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

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***Abstract*—RCN has attracted special attention in the field of WPT since it was 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 rectifier incorporating RCN which operate at various of circuit forms and physical forms are proposed. RCN and all kinds of modified versions are studied deeply in these paper, the rectifiers related to which are analyzed also. The results show that RCN only play the role of BPF in the rectifying circuit, which are not reaching the original idea of the first proposer.**

***Index Terms*—RCN, impedance matching, rectifying circuit, WPT.**

I. Introduction

WPT is a promising technology that has been refocused again, which has attracted so more increasing 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 increase the quality of WPT system, but it is a significant challenge that the nonlinear nature of rectifier which will cause the variations of input impedance changing with the varies of 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 problem [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.

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In the literature many designs with RCN which are depending on the various application scenarios have been presented. In order to overcome the disadvantages of RCN using lumped element, 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 multi-stage TLRCNs [18]. A dual-band RCN was proposed for operating at the dual band not a single frequency previously [19]. HRCT aiming at expanding operating frequency band can be synthesized by RCN and impedance matching network [20]. In [21], a differential rectifier including differential RCN solve the problem of single input port previously and satisfy the need of 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 II, where we have a different understanding of 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 III. Section IV analyze the rectifier [20] in the same way. We draw conclusions in Section V.

II. THE ANALYSIS OF RCN

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

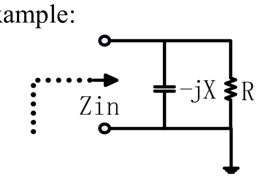

Fig.1. Capacitance and resistance in parallel

For instance, we calculate the impedance in Fig.1.

$$\frac{1}{Z_{in}}=\frac{1}{-jX}+\frac{1}{R} \qquad (1)$$

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 Fig.2, which is one part of Fig.11.

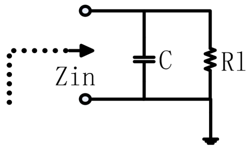

Fig.2. A specific parallel circuit

Where: f=100MHz, Rl=20ohm, C=1.9uf.

then: $Z_c = \frac{1}{j1193}$,

$$\frac{1}{Z_{in}} = \frac{1}{20} + j*1193 \,, \quad Z_{in} \approx 0 + Z_c = 0 + \frac{1}{j1193}$$

From the results above, The real part of Z_{in} tends to 0 while the imaginary part is decided by reactance component.

Now, we will analyze the RCN theory [16]. The RCN model is illustrated in Fig. 3.

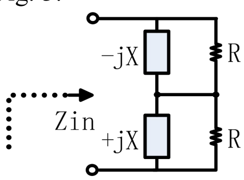

Fig.3. Structure of the two basic resistance compression networks

Working at the designed operating frequency:

$$Z_{in} = \frac{2R}{1+(\frac{R}{X})^2} \tag{2}$$

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 fig.3.This conclusion has been given in [1].

If we adjust the reactance component and w_0 is unchanged, as shown in the Fig.4, we'll get the following results.

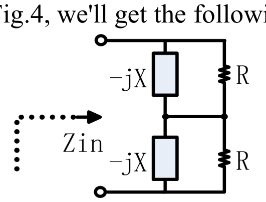

Fig.4.The modified RCN(Two identical reactance components)

$$Z_{in} = 2\left(\frac{R}{1+(\frac{R}{X})^2}\right) - 2\left(\frac{j(\frac{R^2}{X})}{1+(\frac{R}{X})^2}\right) \tag{3}$$

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

Only a certain impedance value is changed, as shown in the Fig.5 and Fig.6：

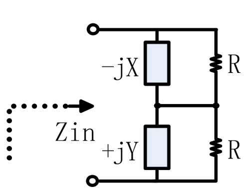

Fig.5. The modified RCN(Two reactance components having different amplitude and phase)

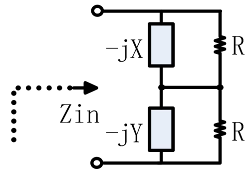

Fig.6. The modified RCN(Two reactance components having different amplitude)

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:

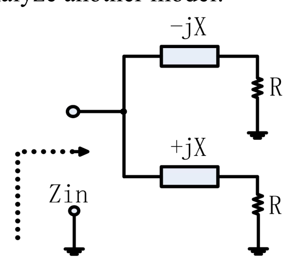

Fig.7. Another structure of the two basic resistance compression networks

$$Z_{in} = \frac{X^2}{2R}(1+(\frac{R}{X})^2) \tag{4}$$

In this case, we can learn that 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; If R<<X, then $Z_{in}=X^2/2R$.

Let's adjust the reactance components in the Fig.7,

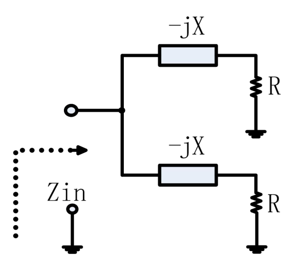

Fig.8. The another modified RCN(Two identical reactance components)

$$Z_{in} = \frac{R}{2} - j * \frac{R^2 X + X^3}{R^2 + X^2} \quad (5)$$

Through the analysis above, we can learn that this mode of circuit is actually the parallel connection of two resistors, and the reactance element -jX contribute to an imaginary part here. If R is changed into 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 Fig.9.a and Fig.9.b.

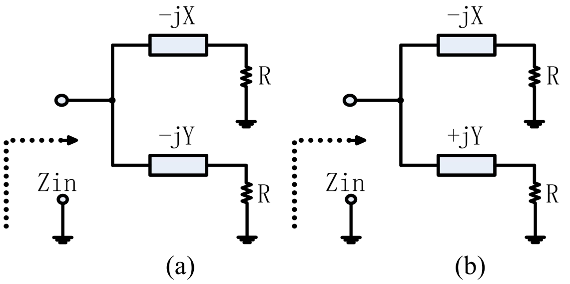

Fig.9. The another modified RCN(Changing the amplitude or phase)

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 parallel connection of two branches. When operating at resonance frequency, Z_{in} is a pure resistance in Fig.7, 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.

III. THE ANALYSIS OF THE INITIAL IDEA

A. *The analysis of input impedance*

The basic block diagram of rectifier is shown in Figure 10, and the rectifying circuit is basically designed basing on this block diagram.

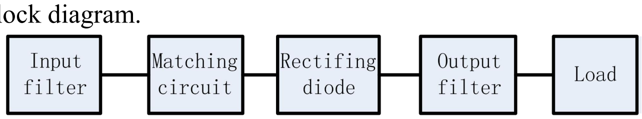

Fig.10. Rectifying circuit topology

It is given the rectifier including RCN as Fig.11[1].

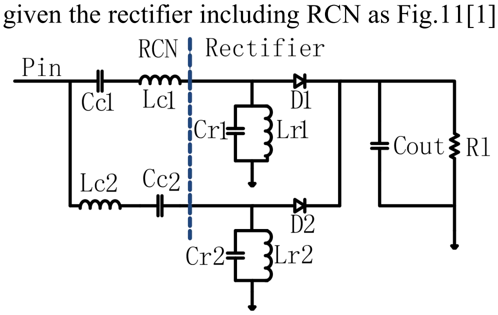

Fig.11. converter incorporating a resistance compression network

According to the author's intention, RCN plays the role of impedance compression. Working frequency is 100MHz, and the central impedance is designed according to 20ohm.

Where: C_{c1}=36.22pf, C_{c2}=66.5pf, L_{c1}=38.1nh, L_{c2}=69.9nh, C_{out}=1.9uf, C_{r1}=32.6pf, L_{r1}=18.9nh, C_{r2}=32pf, L_{r2}=18.7nh.

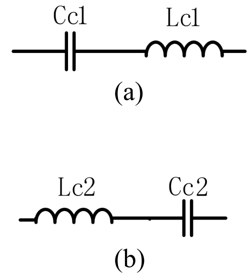

Fig.12. Two branch of RCN

One branch is designed as Fig.12.a, the impedance of which is -j*20. The impedance of another branch is +j*20 designed as Fig.12.b. Let's analyze it step by step.

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

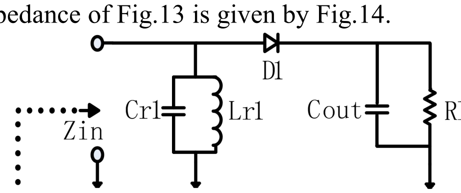

Fig.13. Rectifier without RCN

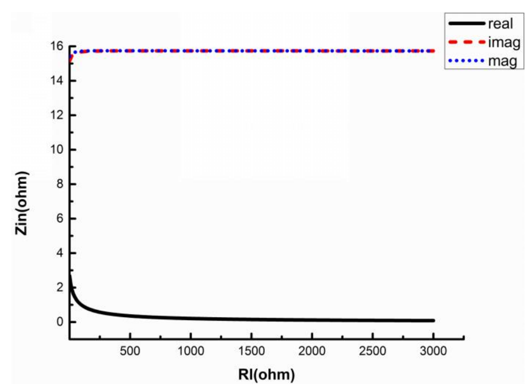

Fig.14. The input impedance of Fig.13

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

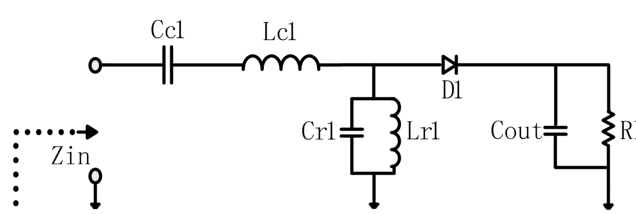

Fig.15. One branch of rectifier

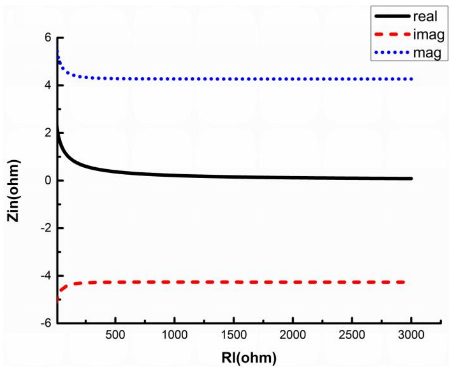

Fig.16. The input impedance of Fig.15

It can be learned that the small change of impedance is not due to the RCN, but to the structure of the circuit. According to the previous analysis, if only the impedance of 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 of input impedance in Fig. 11 is also very small. The reason is different from the theoretical analysis of resistance compression network.

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

Each branch in Fig.11 is also the basic structure of 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.

B. The analysis of rectification efficiency

Firstly, we will analyze the rectification efficiency by changing Rl in Fig.11. According to the design idea of RCN in reference document [16], the compressed network operates at 100MHz and the central impedance is 20ohm. The conversion efficiency is shown in Fig.22.

We adjust one branch of RCN as Fig.17. The circuit diagram and conclusion are shown in Fig.18 and Fig.22. The conversion efficiency has no obvious change.

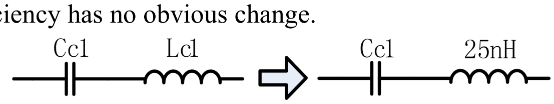

Fig.17. Adjust the first branch of RCN

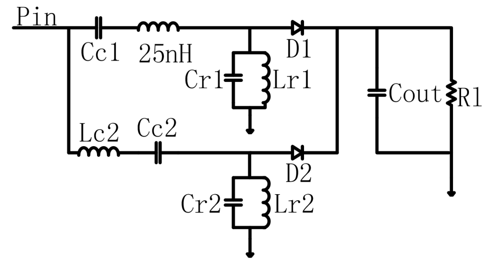

Fig.18. Rectifier adopting the design of Fig.17

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 Fig.19 and Fig.20. The conversion efficiency has no obvious change also, and the same conclusion can be drawn. The circuit of one branch is shown in Fig.21.

Fig.19. Adjust the second branch of RCN

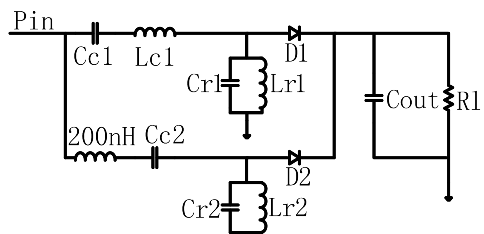

Fig.20. Rectifier adopting the design of Fig.19

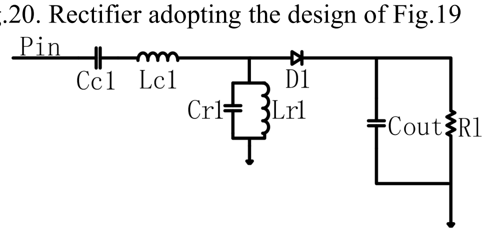

Fig.21. Rectifier only with one branch

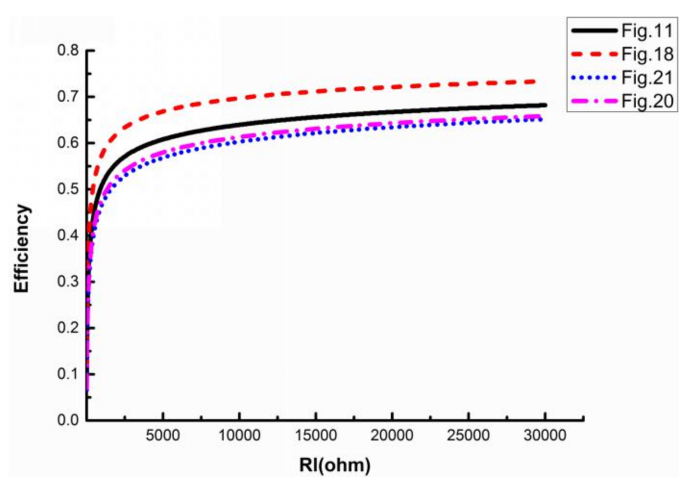

Fig.22. The conversion efficient at various circuits above

Basing on the analysis above, RCN does not achieve the original intention, and it is the most basic design idea of rectifier in Figure 10. 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 Fig.23 and Fig.24. Approximate efficiency can be achieved also.

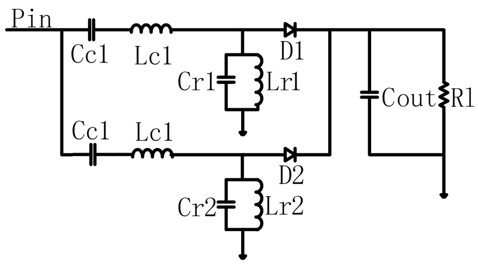

Fig.23. Rectifier of two branch adopting the first branch

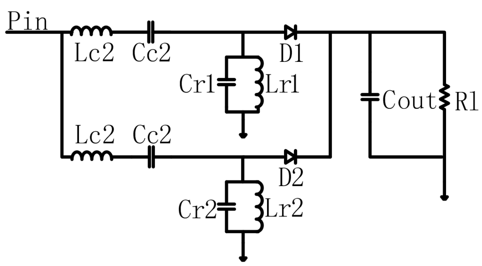

Fig.24. Rectifier of two branch adopting the second branch

Therefore, it can be concluded that RCN is only a BPF, and it has not reached the original purpose of the designer.

IV. THE ANALYSIS OF OTHER RECTIFIER

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

Firstly, we will analyze the input impedance of RCN branches and Rl. The circuit diagram is shown in Fig.25, and the component values are given. Where: f=850MHz, L1=6.8nh, C1=3.8pf, L2=1.8nh, C2=2.5pf, L3=22nh, L4=68nh, Cr=100nf.

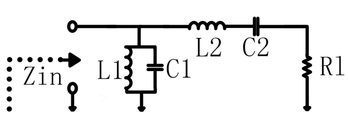

Fig.25. The circuit with one branch of RCN and load

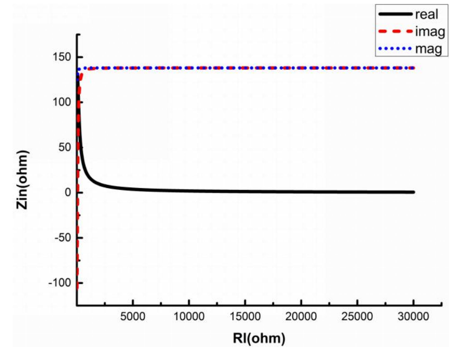

Fig.26. The input impedance of Fig.25

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

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

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

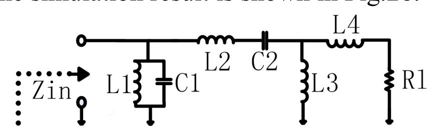

Fig.27. Adding matching circuit on the base of Fig.25

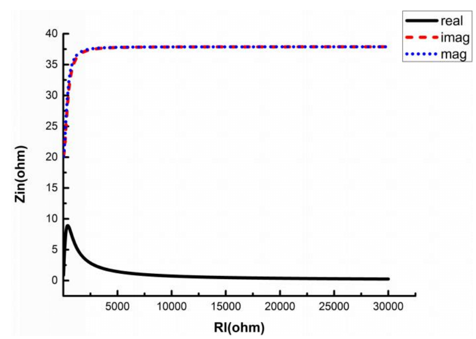

Fig.28. The input impedance of Fig.27

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

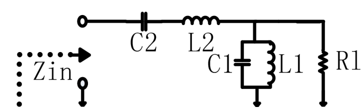

Fig.29. The circuit with another branch of RCN and load

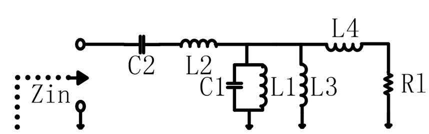

Fig.30. Adding matching circuit on the base of Fig.29

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

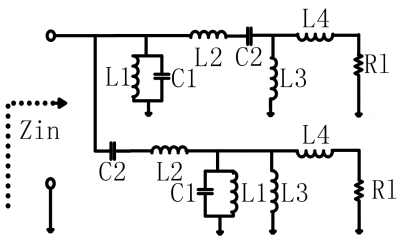

Fig.31. The circuit of parallel of Fig.27 and Fig.30

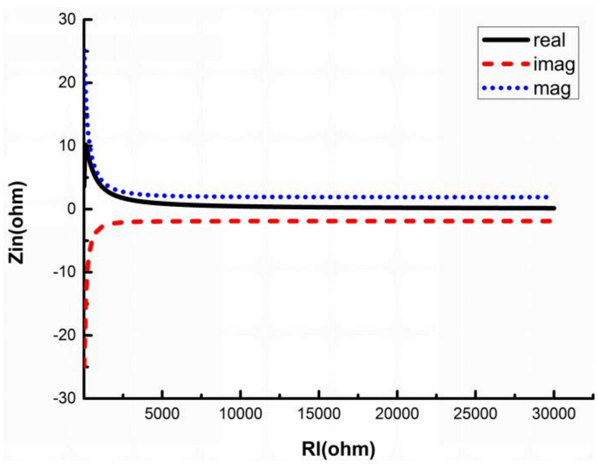

Fig.32. The input impedance of Fig.31

For a branch, the impedance does not change. After parallel connection, it also does not change. The impedance compression of the load is determined by the circuit form 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 Fig.33. The circuits adopting the same branches are shown in Fig.34 and Fig.35. Single branch circuit is shown in Fig.36. We will learn that the conversion efficiency of various schemes are similar from Fig.37. One branch of RCN also plays the role of BPF, which is still the rectifier structure in essence.

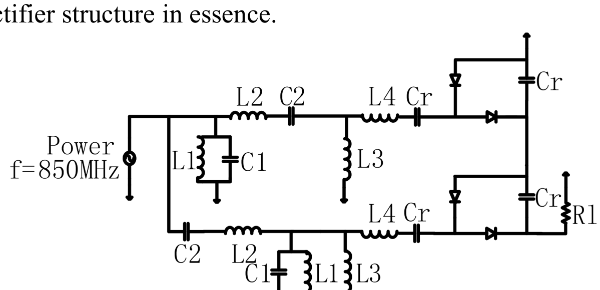

Fig.33. The initial rectifier [5]

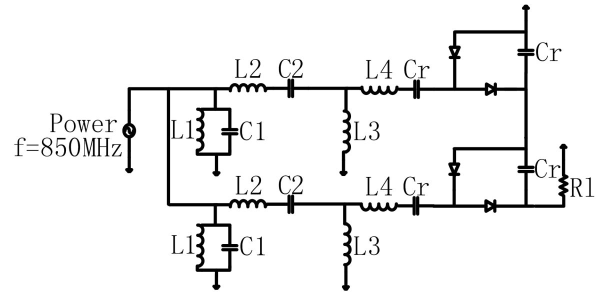

Fig.34. Rectifier with the first branch of RCN

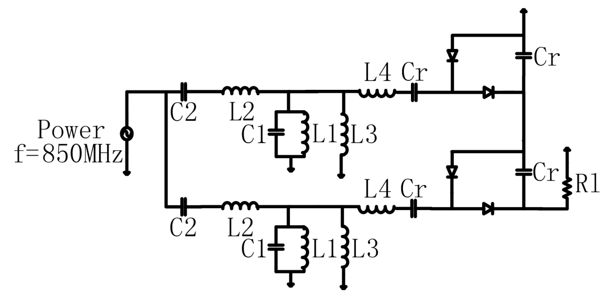

Fig.35. Rectifier with the second branch of RCN

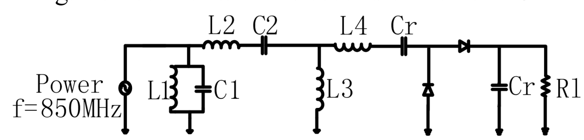

Fig.36. The rectifier with one branch only

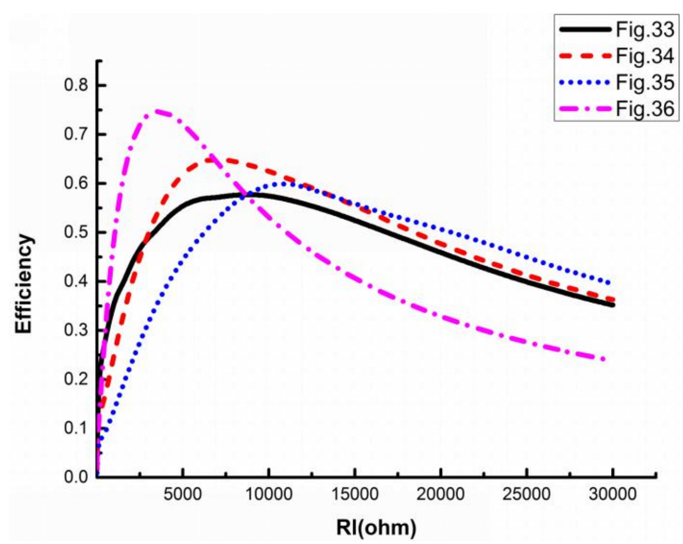

Fig.37. The conversion efficient at various circuits above

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

V. CONCLUSION

The detailed analysis of RCN and related rectifier are carried out gradually in this paper. The results show that the phenomenon of impedance compression in rectifier is determined by the circuit forms, and is independent to the theory of RCN itself. Here 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.

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