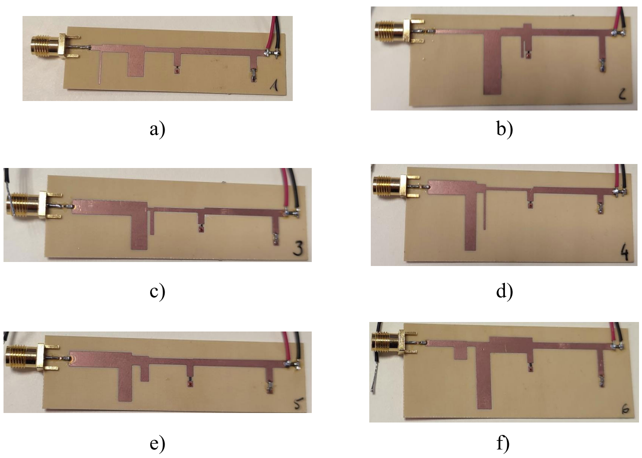

FIGURE 25. Manufactured RF-DC converters using a) BAT24 high impedance; b) BAT24 complex conjugate; c) MA4E1317 high impedance; d) MA4E1317 complex conjugate; e) NSVR201 high impedance; f) NSVR201 complex conjugate.

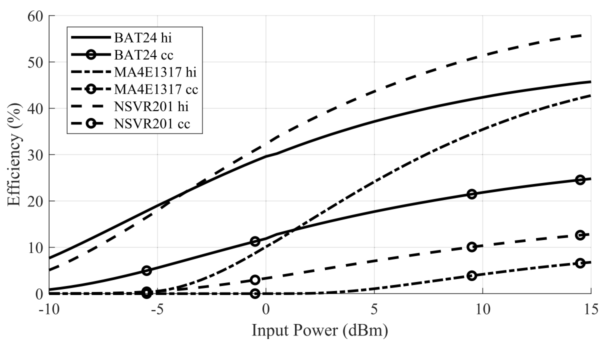

FIGURE 26. Comparison of the efficiency between the manufactured RF-DC converters for different diodes (in which *cc* stands for *complex conjugate* and *hi* stands for *high impedance*).

V. CONCLUSION

This work analyzed the impacts of the antenna's impedance on the diode's performance, through simulation and experimental implementation of design methods. Theoretically, the antenna should have a high impedance to increase the output voltage and improve the diode's performance. The source-pull simulation also provided the same conclusion.

Through the comparison of the RF-DC converters with an input block with high impedance and the complex conjugate impedance it was possible to conclude that the impedance chosen in the input block has a significant impact on the diode's behavior, being the most favorable choice using high impedance.

When comparing the numerical and theoretical studies, source pull simulation, and experimental results it is possible to observe that the results are coherent. To obtain the maximum performance from the diode in a single shunt configuration for low-power the antenna should have high impedance.

The same results were also verified for different diodes available in the market.

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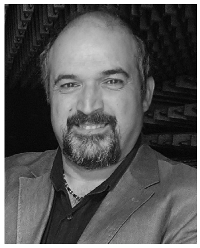

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