a single-branch impedance compression network (ICN) optimized by particle swarm optimization algorithm for RF energy harvesting system

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Abstract. Most previous works regarding the impedance compression network ICNs reported in the literature consist of dual branches to carry out the compression functionalities. Although this type of circuits are efficient, they are complex and have large sizes. This work proposes a complex impedance compression network with only a single branch for wireless power transfer (WPT) circuits, operating at 2.4GHz under a wide input power range and a variable load. The design size is about 4x4.2mm² which thereby, produces a simple and small design. The simulation results demonstrate that the improvement in efficiency is by 10%, as compared to a design without ICN. The improvement can increased by utilizing the particle swarm optimization (PSO) algorithm where the best dimensions of the ICN components will be selected relying on the suitable fitness function in the PSO algorithm to the given desired goals. The impedance matching is also enhanced in which it stands behind the conversion efficiency increment. The circuit size is very slightly increased and it becomes 4.2x4.3mm². The final design has a conversion efficiency about 76%, with more than 15% improvement to a design with only a matching circuit or without using the automation techniques. Eventually, results show that the enhancement is obtained not only the designated input power but also along a range of the input power.

1. Introduction

RF Energy harvesting technique is one type of the wireless power transfer systems used to power the wireless sensors instead of batteries, so it prohibits the frequent replacement and it also reduces the maintenance cost. Wireless sensor networks are the backbone of the internet of things (IoT) [1]. In the ambient RF energy harvester, the antenna captures the electromagnetic power from various ambient RF sources, for instance, GSM, CDMA, 3G, 4G, and ISM (industrial scientific medical) and WiFi [2]. Then it is excited as AC power over the antenna and enters into the rectifier through the ICN. Moreover, the AC power is converted into DC power by the rectifier circuit. To ensure the maximum power transfer from the antenna to the rectifier circuit, the matching network must exist. The rectifier circuit depends primarily on diodes in their underlying design. In other words, we can say that the diodes have variable impedances with frequency, input power, and load resistance owing to their nonlinear characteristics. As a result...
the design performance will be sensitive for these three parameters, and reducing their impact on the overall performance is a hot research topic.

There is a variety of matching circuit designs to circumvent this problem. In [3] RLC series resonance matching circuit is used to match the rectifier input impedance with output antenna impedance but at a fixed input power. The matching circuit proposed in [4] provides variable input power but does not manipulate a wide range of input impedance variations as various matching circuit designs. A rectifier circuit with wide range of input power in [5] implemented by using coupling reconfigurable coupler. Also, in [6] a rectifier based on miniaturized branch line hybrid coupler (MBLHC) introduced to get a wider range for input power, but a complexity and large dimensions are the mean unfavorable features in [5], [6]. The authors in [7] have proposed a special case of the matching network aiming to compress the variations in input impedance thereby enhancing the overall performance. The compression network technique acts to reduce the impedance variation to maintain a good matching over wide ranges of frequencies, input powers, and load resistances. Some research efforts have been done. Their works were depended on dividing the load resistance into parallel branches with the same current and opposite phase. The resulting load will be a pure real impedance and it has a slow change in its value.

In [7] researchers have designed an RCN (Resistance Compression Network) operating with only a single frequency, in [8] a dual-band RCN has been implemented, and an RCN working with a wide range of frequencies is reported in [9]. All these designs, in their RCN circuits, rely on lumped elements. The lumped elements have inherent problem which is the parasitic effects. Parasitic effects enforce them to behave differently from their main functionalities (i.e., the capacitor will have dominant inductance behavior or vice versa), especially at high microwave frequencies. Alternatively, the transmission lines are the optimum candidate, as investigated in [10], [11]. It is a dual-branch design, so RCN increases the design complexity. In [12] a single branch RCN has proposed to reduce the input impedance variation where the design complexity is reduced as well but still using an auxiliary component to remove the imaginary part. The RCN needs only a real resistance to deal with and this is a big constraint because most nonlinear circuits have complex impedances. A procedure using the auxiliary part increases the complexity of the design. Based on that, the compression network compresses both the real and imaginary part at the same time being preferred to improve the efficiency of the overall performance of a circuit with as few as possible a number of the lumped components.

Therefore, some researchers have reported works regarding this issue as in [13], with dual-branch work and [14] with single and dual band works. In [15] author also has proposed a single branch ICN to the compress complex impedance but with a circuit has a big footprint.

In this paper, a single-branch complex impedance compression network is investigated theoretically, optimize by the PSO algorithm, and simulated to demonstrate the compression in the input impedance variations of the microwave rectifier. By using only three transmission lines in the proposed design, the results show that compression of the input impedance has been noticeably obtained when the load and input power vary over wide ranges. The ICN has been analyzed by two ways. First, its performance has been analyzed using the Advanced Design System ADS software from Keysight Inc. without using the optimization. This process has lasted for days to come up with reasonable results. In contrast, this process has been expedited with optimization techniques as in the second way. The PSO algorithm aids to come up with the optimal results with only few minutes. Finding the optimal designs in a quick way is required nowadays. Therefore, the main contribution in this paper is to combine between the MATLAB based PSO and ADS to accelerate finding the results, and the example given in this paper is ICN for the energy harvesting systems. Moreover, the same procedure can be applied to any circuit such as power amplifiers, low noise amplifiers, Mixers, filters, etc. Finally, the ICN performs the matching and compression functionalities simultaneously, so the adopted circuit here is very compact.
2. ICN design

Figure 1 shows the schematic of the single branch ICN. It consists of three main parts, open-ended stub with an impedance characteristics $Z_{o1}$ and electrical length $\theta_1$, short-ended stub with an impedance characteristics $Z_{o2}$ and electrical length $\theta_2$, and a transmission line with an impedance characteristics $Z_{o3}$ and electrical length $\theta_3$. They are connected in parallel. $Z_D$ represents the variable load, but in the real-life application this variable load is active microwave circuit such as power amplifier, low noise amplifier, mixer, rectifier, etc. All these circuits contain nonlinear electronic elements such as transistors and diodes where their internal impedances vary with RF power, frequency and loads. $Z_{in}$ denotes the compressed impedance.

After capturing the RF signals from space, they will travel through the ICN to reach the $Z_D$. $Z_1$ acts to compress the $Z_D$ but it has a high mismatch. $Z_1$ and $Z_2$ maintain the compression and match the input impedance. Figure 2 displays different impedances on the Smith chart. As can be seen, the input impedance is compressed and matched. Our ICN can perform both compression and matching by the same so circuit, so our design is very compact and simple as well. The circuit is designed and simulated using the advanced design system to come up with the final values for our circuit. The $Z_{o1}$, $Z_{o2}$, and $Z_{o3}$ are 20.2Ω, 51.3Ω, and 9.85Ω, respectively, while $\theta_1$, $\theta_2$, and $\theta_3$ are 6.45°, 13.75°, and 28.78°, respectively.

By virtue of [16], the mathematical model of the ICN can be derived as in the following.
The input impedance of the open-ended stub is:

$$Z_1 = jZ_{o1} \cot(\theta_1)$$  \hspace{1cm} (1)

To obtain the compression, electrical lengths of stubs should obey the role $\theta_1 = 90^\circ - \theta_2$, accordingly:

$$Z_1 = jZ_{o1} \tan(\theta_2) \hspace{1cm} (2)$$
$$Z_2 = -jZ_{o2} \tan(\theta_2) \hspace{1cm} (3)$$

$Z_3$ is given as

$$Z_3 = Z \left( \frac{Z_D + jZ_{o3} \tan(\theta_3)}{Z_{o3} + jZ_{o3} \tan(\theta_3)} \right) \hspace{1cm} (4)$$

where $Z_D$ is assumed to be complex.

$$Z_D = R - jX \hspace{1cm} (5)$$

$Z_D$ is the rectifier impedance. The rectifier circuit consists of a voltage doubler diode with variable resistance load. The input impedance of ICN circuit can be calculated as

$$Z_{in} = Z_1 || Z_2 || Z_3 \hspace{1cm} (6)$$

By substituting (2), (3), and (4) into (6) lead to:

$$Z_{in} = \frac{Z_D + jZ_{o3} \tan(\beta L_3)}{(1 - \frac{Z_{o3}(Z_{o1}+Z_{o2}) \tan(\beta L_3)}{Z_{in}Z_{o3} \tan(\theta_3)}) + jZ \tan(\beta L_3)} \left( \frac{Z_{o1}+Z_{o2}}{Z_{in}Z_{o3} \tan(\theta_3)} \right) \hspace{1cm} (7)$$

![Figure 3. The variation range of input impedance of diode impedance comparing with mathematical compressed impedance results after utilized of singlebranch ICN proposed.](image)

Depending on, the input impedance equation (7), $Z_{in}$ is controlled by five parameters ($Z_{o1}$, $Z_{o2}$, $\theta_2$, $Z_{o3}$, $\theta_3$). Therefore, the input impedance is the best fitness function utilized to optimize the ICN performance by using the particle swarm optimization.

3. PSO Concept

Particle swarm optimization PSO is one type of meta-heuristic algorithms for optimization technique which learning from nature specifically, the principle of the survival of the fittest to solve a wide range of optimization problems where just the best and robust solution can be obtained [17]. PSO was developed by Kennedy and Eberhart in 1995 [18]. Furthermore, it is simple to be implemented because there is no crossover, selection, and as in mutation as Genetic Algorithm GA and Differential Evolution DE. Also, there are few parameters to be modified. Meanwhile, it is efficient in solving a large number of optimization problems.
In this paper, PSO is utilized to obtain the optimal dimensions of ICN components to reach as maximum as conversion efficiency of the proposed circuit. The ICN consists of only three transmission lines connected in parallel to give a maximum compression for input impedance variations. Consequently, the input impedance equation of ICN will be as a fitness function of PSO. The PSO finds the optimal possible solutions based on the movement of the particle. The search starts with initializing random swarms containing a number of particles (search points), each each single particle represents a candidate solution and encoded by a position vector with N elements where N refers to a number of decision variables. Each position vector is evaluated by the fitness function, for a finite number of iterations.

The particle swarm positions are updated by movement within the solution space and the velocity vector computed by using the velocity equation. In each iteration, comparing the best particle in the swarm (Global best position $G_{best}$) for each particle in the best swarm (personal best position $P_{best}$) to provide the optimal global best position particle which guides the swarms toward the optimum solution. The equation of velocity is obtained as following:

$$V_{i,t+1} = W \times V_{i,t} + C_1 \times rand(N) \times (P_{best,i,t} - X_{i,t}) + C_2 \times rand(N) \times (G_{best,i,t} - X_{i,t})$$

Where $W$ is the inertia weight and it is a constant number that provides a balance between personal exploitation and global exportation. Moreover, $W$ enhances the accuracy and the production results. $t$ is a number of iterations, $i$ is a number of population. $C_1$ and $C_2$ are the personal and social acceleration coefficient. The updated position equation is obtained as following:

$$X_{i,t+1} = X_{i,t} + V_{i,t+1}$$

The Figure 4 illustrate the flow chart of the adopted PSO algorithm.

![Flow chart of the PSO algorithm](image-url)
4. Implementation and results
The ICN, allows the circuit to operate at a wide range of the input power from -5dBm to 20dBm, load range from 400Ω to 1400Ω and a 2.4GHz operating frequency. All works presented in this paper have been done using the Advanced Design System (ADS) software from keysight Inc., and the substrate used in all simulations was the Rogers 3010 with a thickness of 0.15mm. The constraint of the input impedance in this work is to make the input impedance 50+i0Ω with a wide range of input power. Fig.5 shown the best personal position (BestCost) convergence of the PSO algorithm. Results are good enough to produce a significantly narrow input impedance variations range despite a wide input power range.

| Parameters       | Range |
|------------------|-------|
| Inertia weight   | 1     |
| C1 , C2          | 2     |
| N                | 5     |
| Swarm No.(i)     | 50    |
| Iterations No.(t)| 200   |

Table 1. PSO parameters.

![Figure 5. Best fitness value of real input impedance with number of iterations.](image)

![Figure 6. Real and imaginary parts of the for input impedance for different numbers of iterations. As can be seen, as a number of iteration is increased, the desired results are obtained.](image)

To show the usefulness of the ICN, efficiency is the most important rectification metric parameter. In addition, the reflection coefficient S11 is determined for different states. Figure 7 significantly illustrates how matching is improved by decreasing the return loss. Figure 8 shows that the efficiency is improved by almost 10% when using the circuit with only ICN and...
15% the ICN and PSO. The efficiency remains above 50% for the input power range of 4.5-19.5 dBm and a load range of 0.4-1KΩ. The results confirm our claims and are as expected. Figure 9 and Figure 10 shows two versions for a rectifier with ICN. The first one is before applying the PSO, and the second one is after applying the PSO.

**Figure 7.** Simulated return loss before and after optimization also, without ICN.

**Figure 8.** Simulated conversion efficiency of the rectifier with and without ICN in addition to PSO efficiency.

**Figure 9.** Configuration of rectifier based on single branch impedance compression network (ICN), before PSO.

**Figure 10.** Configuration of rectifier based on single branch impedance compression network (ICN), after PSO.

5. **Conclusion**

This paper was about to design a vital circuit that can beat the nonlinear impacts of diodes. This circuit was the impedance compression network ICN. As known, most ICN circuits consist of two branches, and an ICN with a single branch is rare in the literature. So this paper aimed to design and simulate a single branch ICN with a very small footprint which is about 4x4.2mm². Both real and imaginary parts of the input impedances show big compression after adding the ICN. Furthermore, the mathematical model of ICN proposed has been introduced. A real-world
application, which was the energy harvesting system is utilized and its efficiency was improved by 10%. The PSO algorithm has been utilized to find the best dimensions of the ICN components. The input impedance equation has been used as a fitness function, and the results demonstrated that fitness function converges very well when employing the PSO.

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