Proceedings
9th International Conference on Structural Health Monitoring of Intelligent Infrastructure
August 4-7, 2019 – St. Louis, Missouri (USA)

A High-Efficiency Wireless Power Link for Structural Health Monitoring

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Abstract

Powering of remote sensors (i.e., bridge sensors, drones, etc.) for long term structural health monitoring is a critical challenge where the electrical power supply is not readily available. Due to the limited energy density, lack of availability of harvested power (i.e., if the node continues to perform tasks while the stored energy is low, it will eventually die), and risk of vandalism, energy harvesting schemes are either unsuitable or applicable for only low data rate sensor applications. A high performance inductive link and subsequent energy conversion blocks as an integral part of the wireless power supply unit can effectively eliminate these challenges. This paper reports a high efficiency inductive power link and follow-up switched-capacitor (SC) DC-DC converter for wireless power transfer. Unlike conventional two-coil wireless link, multiple coupled inductive coils in resonance mode can provide higher degrees of freedom, increase transmission distance and overall power-transfer-efficiency from a transmitter unit to a receiver unit with low coupling coefficient. A new complementary SC DC-DC converter is proposed to recover the power efficiently on the receiver side. The proposed complementary SC DC-DC converter can achieve multiple conversion ratios by changing switching sequence as well as decreases the DC ripple voltage. The overall power consumption of complementary SC DC-DC converter is only 2.25 µW. The system has been designed using 0.13-µm standard CMOS process with off-chip opamp, Zener diode and inductors.

1. Introduction

With the continuous improvement of communication frequency and bandwidth, internet of things (IOT) has developed rapidly. In such a large-scale application of the IOT, powering of remote sensors for long term structural health monitoring is a critical challenge where the power supply is not readily available. Wireless power transfer (WTF) is a non-contact power supply technology, which effectively solves the problem that some sensor limited to energy density and lack the ability to harvest power [1].

Inductive power link is the main component in wireless power transfer technology, which helps wirelessly transfer power from a power source (inductive transmitter) to a power load (inductive receiver). According to the electromagnetic coupling principle, the inductive transmitter uses an induction coil to establish an alternating electromagnetic field from the charging base, and at the same time, a second coil embedded in the portable device receives the electric power from the electromagnetic field, and then converts it into an electric current for use in either supplies power to device or charges the battery.

Inductive power transmission is especially interesting in near-field, where a high efficiency can be realized. However, the RF power transfer suffers from long distance and poorly coupled coefficient.

And for battery's fast wireless charging and DC type load driving circuit, the inductive power transmission lacks the ability to handle DC variability [2][3][4][5].

In this paper, a high efficiency inductive power link is proposed shown in Fig.1. The inductive power transmission system contains a three-coils loosely coupled architecture with a differential injection-locked power oscillator to achieve high power-transfer-efficiency (PTE). And a complementary switched-capacitor (SC) DC-DC converter block achieves multiple conversion ratios and decreases the DC ripple voltage connected between the rectifier and the load block.

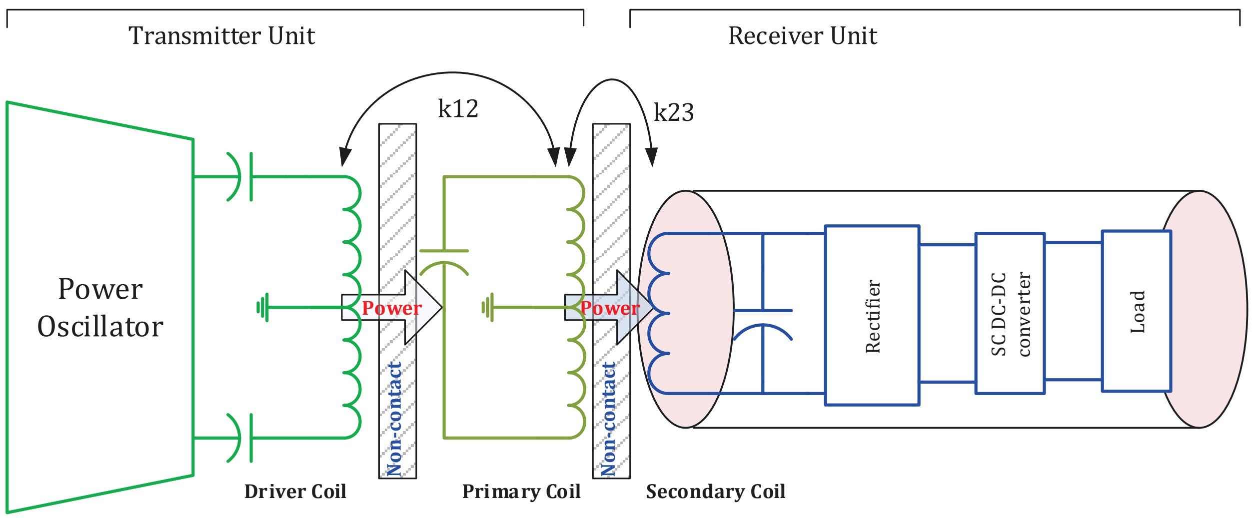

Fig.1 System block diagram

2. Proposed System Architecture

The system block diagram of the proposed inductive power link has been shown in Fig.1. The heart of the inductive power link system is the three resonant link coils and the multiple conversion ratios SC DC-DC converter. The proposed wireless power link contains a transmitter unit and receiver unit separately. In the transmitter unit, a differential injection-locked power oscillator as a driver circuit to improve the PTE connects with the driver coil of the three-coils inductive link. In the receiver unit, an optimized full integrated SC DC-DC converter circuit connects with a voltage regulator to power the load circuit.

2.1 Inductive Link Coils

For a three coils power transfer model, the link system manifests a driver coil, a primary or dummy coil and receiver load coil. Unlike a couple-mode theory, it is much more convenient for the circuit designer to use circuit theory to track down the currents and voltages [5]. Since the differential architecture of inductor design offers higher quality factor with compact design area, the proposed project is intended to implement all the coils with differential architectures. The PTE of a 3-coil system is:

$$\eta = \frac{k_{12}^2 Q_1 Q_2}{1 + k_{23}^2 Q_2 Q_3} \quad (1)$$

when Q2 >> Q3 > Q1, where Q1, Q2 and Q3 represent the quality factors of the driver coil, the primary coil and the receiver load coil, respectively. k12 and k23 represent the coupling coefficients between the driver coil and the primary coil, and in between the primary coil and the receiver load coil, respectively.

2.2 Complementary SC DC-DC Converter

The SC DC-DC converter is one subset of the power DC-DC converter, which is only consisted of switches and capacitors [5][6]. As there is no inductive component in an SC DC-DC converter, it is suitable for inductive power link since it does not affect the coupled coefficient. An SC DC-DC converter could implement one or several different topologies, where the converter can achieve multiple conversion purposes. By changing the control signal's timing sequence, the capacitors will be into charging state and discharging state alternately. The proposed 3:1 complementary ladder SC DC-DC converter is shown in Fig. 2, which the output voltage is one-third of the input voltage.

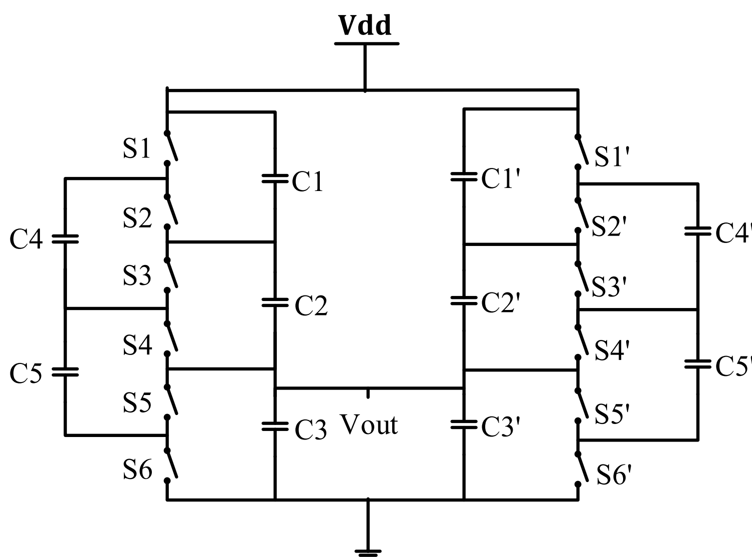

Fig.2 Complementary ladder SC DC-DC converter diagram

The proposed converter circuit controlled by two non-overlapped square wave signals, Φ1 and Φ2. Switches group S1, S3, S5, S2', S4' and S6' are controlled by Φ1, the other group S2, S4, S6, S1', S3' and S5' are controlled by Φ2.

3. Simulation results

3.1 Impact of three coils inductive link

Equation (1) is a combinatorial problem and the highest efficiency could come from different combinations of k12, k23, Q1, Q2 and Q3. Simulation results as shown in Fig. 3 show the effects of Q1 and Q2 variations for a typical combination of Q3=5, k12 = 0.16 and k23 = 0.45. Theoretically infinite combinations are possible, but the research question is what option is optimal for a typical battery wireless power transfer application.

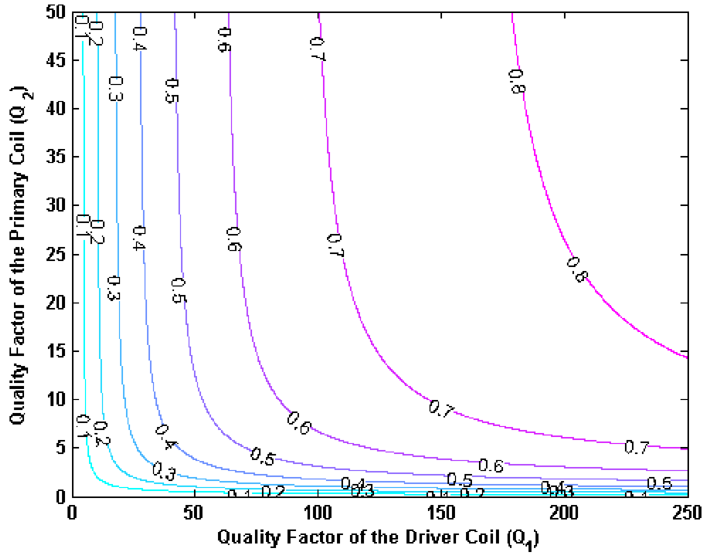

Fig.3 Effect of Q1 and Q2 on PTE using Eq.1

3.2 Impact of Complementary SC DC-DC Converter

Under a resistive load of 50Ω, input voltage of 1 Volt, and switching frequency of 200 MHz, the DC output voltage of the complementary converter is 328.7 mV and the ripple voltage is 12.7 mV under steady state. The SC converter with complementary topology improve the steady-state output voltage and decrease the DC voltage ripple. The overall power consumption of complementary SC DC-DC converter is 2.25 μW. The circuit is simulated under Cadence with IBM cmrf8sf 0.13-μm standard CMOS process.

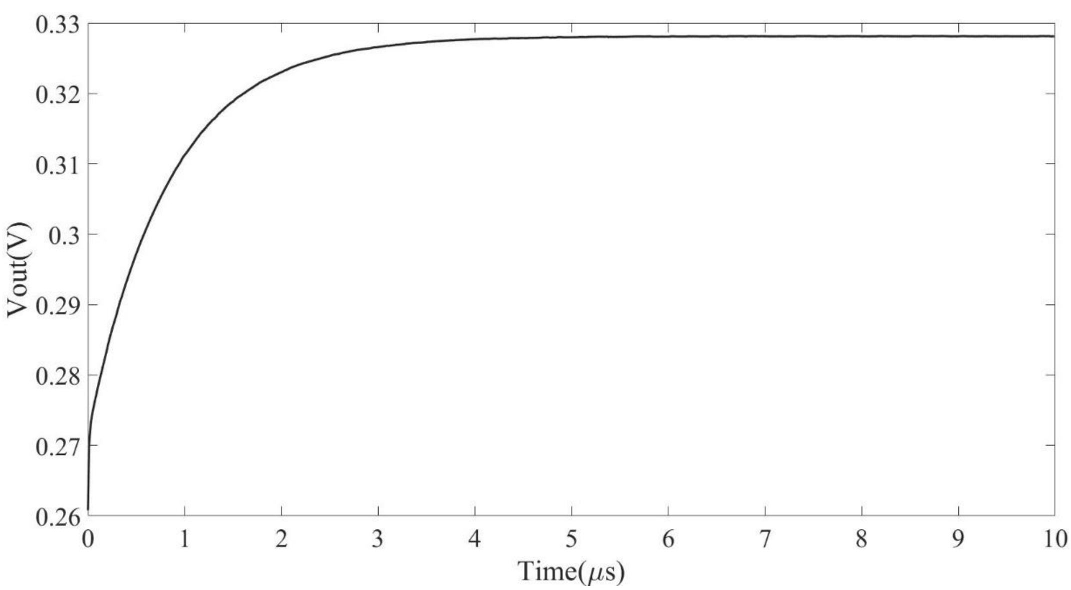

Fig.4 Output for complementary SC DC-DC converter

4. Conclusion

In this paper, a high efficiency inductive power link and complementary SC DC-DC converter for structural health monitoring applications have been presented. In this design, the conventional two stage inductive coils have been replaced by a high efficiency three stage coils to achieve higher PTE. The linked power signal is converted to DC signal by a rectifier and an SC DC-DC converter unit. The SC DC-DC converter achieves multiple conversion ratios by changing the switching sequence. The system has been designed and simulated using 0.13μm cmrf8sf CMOS process with off-chip inductors, Zener diode. The proposed inductive link with SC DC-DC converter circuit is designed and simulated for long term structural health monitoring applications to solve the difficulties in the energy harvesting and to enhance the power transfer efficiency under large scale sensors network.

Acknowledgment

The work was supported in part by National Science Foundation (NSF) Award CNS-1645863 and Award ECCS-1813949.

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