

PERVASIVE RF ENERGY HARVESTING SYSTEM USING MAGNETIC COUPLED RESONANCES

Field of the Invention

5 This invention relates to an apparatus for harvesting RF energy from the environment. More particularly, this invention relates to an apparatus having a receiver to harvest RF energy from the environment. Still more particularly, this invention relates to an apparatus having a particular antenna arrangement to harvest RF energy from the environment.

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Prior Art

 The advances of technologies have allowed the decrease in both size and power consumption of complex electronics system. This reduction in size and power has also made it possible for small devices such as wearable and wireless sensor networks to perform complex task and run on small low-voltages portable batteries. However, batteries present several disadvantages such as the need to replace and recharge periodically. As the number of body-worn electronics continues to increase, the continuous reliance on batteries can be both cumbersome and costly.

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20 More recently, an alternative to battery has been explored to supplement or even replace the batteries altogether, namely harvesting energy from the environment. For purposes of this discussion, harvesting energy from the environment means to draw part or all of its power from the environment. As power requirement continues to decrease with new technology, ambient energy sources are becoming more feasible to replace the traditional battery.

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In a battery-powered device, the typical power management goal is to minimise the energy consumption thus prolonging the lifetime of the battery while meeting the performance constraints. In an energy-harvesting device, the harvested energy is used to supplement the battery thus prolonging the life of the battery and if the energy can be
5 harvested continuously at an appropriate rate, the system can operate indefinitely in such devices. A key distinction of this energy harvested from the environment and then stored in the battery is that this energy is potentially infinite; although there may be a limit on the rate it can be used.

10 Radio frequency (RF) energy is transmitted by source that generates high electromagnetic fields. RF energy is most pervasive as it can be transmitted from the source to many receivers or energy harvester sensor nodes. Unlike thermal, vibrational or acoustic, no extreme operating condition is required. The amount of energy picked up by the wearable or sensor nodes in mW or μ W can be used to charge the battery or to power
15 battery-free micro-devices.

Harvesting energy from ambient sources to power up mobile devices makes wireless sensor network not only environmentally friendly but also self-sustaining. One method is described in "A. M. Zungeru, L. M. Ang, S. Prabaharan, and K. P. Seng, "Radio
20 frequency energy harvesting and management for wireless sensor network," Green Mobile Devices and Netw.: Energy Opt. Scav. Tech., CRC Press, pp. 341-368, 2012". In Zungeru et al., the product disclosed achieved harvesting power of 3.5mW at a distance of 0.6 meter and 1μ W at a distance of 11 meter using Powercast RF energy harvester operating in 915MHz. However, one of the drawbacks of this product is that the product
25 requires a RF transmitter to make the RF energy harvesting system work. This defeats the purpose of demonstrating RF energy harvesting from the environment.

Hence, those skilled in the art are striving to provide a system that is capable of harvesting RF energy from the environment.

Summary of the Invention

5 The above and other problems are solved and an advance in the art is made by a Radio Frequency (RF) energy harvesting apparatus in accordance with this invention. A first advantage of a Radio Frequency (RF) energy harvesting apparatus in accordance with this invention is that the Radio Frequency (RF) energy harvesting apparatus provides a high quality factor. A second advantage of a Radio Frequency (RF) energy harvesting
10 apparatus in accordance with this invention is that the Radio Frequency (RF) energy harvesting apparatus is able to harvest ambient RF energy which would otherwise be wasted. This means that ambient RF energy can be recycled and used for powering electronic devices.

15 In accordance with an aspect of the invention, a RF energy harvesting apparatus is provided. The RF energy harvesting apparatus for harvesting ambient RF energy includes an antenna assembly, a RF-DC converter and an energy storage. The antenna assembly comprises a first magnetic coil, a second magnetic coil in parallel connection with the first magnetic coil, a capacitor in parallel connection with the first magnetic coil,
20 and a load resistor in parallel connection with the capacitor. The first magnetic coil has a greater inductance value than the second magnetic coil, wherein the first magnetic coil is arranged to capture the ambient RF energy and the second magnetic coil reduces the total inductance to achieve a high quality factor. The RF-DC converter is coupled to the load resistor for converting the ambient RF energy captured from the antenna assembly
25 to Direct Current voltage. The energy storage is coupled to the RF-DC converter for storing the DC voltage.

In accordance with an embodiment of the invention, the first magnetic coil includes at least two rectangular coils and the second magnetic coil includes a rectangular coil.

5 In accordance with an embodiment of the invention, the RF-DC converter is a 8 stage rectifier circuit. Further, the energy storage is in a form of a material that stores electrical energy. Preferably, the capacitor is a variable capacitor. Preferably, the first magnetic coil has a bigger surface area than the second magnetic coil.

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Brief Description of the Drawings

The above and other features and advantages in accordance with this invention are described in the following detailed description and are shown in the following drawings:

15 Figure 1 illustrating a block diagram of a RF energy harvesting apparatus in accordance with an embodiment of this invention;

Figure 2 illustrating a first antenna arrangement in accordance with embodiments of this invention;

20 Figure 3 illustrating a circuit for the first antenna arrangement in accordance with an embodiment of this invention;

Figure 4 illustrating a second antenna arrangement in accordance with an embodiment of this invention;

Figure 5 illustrating a circuit for the second antenna arrangement in accordance with an embodiment of this invention;

25 Figure 6 illustrating a third antenna arrangement in accordance with an embodiment of this invention;

Figure 7 illustrating a circuit for the third antenna arrangement in accordance with an embodiment of this invention;

Figure 8 illustrating a simplified circuit of the circuit for the third antenna arrangement in accordance with an embodiment of this invention;

5 Figure 9 illustrating an antenna configuration in accordance with an embodiment of this invention;

Figure 10 illustrating an example of an 8 stage rectifier circuit;

Figure 11 illustrating a RF energy harvesting apparatus being conducted with 7 antennas in accordance with an embodiment of this invention; and

10 Figure 12 illustrating an antenna assembly of the RF energy harvesting apparatus in accordance with an embodiment of this invention.

Detailed Description

This invention relates to an apparatus for harvesting RF energy from the environment. More particularly, this invention relates to an apparatus having a receiver to
15 harvest RF energy from the environment. Still more particularly, this invention relates to an apparatus having a particular antenna arrangement to harvest RF energy from the environment.

20 Fig. 1 shows a block diagram of a RF energy harvesting apparatus 100. The RF energy harvesting apparatus 100 includes an antenna assembly 110, a RF to DC converter 120, energy storage 140. One skilled in the art will recognise that other optional circuitries may be included without departing from the invention such as a DC to DC converter 130 between the RF-DC converter 120 and energy storage 140 for stepping
25 up or stepping down the voltage to a suitable level.

Antenna assembly 110 receives the RF energy in the surrounding. Antenna assembly 110 is in a particular arrangement that achieves high Quality factor. Further details of the antenna assembly 110 will be described below.

5 RF energy received by the antenna assembly 110 will be transmitted to an RF-to-DC converter 120. The RF to DC converter 120 converts the signal in RF domain to DC energy. Further details of the RF to DC converter 120 will be described below.

Energy harvested is stored in energy storage 140. Energy storage 140 is material
10 that stores electrical energy such as electrical batteries, super capacitor, etc.

The RF energy harvesting apparatus 100 requires an antenna arrangement that is able to harvest sufficient electrical energy in order to drive the RF energy harvesting apparatus 100. Therefore, it is desirable for the antenna arrangement to have a high
15 Quality factor, Q , which translates to higher efficiency of harvesting ambient energy.

Figure 2 shows a first antenna arrangement 200. First antenna arrangement 200 includes a capacitor 210, inductor coil (round coil) 220 and load resistor 230. The capacitor 210 is in parallel connection with an inductor coil 220. The capacitor 210 is also
20 in parallel connection with the load resistor 230. The capacitor 210 may be a variable capacitor to allow the flexibility to harvest ambient RF energy at different frequency.

Figure 3 shows the equivalent circuit 300 of the first antenna arrangement 200 in a schematics diagram. The inductor coil 220 can be model as an inductor 222 in series
25 with a resistance R_s 221. The resistance R_s 221 is the loss of the inductor coil 220 and since the inductor coil 220 is made of conductor material, the resistance R_s 221 is very small and negligible. Hence resistance R_s 221 can be ignored for this case. Therefore,

first antenna arrangement 200 can be modelled as inductor L 222 parallel with capacitor C 210 parallel with load resistance R_L 230 after R_S is ignored. The circuit 300 presents a parallel resonant. The formula to compute the Quality Factor Q for parallel resonant is as following:

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$$Q = \frac{R_L}{X_L} = \frac{R_L}{2\pi fL}$$

where Q is the Quality factor, R_L is the load resistance, X_L is the reactance of the inductor, f is the resonance frequency and L is the inductor value.

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In order to achieve a high Q , we need to increase R_L and decrease X_L as shown in the following expression indicated by the arrows.

$$Q \uparrow = \frac{R_L \uparrow}{X_L \downarrow} = \frac{R_L \uparrow}{2\pi fL \downarrow}$$

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However, it is unlikely to change R_L because R_L is the resistance of the load (i.e. resistance of application device). Hence, we can only attempt to decrease X_L by reducing inductor L since the resonance frequency f is dependent on the ambient frequency to be harvested. Inductor L is proportional to the surface area of catchment as inductor L is proportional to width and height of the antenna and the number of turns as shown in the following expression,

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$$L \approx N^2 \frac{\mu_0 \mu_r}{\pi} \left[-2(w + h) + 2\sqrt{h^2 + W^2} - h \ln \left(\frac{h + \sqrt{h^2 + W^2}}{W} \right) - W \ln \left(\frac{W + \sqrt{h^2 + W^2}}{h} \right) + h \ln \left(\frac{2h}{a} \right) + W \ln \left(\frac{2W}{a} \right) \right]$$

Where N is the number of turns, W is the width of the rectangular in meter, h is the height of the rectangular in meter, a is the wire radius in meter, μ_r is the relative permeability of the medium, and L is the inductance (H).

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Hence it is very challenging to achieve a high Q by lowering inductor L based on first antenna arrangement 200.

Figure 4 illustrates a second antenna arrangement 400. The second antenna arrangement 400 includes a capacitor 410, a first inductor coil 420, a second inductor coil 425 and load resistor 430. The capacitor 410 is in parallel connection with first inductor coil 420 while the load resistor is in parallel connection with the second inductor coil 425. The capacitor 410 may be a variable capacitor to allow the flexibility to harvest ambient RF energy at different frequency. Second antenna arrangement 400 includes two receiver coils 450 and 460. One of the coils 450 is connected with a capacitor and the other coil 460 is connected with the resistance load R_L .

Figure 5 shows the equivalent circuit 500 of the second antenna arrangement 400 in a schematics diagram. The first inductor coil 420 can be modelled as first inductor L 421 in series with a resistance R_S 422 and the second inductor coil 425 can be modelled as second inductor L 426 in series with a resistance R_S 427.

Essentially, second antenna arrangement 400 is such that the capacitor 410 is separated from the load resistance 430. First receiver coil 450 is intended to receive the ambient energy dissipated by a transmitter. The ambient energy received by first receiver coil 450 is then passed to second receiver coil 460 through magnetic coupling.

Hence in the second antenna arrangement 400, instead of parallel resonant, the schematics show a series resonant for first receiver coil 450. The resistance of the inductor coils, R_s 422 cannot be ignored for this case. From the equivalent circuit 500, the formula to compute the Quality Factor Q for series resonant is as following:

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$$Q = \frac{X_L}{R_s} = \frac{2\pi fL}{R_s}$$

where Q is the Quality factor, R_s is the resistance of the inductor coils (R_s 422), X_L is the reactance of the inductor, f is the resonance frequency and L is the inductor value.

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In order to achieve a high Q , we need to increase X_L and decrease R_s as shown in the following expression indicated by the arrows.

$$Q \uparrow = \frac{X_L \uparrow}{R_s \downarrow} = \frac{2\pi fL \uparrow}{R_s \downarrow}$$

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In physic, the bigger the catchment area or surface area, the more RF energy we can harvest and hence in turn we have a high inductor value. It is very easy and desirable for this case to obtain a high L which in turn produces a high X_L . R_s by nature is small and hence the overall Q will be much larger as compared to the first antenna arrangement 200. However, the first receiver coil 450 needs to re-transmit the energy to second receiver coil 460 through inductive coupling. Hence, the distance between the first receiver coil 450 and second receiver coil 460 needs to be close together and even though when they are very close to each other, the efficiency is around 70%. Thus, there is quite a sustainable loss for RF energy harvesting.

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Figure 6 shows a third antenna arrangement 600. The third antenna arrangement 600 includes a first receiver coil 650 and second receiver coil 660. The second receiver coil 660 is smaller than the first receiver coil 650. The first receiver coil 650 includes a capacitor 610, inductor coil 620 and load resistor 630. The capacitor 610 is in parallel connection with an inductor coil 620. The capacitor 610 is also in parallel connection with the load resistor 630. The second receiver coil is in parallel connection with the load resistor 630. The capacitor 610 may be a variable capacitor to allow the flexibility to harvest ambient RF energy at different frequency.

Figure 7 shows the equivalent circuit 700 of the antenna arrangement 600 in a schematics diagram. The first inductor coil 620 can be modelled as first inductor L_1 621 in series with a resistance R_s 622 and the second receiver coil 660 can be modelled as second inductor L_2 661 in series with a resistance R_s 662. The R_s 622 and 662 are very small and negligible. Hence R_s 622 and 662 can be ignored for analysis purpose. The equivalent circuit 700 can be simplified by combining the 2 parallel inductors as shown in figure 8. The equation to combine the parallel inductors L 661 and 621 to derive at inductor L_T 710 is as follows,

$$L_T = \frac{L_1 \times L_2}{L_1 + L_2}$$

As mentioned above, the formula to compute the Quality Factor Q for parallel resonant is as follows:

$$Q = \frac{R_L}{X_L} = \frac{R_L}{2\pi f L_T}$$

In order to achieve a high Q , we need to increase R_L and decrease X_L as shown in the following expression indicated by the arrows.

$$Q \uparrow = \frac{R_L \uparrow}{X_L \downarrow} = \frac{R_L \uparrow}{2\pi f L_T \downarrow}$$

Based on the equation above for combining parallel inductors, L_T is almost equal to the smaller number of L_1 or L_2 . Hence, we can conclude the L_T has the lower inductor value between L_1 and L_2 . Hence, we can have a high L_1 to capture the RF energy in the surrounding and a low L_2 so that the overall inductor L_T is small and in turn achieve a high Q. One skilled in the art will recognise that when the coil 620 is larger than the coil 660, in terms of physical size, the inductance value of the coil 620 is greater than the inductance value of coil 660. This can also work if we replace the coil with a smaller inductance value with a high Q lump element.

Figure 9 illustrates an antenna assembly 900 which is based on third antenna arrangement 600. Antenna assembly 900 includes a first magnetic coil 910 and a second magnetic coil 920. The first magnetic coil 910 has a bigger surface area and hence a bigger inductor value that is intended to capture the RF energy in the air. The first magnetic coil 910 includes a first rectangular coil 911 and a second rectangular coil 912. Diamond shape coils 913 and 914 are provided within each of the first and second rectangular coils 911 and 912 respectively. One skilled in the art will recognise that the diamond shape coils 913 and 914 may be altered into other shapes without departing from the invention. The second magnetic coil 920 includes a third rectangular coil 921. The second magnetic coil 920 has a smaller inductor values to achieve a smaller overall inductor L_T . The second magnetic coil 920 is in parallel connection with the first magnetic coil 910. The first, second and third rectangular coils 911, 912 and 921 are identical in dimension. This allows the antenna assembly 900 to be easily reproduced. Nevertheless, one skilled in the art will recognise that the rectangular coils 911, 912 and 921 may be

altered into other shapes without departing from the invention. Briefly, the antenna assembly 900 requires two magnetic coils 910 and 920 in parallel connection, one having a higher inductance value to capture the energy in the air and the other having a smaller inductance value to reduce the total inductance value so as to achieve a high Q. In other words, the magnetic coils may be in any other shapes without departing from the invention.

The RF energy harvested from the antenna assembly is being converted to DC voltage by the RF-DC converter 130. The RF-DC converter 130 is a rectifier circuit. Figure 10 shows a schematic of an eight-stage voltage doubler. Some examples of RF-DC converters are Cockcroft-Walton voltage multiplier, Dickson charge pump, Seiko S-882Z IC Charge pump, etc.

Figure 11 shows a RF energy harvesting apparatus with 7 antennas being assembled for a test. Figure 12 shows one of the 7 antennas being used when conducting the test. As shown in figure 12, the antenna corresponds with the antenna assembly 900 described above. The antenna is being configured such that the capacitor is being tuned to receive frequency of 900MHz for harvesting the ambient RF for GSM900 network. When the RF energy harvesting apparatus is being placed at a location in Singapore, the RF energy harvesting apparatus is able to harvest energy from ambient air of 3.72v. A further test using a scientific calculator is being conducted to determine if the energy harvested is sufficient to drive the scientific calculator by connecting the scientific calculator to the energy storage. The test results are favourable and the scientific calculator is able to function properly. Although figure 11 shows an example of a RF energy harvesting apparatus with 7 antennas, one skilled in the art will recognise that any other number of antennas may be implemented without departing from the invention.

The above is a description of exemplary embodiments of a RF energy harvesting apparatus in accordance with this invention. It is foreseeable that those skilled in the art can and will design alternative apparatus or system based on this disclosure that infringe
5 upon this invention as set forth in the following claims.

Claims:

1. A Radio Frequency (RF) energy harvesting apparatus for harvesting ambient RF energy comprising:

an antenna assembly comprising a first magnetic coil, a second magnetic coil in parallel connection with said first magnetic coil, a capacitor in parallel connection with said first magnetic coil, a load resistor in parallel connection with said capacitor, said first magnetic coil has a greater inductance value than said second magnetic coil, wherein said first magnetic coil has a bigger surface area than said second magnetic coil and is arranged to capture said ambient RF energy and said second magnetic coil reduces the total inductance to achieve a high quality factor;

an RF-DC converter coupled to said load resistor for converting said ambient RF energy from said antenna assembly to Direct Current (DC) voltage; and

an energy storage coupled to said RF-DC converter for storing said DC voltage or energy.

2. The RF energy harvesting apparatus according to claim 1, wherein said first magnetic coil includes at least two rectangular coils and said second magnetic coil includes a rectangular coil.

3. The RF energy harvesting apparatus according to claim 1, wherein the RF-DC converter is a 8-stage rectifier circuit.

4. The RF energy harvesting apparatus according to claim 1, wherein said energy storage is in a form of a material that stores electrical energy.

5. The RF energy harvesting apparatus according to claim 1, wherein said capacitor is a variable capacitor.

6. The RF energy harvesting apparatus according to claim 1 further comprising a DC-DC converter.