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Stabilizing the Operating Frequency of a Resonant Converter for Wireless Power Transfer to Implantable Biomedical Sensors

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Abstract

Resonant converters have been applied in wireless power supplies for implantable sensors due to their inherent advantages of low cost, high frequency and high reliability. However, the operating frequency of the resonant converter varies with the load and circuit parameters changes, which can significantly reduce the maximum power that the system can transfer. As a result the implanted sensors may not work properly because of insufficient power delivery. Uncertainty in frequency associated with system instability can contribute to electromagnetic interference for the implanted sensors, wireless communication networks, and other peripheral electronic devices. This paper proposes a new method to stabilize the system operating frequency using a fixed capacitor whose equivalent capacitance is controlled by semiconductor switches. Two control strategies based on Zero Voltage Switching techniques are analysed in details and practically implemented. The simulation and experimental results have demonstrated that the proposed method performs well in stabilizing the operating frequency of a wireless power supply system while maintaining the complete soft switching operation of the resonant converter.

Keywords: wireless power, implantable sensor, frequency stabilization, resonant converter.

1 Introduction

A novel wireless power (WP) supply system has been developed by the Department of Electrical and Computer Engineering, the Bioengineering Institute of the University of Auckland, to supply contactless power over a highly variable air gap to implanted sensors. The aim of this research is to develop a power supply system suitable for powering implantable physiological sensors for use in humans and animals. The WP supply system offers continuous operation with complete freedom of movement mitigating the need for any percutaneous link [1, 2]. In addition, where power needs are high, a WP system can provide continuous operation with reduced size compared to systems relying on implanted batteries.

Figure 1 shows the basic topology of a WP supply system. A current-fed push-pull type of converter is selected to drive a resonant circuit because it is low cost, small in physical size, very reliable and has high efficiency [3]. This type of current-fed resonant converter can easily be designed to operate at high frequencies at hundreds of kHz level, which is a major factor contributing to minimizing the physical size of the implanted power pick-up circuit. Meanwhile, the resonant circuit enables soft-switching operation of semiconductor switches, which help to reduce circuit losses and system EMI (Electro-magnetic interference) [4]. A high frequency magnetic field is generated by the resonant circuit formed by capacitor C and inductor L in figure 1. This magnetic field induces electrical power from an implanted pick-up to power the implanted sensors.

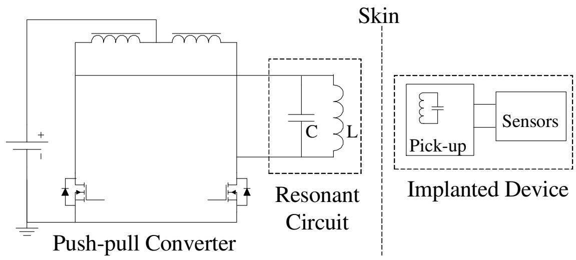


Figure 1: Basic configuration of a WP supply system.

One problem with the basic circuit configuration is that the operating frequency of this type of current-fed resonant converter varies with the load and circuit parameter changes. The frequency variation can significantly reduce the maximum power that can be transferred due to the resultant detuning of the power pick-up. The implanted sensors may not work properly due to insufficient power delivery. This problem can be overcome by implementing a constant frequency resonant converter [4-7]. Constant frequency operation is straight forward for hard switched pulse width modulation (PWM) converters but it has been a challenging task for resonant converters due to the difficulties involved in the soft switched operation. This paper proposes a new approach to stabilizing the operating frequency of a wireless power system for implantable sensors, while maintaining full ZVS (Zero Voltage Switching) operation of a push-pull current-fed resonant converter.

2 Proposed Method for Stabilizing Operating Frequency

Figure 2 shows the proposed circuit configuration for stabilizing frequency of a WP supply system based on a current-fed resonant converter. In addition to the power source and the inverting network, there is a resonant circuit including an inductor L, a fixed capacitor C and a variable capacitor C_s [8, 9]. Under steady state conditions, if harmonics are ignored, the resonant voltage v_r is approximately a sinusoidal waveform [4]. The circuit oscillation depends on the inductance L and the total parallel capacitance consisting of C and C_s in the resonant circuit. As a result, the operating frequency can be approximated using equation (1). Here C_{eq} is the equivalent variable capacitance of the capacitor C_s.

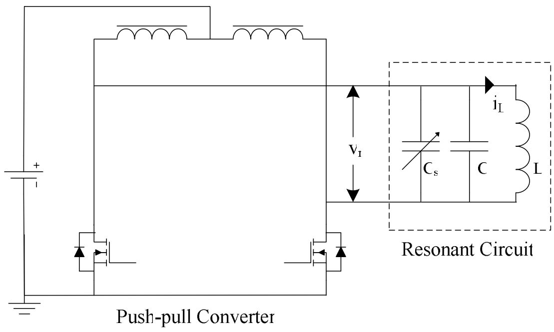
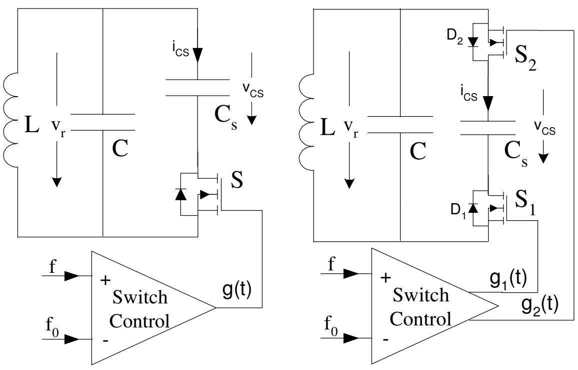


Figure 2: Proposed strategies for stabilizing frequency.

$$f = \frac{1}{2\pi\sqrt{L(C + C_{eq})}} \tag{1}$$

The true operating frequency of the converter is more complicated than that given by equation (1). The resonant frequency is also influenced by factors including the load, switching harmonics, component tolerances and temperature. However, equation (1) shows that by varying the equivalent capacitance C_{eq}, the final operating frequency of the converter can be compensated for multiple causes of frequency changes.

Dynamically varying the capacitance can be achieved in a number of ways. Figure 3 illustrates two strategies for implementing a variable capacitor controlled by a frequency feedback loop. In figure 3 (a), the capacitor C_s is switched by a single semiconductor switch S, the equivalent capacitance of C_s can be varied by changing the on duty-cycle of this switch. In figure 3 (b) the capacitor C_s is switched using two identical switches S_1 and S_2 [8]. Similarly, the equivalent capacitance of C_s of the dual switches can be adjusted by controlling the duty-cycles of the switches, but for a larger range than figure 3 (a). In both the situations shown in figure 3, f_0 is the reference frequency which is set to the constant value required. The measured real-time operating frequency f is compared with f_0 to generate a gate control signal g(t) for switch S in figure 3 (a), or $g_1(t)$ and $g_2(t)$ for switches S_1 and S_2 in figure 3(b), to control the semiconductor switches for frequency stabilisation. If for some reason (e.g. magnetic field saturation) inductance L decreases, frequency f will increase according to equation (1). Due to the increased difference between f and f_0, the on duty-cycle of the gate control signal will also increase. Thus, the equivalent capacitance of C_s will increase, leading to a decrease in frequency. If the controller is designed properly the system frequency should move back towards its original setting, thus the frequency is stabilised.



(a) Single side switch (b) Dual side switch

Figure 3: Switched capacitors in a resonant tank.

3 Theoretical Analysis of Frequency Variation

The equivalent capacitance of the switched capacitor is analysed to evaluate its effect on the operating frequency of a resonant circuit. The two switching strategies shown in figure 3 are analysed individually.

3.1 Equivalent Capacitance of a Single Side Switched Capacitor

For the resonant circuit using a single side switched capacitor as shown in figure 3 (a), if voltage v_r is assumed to be pure sinusoidal, the waveforms of the voltages across capacitor C and C_s can be illustrated as v_C and v_{CS} shown in figure 4. θ is defined as the switching angle, its value has to be between 0 and π/2. The switch S is switched off only during the interval of [θ, π-θ], and in this interval the voltage across capacitor C_s is a constant V_{dc}.

The relationship between switching angle and voltages can be expressed below:

$$\theta = \arcsin\left(\frac{V_{dc}}{V_{ac}}\right) \tag{2}$$

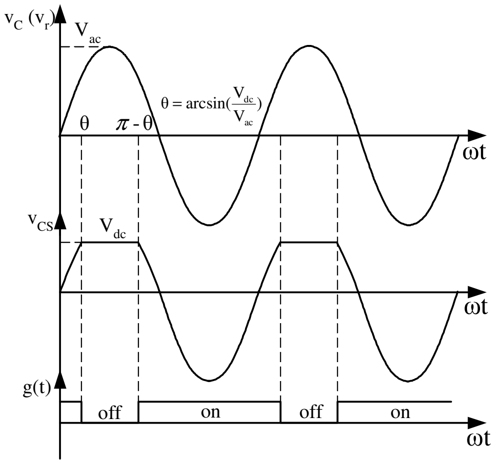


Figure 4: Voltages and control signal in single side switching.

Considering that the absolute value of electric charge Q of a switched capacitor C_s during one period should be the same as that of using an equivalent capacitor with capacitance C_{eq}, an integral equation can be obtained as:

$$\int_0^{2\pi} C_{eq} V_{ac} \left|\sin(\omega t)\right| d(\omega t) = \int_0^{2\pi} C_S \left|v_{CS}\right| d(\omega t) \quad (3)$$

where ω is angular frequency ω=2πf. Equation (3) can be further extended to be:

$$\begin{aligned} 4C_{eq}V_{ac} &= \int_0^{\theta} C_S V_{ac}\sin(\omega t)d(\omega t) + \int_{\theta}^{\pi-\theta} C_S V_{dc} d(\omega t) \\ &+ \int_{\pi-\theta}^{\pi} C_S V_{ac}\sin(\omega t)d(\omega t) + \int_{\pi}^{2\pi} C_S V_{ac}\left|\sin(\omega t)\right|d(\omega t) \end{aligned} \quad (4)$$

By solving equation (4), the equivalent capacitance C_{eq} of a single side switched capacitor can be obtained as shown below:

$$C_{eq} = \frac{2C_S\left[2 - \cos(\theta)\right] + C_S \sin(\theta)\left[\pi - 2\theta\right]}{4} \quad (5)$$

It can be obtained from equation (5) that the equivalent capacitance C_{eq} in the single side switching method is equal to $C_s/2$ when the switch always keeps off (θ=0 and V_{dc}=0), and C_s when switch always keep on (θ=π/2 and $V_{dc}=V_{ac}$).

3.2 Equivalent Capacitance of a Dual Side Switched Capacitor

In the resonant circuit using the dual side switched capacitor C_s as shown in figure 3 (b), switch S_1 and S_2 are separately switched off during [θ, π-θ] and [π+θ, 2π-θ] periods. Figure 5 shows the waveforms of the voltages across capacitor C and C_s. It should be noted that the voltage across C_s is V_{dc} during [θ, π-θ] and -V_{dc} during [π+θ, 2π-θ].

Similar to analyzing the single side switched capacitor, the equivalent capacitance of a dual side switched capacitor can be analyzed based on the following integral equation:

$$\int_0^{\pi} C_{eq} V_{ac} \sin(\omega t) d(\omega t) = \int_0^{\pi} C_S v_{CS} d(\omega t) \quad (6)$$

Equation (6) can be further extended as:

$$\begin{aligned} 2C_{eq}V_{ac} &= \int_0^{\pi} C_S v_{CS} d(\omega t) \\ &= \int_0^{\theta} C_S V_{ac}\sin(\omega t)\,d(\omega t) + \int_{\theta}^{\pi-\theta} C_S V_{dc} d(\omega t) + \int_{\pi-\theta}^{\pi} C_S V_{ac}\sin(\omega t)d(\omega t) \end{aligned} \quad (7)$$

By solving equation (7), the equivalent capacitance C_{eq} can be obtained as shown below:

$$C_{eq} = \frac{2C_S\left[1 - \cos(\theta)\right] + C_S \sin(\theta)\left[\pi - 2\theta\right]}{2} \quad (8)$$

Similar to the result of analyzing the single side switching, equation (8) shows that C_{eq} equals to zero when both switches always keep off (θ=0 and V_{dc}=0), and equals to C_s when both switches always keep on (θ=π/2 and $V_{dc}=V_{ac}$).

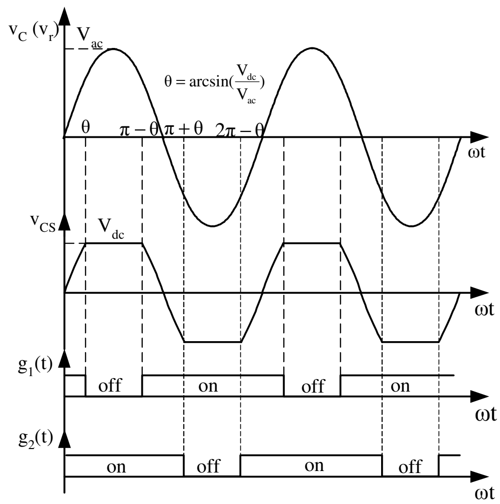


Figure 5: Voltages and control signal in dual side switching.

3.3 Effects of Switched Capacitor on Operating Frequency

If the maximum frequency variation is a result of the variation of the inductance L, then the equivalent capacitance required to compensate can be determined according to the following equation:

$$C_{eq} = \frac{1}{\omega_0^2 (L + \Delta L)} - C \quad (9)$$

Where ω_0 is the pre-designed angular frequency, $\omega_0 = 2\pi f_0$, ΔL is a disturbance of inductance L.

If the dual side switching method is used and the maximum increase in L is ΔL_+, then the capacitor C_s should be fully switched off (θ=0), corresponding to an equivalent capacitance of zero. Under such a condition, the resonant tank inductance should be fully tuned with the fixed capacitor to keep the operating frequency constant:

$$\frac{1}{\omega_0^2(L+\Delta L_+)} - C = 0 \tag{10}$$

Therefore, C can be determined by:

$$C = \frac{1}{{\omega_0}^2(L+\Delta L_+)} \tag{11}$$

After determining the value of fixed capacitor C, the maximum equivalent capacitance of the switched capacitor can then be calculated using equation (12). In this equation, ΔL_- is the maximum decrease in the value of L. Under these circumstances, the capacitor C_s should be fully switched on ($\theta = \pi/2$) for stabilizing the operation frequency.

$$C_{eq} = \frac{1}{\omega_0^2(L-\Delta L_-)} - C \tag{12}$$

As discussed before, C_{eq} in equation (12) is the maximum equivalent capacitance of a switched capacitor, which is also the value of C_s.

4 Complete ZVS Operation

Considering the power losses and power ratings of the semiconductor switches, as well as the current-fed push-pull switching network topology used, it would be ideal to achieve ZVS (Zero Voltage Switching) in the whole WP supply system. This eliminates the surge currents which can be potentially destructive in switching a capacitor. To ensure a ZVS operation, a phase shift control method is employed. Its basic structure is illustrated in figure 6. A f-v block converts frequency signal to a DC reference voltage v_{ref}. Then, this reference is compared with an ac signal v_{syn} to generate switch control signal(s). Because v_{syn} is designed to synchronize with the resonant voltage v_r (shown in figure 3) while v_{ref} varies with f, the switching angle θ will also vary with the measured frequency.

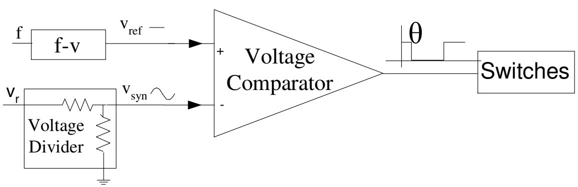


Figure 6: Basic structure of phase shift control.

Figure 7 shows the voltage v_{CS} and current i_{CS} of a dual side switched capacitor C_s as shown in figure 3 (b). It should be noted that when switch S_1 is switched on at phase angle π-θ, the current flow through the C_s is negative ($i_{CS} \leq 0$ as shown in figure 7), which means the current is flowing through the body diode D_1 (shown in figure 3 (b)). If the voltage drop of the body diode is ignored, ZVS is achieved because voltage across switch S_1 is zero when it is switched on. The situation with the single side switched capacitor (shown in figure 3 (a)) is similar, although only half a cycle is controlled.

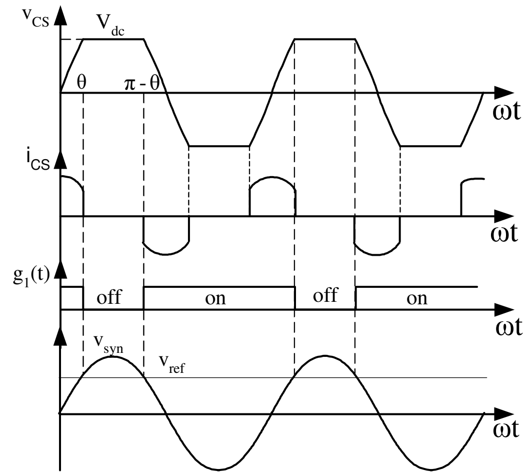


Figure 7: Voltage and current waveforms of C_s.

5 Simulation Results

Figure 8 shows the PSPICE simulation results of the proposed method as shown in figure 2. The variable capacitor is switched using the dual side switching strategy as shown in figure 3 (b). The capacitances of capacitor C and C_s are 150nF and 85nF respectively. The inductance of L is 25uH. It can be seen that the voltage and current waveforms are consistent with the analyzed results shown in figure 7.

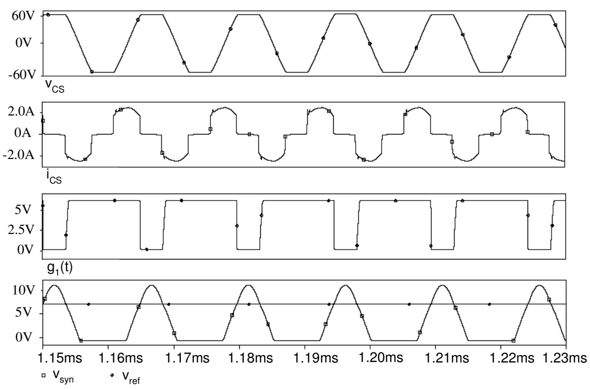
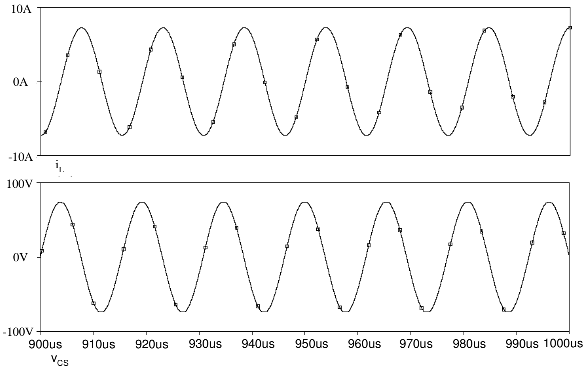


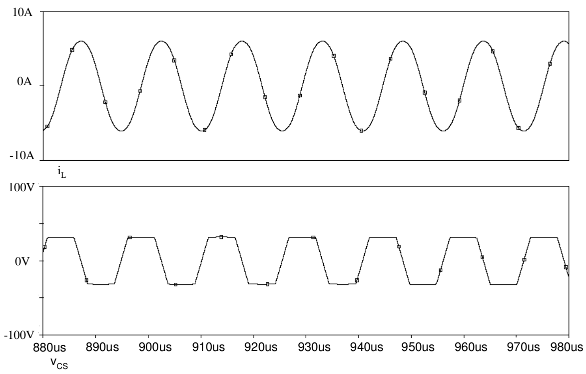
Figure 8: Simulation results of dual side switching.

Figure 9 illustrates that although resonant inductance L is changed from 25uH to 30uH, the frequency of the current i_L flowing through L is stabilized at a predetermined constant frequency (65kHz). That is achieved by decreasing switching angle θ to reduce the equivalent capacitance of the switched capacitor C_s, so that the increased inductance is compensated.

Based on the structure shown in figure 2, the single side switched capacitor method (shown in figure 3 (a)) is also simulated using PSPICE. Table 1 shows the calculated results f_{cal} of the operating frequency using equation (1) and (5), which is compared with simulated results f_{sim} by replacing switch and switched capacitor C_s with only a fixed capacitor, whose capacitance equals to the equivalent capacitance of switched C_s determined by equation (5). It can be seen that the calculated results are in good agreement with the simulation results. Also, it should be noted that the equivalent capacitance of C_S equals to the maximum value 100nF when the switching angle is about 1.57 rad (90^o), which is also consistent with the analytical results. These results show the validity of the derived equations for analyzing the equivalent capacitance of a switched capacitor.



(a) L=25uH



(b) L=30uH

Figure 9: Operations with constant frequency 65kHz.

Table 1: Calculated equivalent capacitance compared with simulation results (C=110nF, C_S=100nF).

θ (rad)	C_{eq} (nF)	f_{cal} (kHz)	f_{sim} (kHz)
0.08	56.14	78.09	77.50
0.16	61.89	76.78	75.83
0.24	67.35	75.58	74.17
0.33	72.53	74.51	73.33
0.42	77.63	73.49	72.50
0.52	82.56	72.54	71.67
0.63	87.37	71.65	70.83
0.77	92.05	70.82	70.00
0.96	96.30	70.08	69.17
1.29	99.63	69.52	68.33
1.57	100	69.46	68.33

6 Experimental Results and Discussion

A prototype resonant converter has been built and tested in laboratory. This converter is actually a current-fed push-pull converter combined with dual side switched capacitor in a resonant tank. The main parameters of the resonant tank used include inductance L=12.3uH, tuning capacitor C=237nF and switched capacitor C_s=147nF. The constant operating frequency of the converter is set at 87kHz. The dual side switching strategy as shown in figure 3 (b) is used to adjust the total capacitance of the resonant tank. Figure 10 shows the measured waveforms of the switched capacitor voltage and inductor current. In this diagram only the positive voltage is shown for easy measurements. Besides, it should be noted from figure 10 that the voltage of the switched capacitor is slightly distorted due to the effects of the switching harmonics. Nevertheless, the experiments show the conduction of the capacitor is fully controllable so that its equivalent capacitance can be varied to stabilize the frequency. Figure 10 clearly shows the system operates at the predetermined frequency of 87kHz. It has been found that under normal load and operating conditions, the maximum frequency drift is less than 300Hz.

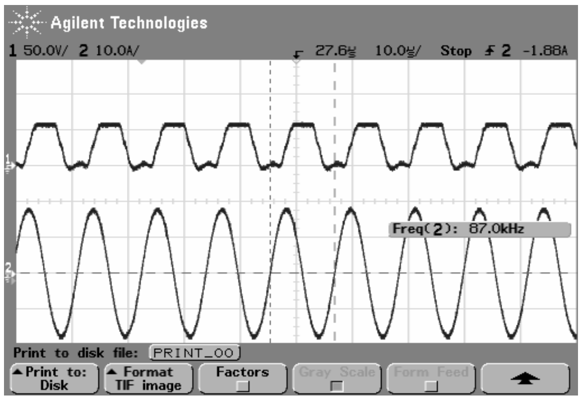


Figure 10: Experimental results of switched capacitor voltage and inductor current.

7 Conclusions

This paper has proposed a new method to stabilize the frequency of a wireless power supply system for implantable sensor applications. The equivalent capacitance of a resonant capacitor of a current-fed resonant converter is analysed in details. Two control strategies, being single side and dual side switching configurations, are proposed and practically implemented. Simulation and practical results have demonstrated that the proposed method is very effective in stabilizing the operating frequency while maintaining the full ZVS operation of current-fed resonant converters.

These methods provide a mechanism to maintain effective power transfer levels by providing a stable resonant frequency by varying the resonant capacitance to compensate for a wide variety of disturbances to the resonant circuit.

8 Acknowledgements

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9 References

[1] Chen, J. H. and Carr, W. N.: "Induction power supply designs for implanted biomedical integrated circuits", *Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, Vol. 12, 1990.

[2] Salim, A. Baldi, A. and Ziaie, B.:"Inductive link modelling and design guidelines for optimum power transfer in implantable wireless microsystems", *Proceedings of the 25th Annual International Conference of the IEEE EMBS*, Cancun, Mexico, 2003.

[3] Hu, A. P. and Si, P.: "A low cost portable car heater based on a novel current-fed push-pull inverter", *AUPEC conference 2004*, Australia, Aug 2004.

[4] Hu, A. P.: "Selected resonant converters for IPT power supplies", *PhD thesis, Department of Electrical and Computer Engineering, University of Auckland*, Oct 2001.

[5] Schuylenbergh, K. V. and Puers, R.: "Self tuning inductive powering for implantable telemetric monitoring systems", *The 8th International Conference on Solid-State Sensors and Actuators, and Eurosensors IX*, Stockholm, Sweden, 1995.

[6] Boys, J. T., Covic, G. A. and Xu, Y.: "DC analysis technique for inductive power transfer pick-up", *IEEE Power Electronics Letters*, Vol. 1, No. 2, 2003.

[7] Si, P. and Hu, A. P.: "Designing the dc inductance for ICPT power pick-ups", *The 5th IASTED International Conference on Power and Energy Systems*, Benalmadena, Spain, 2005.

[8] Hu, A. P. and Hussmann, S.: "*Improved* power flow control for contactless moving sensor applications" *IEEE power Electronics Letters*, pp:1 - 4, Issue: 99 , 2004.

[9] Hu, A. P., Chen, Z. J., Hussmann, S., Covic, G. A. and Boys, J. T.: "A dynamically on-off controlled resonant converter designed for coalmining battery charging applications", *Power System Technology, 2002. Proceedings. PowerCon 2002*. Volume 2, 13-17 Oct. 2002.