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Research Article

The Research on Application of Resistance Compression Network (RCN) in Microwave Rectifying Circuit

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Resistance compression networks (RCNs) have attracted special attention in the field of wireless power transmission (WPT) since they were put forward. A lot of research work has been done in rectifier basing on RCN for the purpose of increasing conversion efficiency. It is reported that many kinds of rectifiers containing RCN which operate in various circuit and physical forms are proposed. RCN and all kinds of modified versions are studied deeply in this paper, the rectifiers related to which are analyzed also. The results show that RCN only plays the role of bandpass filter (BPF) in the rectifying circuit, which does not reach the original idea of the first proposer. We have different understandings of the rectifying circuits presented in other papers.

1. Introduction

WPT is a promising technology that has been refocused again, which has attracted so much attention that it is one of the hot spots in recent years for realizing energy harvesting over distances [1–9]. Due to the increasing demand for efficient and self-service maintenance equipment and the advantages of being able to reach places where the wired power is inconvenient and impossible to reach, this technology has great potential application values. In many fields, various rectification and energy collection schemes have been presented [10–15]. It is an urgent hope to collect RF energy and convert it into DC energy efficiently. Improving the rectifier efficiency is the key to increasing the quality of the WPT system, but it is a significant challenge because of the nonlinear nature of the rectifier which will cause the variations of the input impedance to change with the varying load and input power level.

How to realize impedance matching effectively between the rectenna and the rectifying circuit for achieving maximum power rectifier efficiency is difficult as the change of the surrounding environment. RCN technical was proposed to improve the situation [16]. The designer thinks that RCN can greatly reduce the sensitivity of the rectifier to loading and input power, which can keep the input impedance as a near-constant in order to obtain better impedance matching and realize high conversion efficiency.

In the literature, many designs with RCN that depend on the various application scenarios have been presented. In order to overcome the disadvantages of RCN using lumped elements, transmission resistance compression network (TRCN) was proposed, which was achieved by changing the length of the transmission line [17]. Basing on this research result, a cascade TRCN like a tree structure emerged, which was called multistage TLRCNs [18]. A dual-band RCN was proposed for operating at the dual band not a single frequency previously [19]. Hybrid Resistance Compression Technique (HRCT) aiming at expanding the operating frequency band can be synthesized by RCN and impedance matching networks [20]. In [21], a differential rectifier including differential RCN solves the problem of a single input port and satisfies the need for differential rectenna.

This paper analyzes RCN again and puts forward different views. Starting from the basic calculation method of impedance, RCN is analyzed from different angles again in Section 2, where we have a different understanding of the compression function of RCN. The rectifier [16] is analyzed from two aspects of impedance and efficiency for demonstrating the viewpoint of this paper further in Section 3. Section 4 analyze the rectifier [20] in the same way. We draw conclusions in Section 5.

2. The Analysis of RCN

In order to analyze the compression idea of RCN, we start with a basic example:

For instance, we calculate the impedance in Figure 1.

$$\frac{1}{\mathrm{Zin}} = \frac{1}{-jX} + \frac{1}{R}. \quad (1)$$

In this case, we can learn that when R increases, the reactance element will play a major role. The real part of Z_{in} tends to 0 while the imaginary part tends to a certain value.

Example is as follows. Calculate the input impedance in Figure 2, which is one part of Figure 3.

Where $f = 100$ MHz, $\mathrm{Rl} = 20$ ohm, and $C = 1.9\,\mu$F.

Then we get $Zc = 1/j1193$ and $1/\mathrm{Zin} = 1/20 + j * 1193$ $\mathrm{Zin} \approx 0 + Zc = 0 + 1/j1193$.

From the results above, the real part of Z_{in} tends to be 0 while the imaginary part is decided by reactance component. The change of R_l has little effect on the change of Z_{in}.

Now, we will analyze the RCN theory [16]. The RCN model is illustrated in Figure 4.

Working at the designed operating frequency:

$$\mathrm{Zin} = \frac{2R}{1 + (R/X)^2}. \quad (2)$$

In (2), if $R >> X$, then Z_{in} will tend to 0. If $R = X$, then $Z_{in} = R$.

If R changes within a certain range, the change of Z_{in} will be relatively small. The circuit shows the function of impedance compression in the Figure 4. This conclusion has been given in [1].

If we adjust the reactance component and w_0 is unchanged, as shown in the Figure 5, we will get the following results:

$$\mathrm{Zin} = 2\left(\frac{R}{1 + (R/X)^2}\right) - 2\left(\frac{j\left(R^2/X\right)}{1 + (R/X)^2}\right). \quad (3)$$

From (3), we can learn that there is no change in the value of the real part comparing with the formula (2), and the imaginary part tends to a definite value.

Only a certain impedance value is changed, as shown in the Figures 6 and 7.

By calculating the impedance, the same conclusion can be drawn that the real part will be compressed. When R increases greatly, the real part tends to 0 while the imaginary part tends to a certain value.

Basing on the analysis above, the important reason why R can be compressed is that there are reactance components in parallel with it. When R increases, the total impedance will compress the real part. If $R >> x$, then jX will play a major role. The real part tends to 0 and the imaginary part tends to a certain value. If $R << x$, then R will play a major role. Here the circuit is equivalent to the series connection of two R.

From [16] we learn that RCN has the advantage that when the resonant frequency is applied, the impedance Z_{in} is a pure resistance while the imaginary part is offset, and the energy will directly act on the load without energy loss.

We will analyze another model in the Figure 8.

$$\mathrm{Zin} = \frac{X^2}{2R}\left(1 + \left(\frac{R}{X}\right)^2\right). \quad (4)$$

In this case, it is seen from (4), when R increases, Z_{in} increases also. When R tends to infinity, Z_{in} tends to infinity also.

If $R >> X$, then $Z_{in} = R/2$; if $R = X$, then $Z_{in} = R/2$; and if $R << X$, then $Z_{in} = X^2/2R$.

Adjust the reactance components in the Figure 8, we will get Figure 9. The input impedance is expressed as follows:

$$\mathrm{Zin} = \frac{R}{2} - j * \frac{R^2X + X^3}{R^2 + X^2}. \quad (5)$$

Through the above-mentioned analysis, we can learn that this mode of circuit is actually the parallel connection of two resistors, and the reactance element $-jX$ contributes to an imaginary part here. If R is changed into a reactance component including both real part and imaginary part, then the result is similar. The result is that the real part is half, and the imaginary part tends to a certain value. If it is at other frequency points or more generally, it can be expressed as Figures 10(a) and 10(b).

Through the derivation, the real part is solved by taking half, and the imaginary part tends to a certain value.

From the above analysis, it can be concluded that the reason why the impedance can be compressed is due to the parallel connection of two branches. When operating at resonance frequency, Z_{in} is a pure resistance in Figure 8, which is essentially the parallel connection of two R resistors. Under other conditions, the result is that the real part tends to $R/2$ while the imaginary part tends to a certain value decided by reactance components.

Based on the deep analysis of the basic theory of RCN, we will analyze the application of RCN in rectifying circuit in the next section.

3. The Analysis of the Initial Idea

In this section, we start from the basic topology of rectifying circuits and analyze the characteristics of rectifying circuits containing RCN further.

3.1. The Analysis of Input Impedance. The basic block diagram of a rectifier is shown in Figure 11, and the rectifying circuit is basically designed based on this block diagram.

It is given the rectifier including RCN as Figure 3 [16].

According to the author's intention, RCN plays the role of impedance compression. The working frequency is 100 MHz, and the central impedance is designed according to 20 ohm. In this paper, the circuits are simulated with

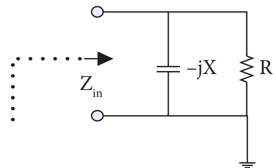

Figure 1: Capacitance and resistance in parallel.

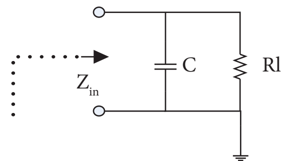

Figure 2: A specific parallel circuit.

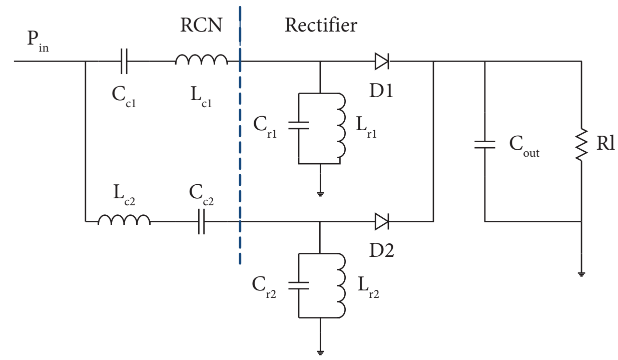

Figure 3: Converter incorporating a resistance compression network.

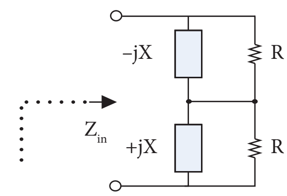

Figure 4: Structure of the two basic resistance compression networks.

advanced design system (ADS) software. The SBD is HSMS286B in circuits. The values of components come from [16].

Where: $C_{c1} = 36.22$ pF, $C_{c2} = 66.5$ pF, $L_{c1} = 38.1$ nH, $L_{c2} = 69.9$ nH, $C_{out} = 1.9\,\mu$F, $C_{r1} = 32.6$ pF, $L_{r1} = 18.9$ nH, $C_{r2} = 32$ pF, $L_{r2} = 18.7$ nH.

One branch is designed as Figure 12(a), the impedance of which is $-j^*20$. The impedance of another branch is $+j^*20$ designed as Figure 12(b). Let us analyze it step by step.

We have analyzed the input impedance in Figure 2. Here, the input impedance of Figure 13 is given by Figure 14.

From the simple analysis above, it can be learned that when RCN is not added, the impedance of the circuit is very stable, and the change in load has been covered by the relevant components in parallel. After adding RCN, the circuit is designed as Figure 15 while the result is shown as Figure 16. The input impedance of the circuit remains unchanged.

It can be learned that the small change in impedance is not due to the RCN but to the structure of the circuit. According to the previous analysis, if only the impedance of the load is changed, it has nothing to do with the original intention of RCN.

After the above analysis, it can be seen that the single-branch impedance change is very small. If the impedance change of each branch is small, the overall impedance change is also very small. That is to say, the change in input impedance in Figure 3 is also very small. The reason is different from the theoretical analysis of a resistance compression network.

Every branch of RCN plays the role of BPF. This conclusion has already been given [16].

Each branch in Figure 3 is also the basic structure of the rectifier topology. A branch of RCN actually acts as a BPF and does not play the desired role of impedance compression.

Whether there are other functions of RCN in the rectifier circuit, it is not enough only through the above analysis. If the structure of RCN is changed and the same rectification results can be obtained, the role of RCN in the circuit can be accurately analyzed.

3.2. The Analysis of Rectification Efficiency. Firstly, we will analyze the rectification efficiency by changing R_l in Figure 3. According to the design idea of RCN in the reference document [16], the compressed network operates at 100 MHz and the central impedance is 20 ohm. The conversion efficiency is shown in Figure 17.

We adjust one branch of RCN as Figure 18. The circuit diagram and conclusion are shown in Figure 19 and Figure 17. The conversion efficiency has not changed obviously.

From the simulation results above, we can see that the value of LC1 has been changed. BPF has not been changed, and the design of RCN has been changed and no longer meets the requirements of RCN.

If change the second branch only, the circuits are shown in Figures 20 and 21. The conversion efficiency has no obvious change also, and the same conclusion can be drawn. The circuit of one branch is shown in Figure 22.

Basing on the analysis above, RCN does not achieve the original intention, and it is the most basic design idea of a rectifier in Figure 11. RCN is only a BPF here. If the parameter value of RCN is changed, as long as the requirements of BPF are reached, the rectifying circuit will also work normally.

To further illustrate the above conclusion, replace the RCN network with each other. The certain circuits are shown in Figures 23 and 24. Approximate efficiency can be achieved also.

RCN can take effect in circuit with a few elements effectively. The rectifying circuits above consist of many capacitors, inductors, and diodes. So, RCN does not play the role that was expected previously. Therefore, it can be concluded that RCN is only a BPF and has not reached the original purpose of the designer.

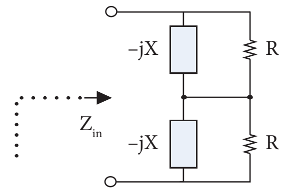

Figure 5: The modified RCN (two identical reactance components).

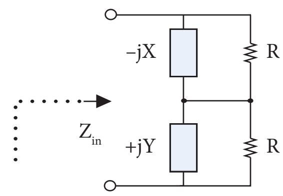

Figure 6: The modified RCN (two reactance components having different amplitude and phase).

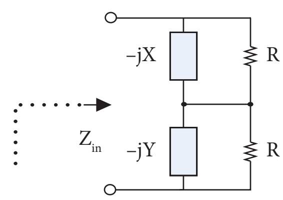

Figure 7: The modified RCN (two reactance components having different amplitude).

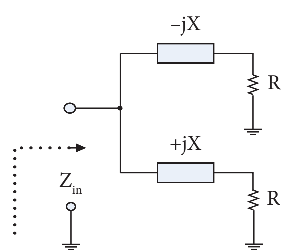

Figure 8: Another structure of the two basic resistance compression networks.

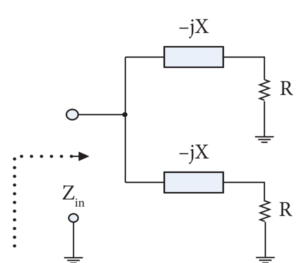

Figure 9: The another modified RCN (two identical reactance components).

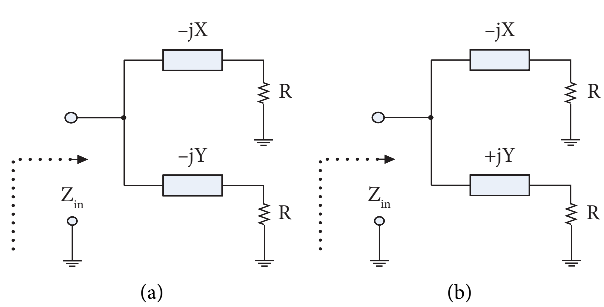

Figure 10: The another modified RCN (changing the amplitude or phase).

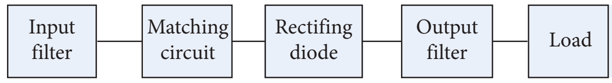

Figure 11: Rectifying circuit topology.

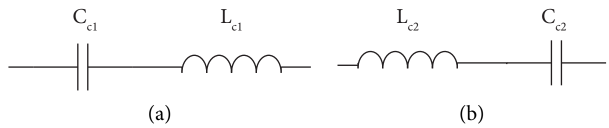

Figure 12: Two branch of RCN.

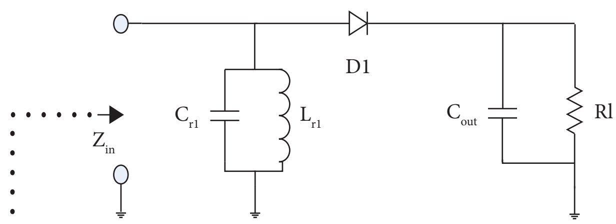

Figure 13: Rectifier without RCN.

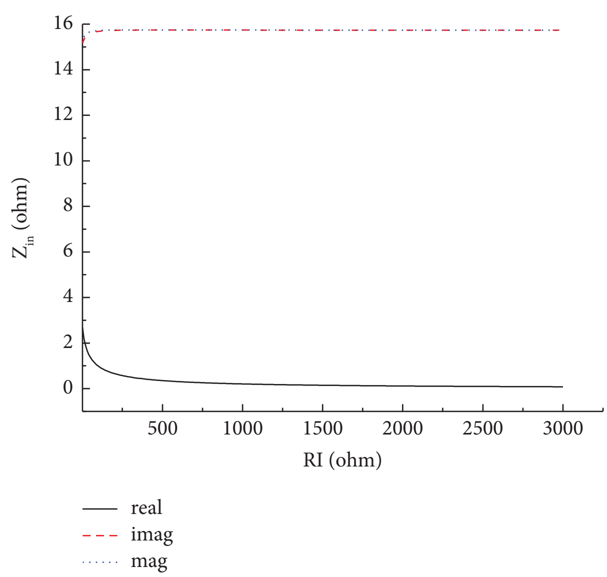

Figure 14: The input impedance of rectifier without RCN shown in Figure 13.

4. The Analysis of Other Rectifier

There are many articles with the idea of RCN, which present a lot of different circuits. Here is an example, and other designs are similar. Now we can get the same result by analyzing the circuit in [20].

Firstly, we will analyze the input impedance of RCN branches and R_l. The circuit diagram is shown in Figure 25, and the component values are given [20]. Where $f = 850$ MHz, $L_1 = 6.8$ nH, $C_1 = 3.8$ pF, $L_2 = 1.8$ nH, $C_2 = 2.5$ pF, $L_3 = 22$ nH, $L_4 = 68$ nH, $C_r = 100$ nF.

As can be seen from Figure 26, Z_{in} has little change with the increasing of R_l.

According to the analysis of the previous chapters, it can be learned that the compression of a single branch is mainly due to the parallel connection with reactance components.

After adding L-network the circuit diagram is shown in Figure 27, and the simulation result is shown in Figure 28.

The same conclusion can be drawn by analyzing another branch such as Figures 29 and 30 in the same way.

The response of two branches to impedance is similar to that of one branch. The circuit diagram is shown in Figure 31. The similar conclusion will be obtained in Figure 32.

For a branch, the impedance does not change. After a parallel connection, it also does not change. The impedance compression of the load is determined by the circuit form

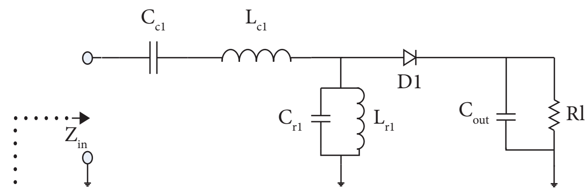

FIGURE 15: One branch of rectifier.

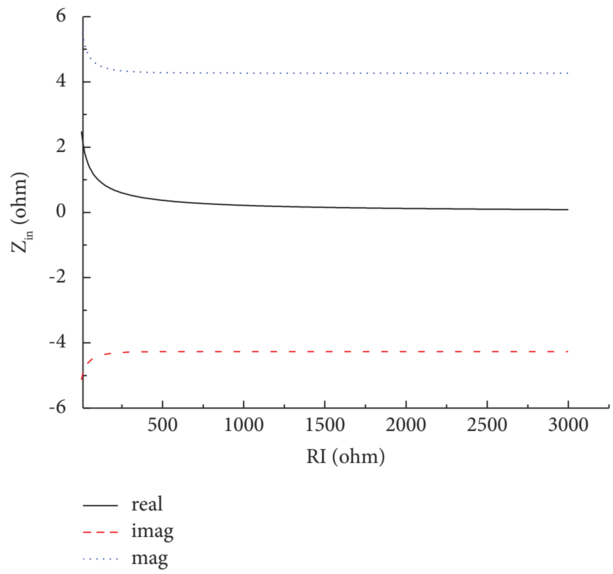

FIGURE 16: The input impedance of circuit with one branch of rectifier shown in Figure 15.

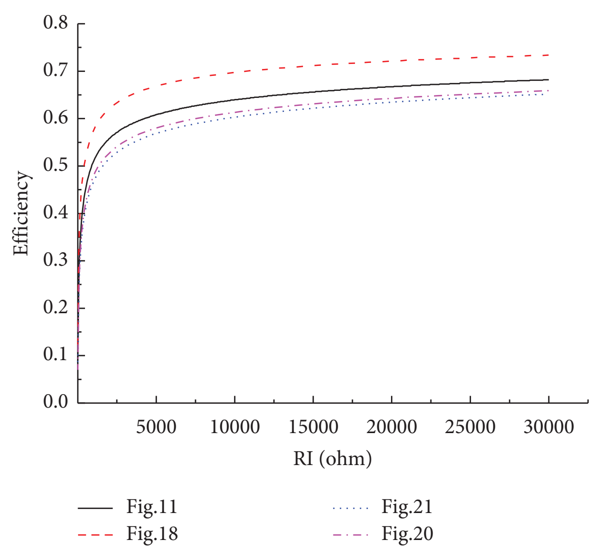

FIGURE 17: The conversion efficient of various circuits shown in Figures 3, 19, 21 and 22.

itself. The RCN idea that the designer hopes to achieve is not reflected here. It is just a coincidence.

We will analyze the conversion efficiency [20]. The original circuit diagram is shown in Figure 33. The circuits adopting the same branches are shown in Figures 34 and 35. A single branch circuit is shown in Figure 36. We will learn that the conversion efficiency of various schemes are similar from Figure 37. Comparing these circuits and Figure 11, one branch of RCN also plays the role of BPF, which is still the rectifier structure in essence.

In other documents [18, 19, 22, 23], the same method can be used to obtain the same conclusion.

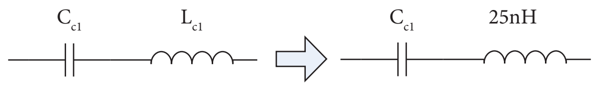

Figure 18: Adjust the first branch of RCN.

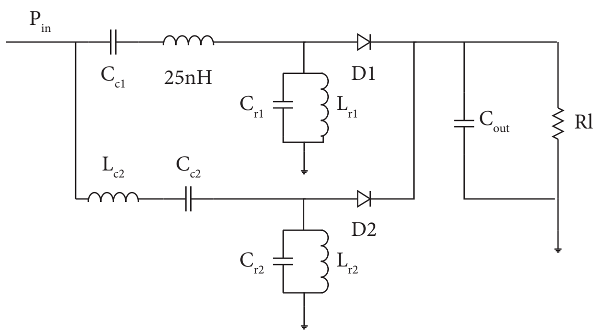

Figure 19: Rectifier adopting the design of Figure 18.

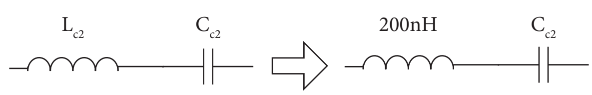

Figure 20: Adjust the second branch of RCN.

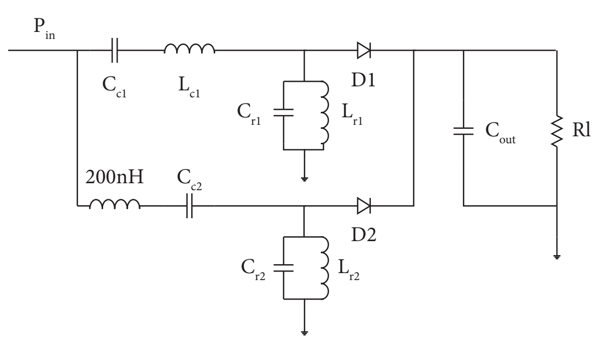

Figure 21: Rectifier adopting the design of Figure 20.

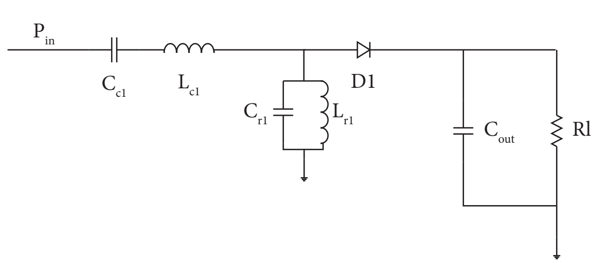

Figure 22: Rectifier only with one branch.

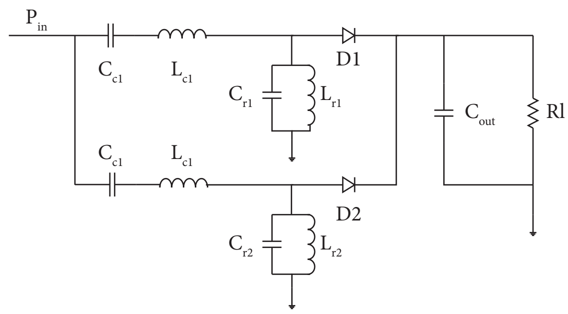

Figure 23: Rectifier of two branch adopting the first branch.

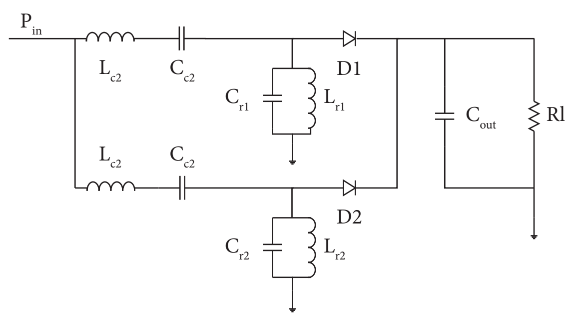

Figure 24: Rectifier of two branch adopting the second branch.

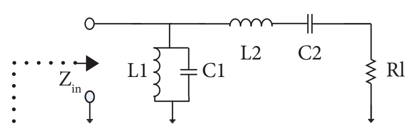

Figure 25: The circuit with one branch of RCN and load.

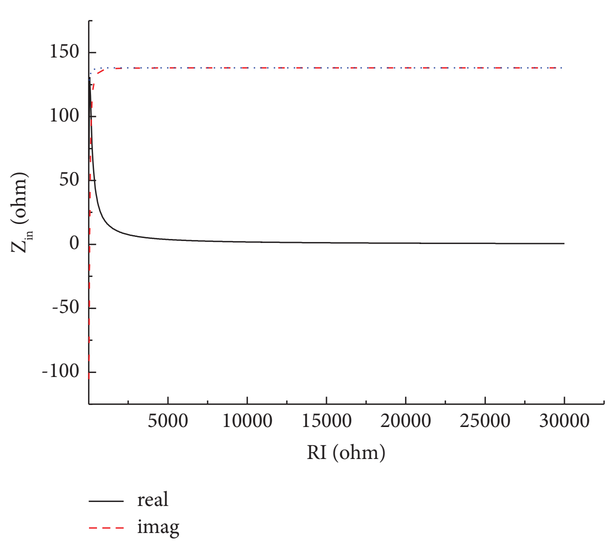

Figure 26: The input impedance of the circuit with one branch of RCN and load shown in Figure 25.

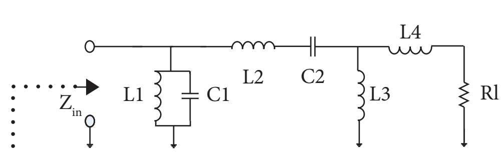

Figure 27: Adding matching circuit on the base of Figure 25.

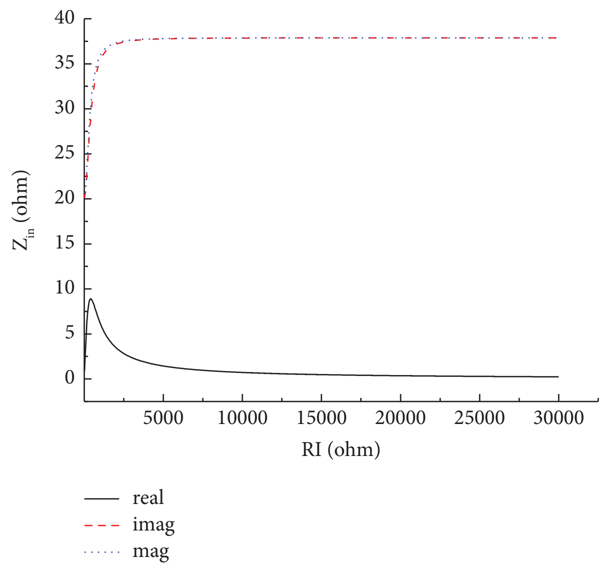

FIGURE 28: The input impedance of the improved circuit shown in Figure 27.

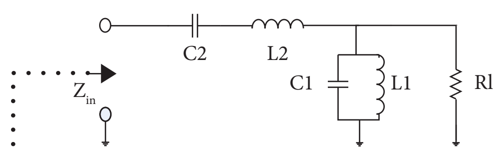

FIGURE 29: The circuit with another branch of RCN and load.

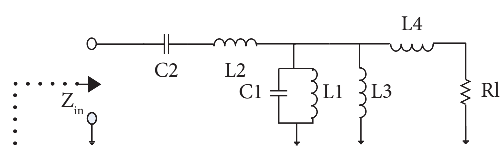

FIGURE 30: Adding matching circuit on the base of Figure 29.

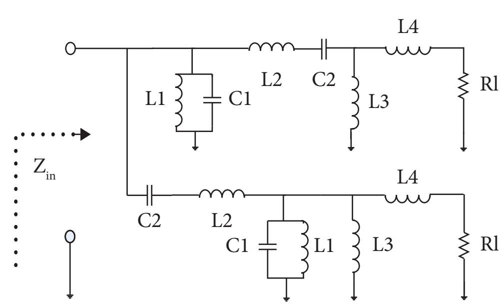

FIGURE 31: The circuit of parallel of Figures 27 and 30.

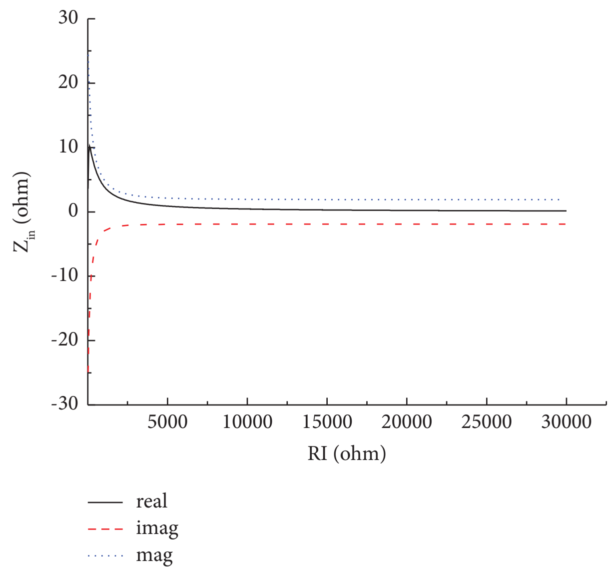

Figure 32: The input impedance of the modified circuit shown in Figure 31.

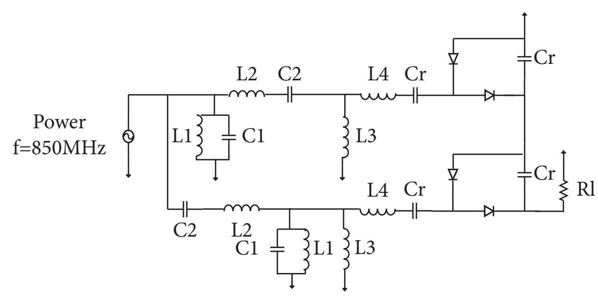

Figure 33: The initial rectifier.[20].

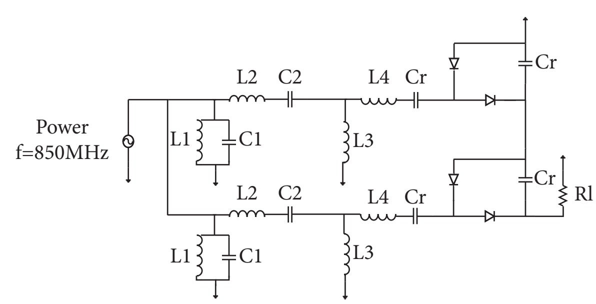

Figure 34: Rectifier with the first branch of RCN.

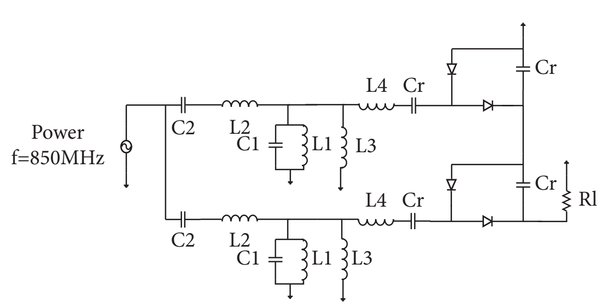

Figure 35: Rectifier with the second branch of RCN.

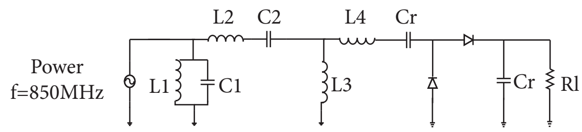

FIGURE 36: The rectifier with one branch only.

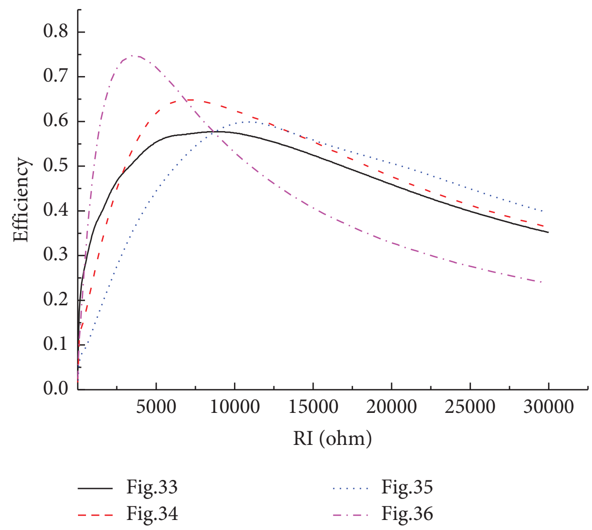

FIGURE 37: The conversion efficient at various circuits above.

5. Conclusion

The detailed analysis of RCN and related rectifiers is carried out gradually in this paper. The purpose of this work is to have an accurate understanding of the rectifying circuit. The results show that the phenomenon of impedance compression in rectifiers is determined by the circuit forms and is independent of the theory of RCN itself. In the related rectifying circuit, RCN has no effect on impedance compression, which only acts as a BPF. The rectifying circuit with RCN is essentially within the basic rectifying topology. It can be concluded that this paper has a completely different understanding of RCN and related applications. It provides a theoretical basis for future circuit design.

Data Availability

The data and the values of components used to support the findings of this study are available from the corresponding author upon request.

Disclosure

An earlier version of this paper has been presented as Preprint in Authorea [24].

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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