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Power Amplifier Frequency Controller Using feedback control techniques for Bio-implanted Devices

***Abstract:** Switch mode power amplifier is used in biomedical devices widely. The power amplifier supplies the required operating power to the implanted devices. Zero voltage switching (ZVS) operation of class-E power amplifier leads to convert DC voltage to AC with high efficiency and workings frequency. Frequency has a great function in powering most of the biomedical implanted devices. Frequency shift caused by inductors and capacitors used in the circuit can cause load variation or changing in mutual displacement or they may lead to instability and data loss of the implanted devices. So switching-mode frequency control is the key problem in the biomedical device powering system. This paper focused on the design of a frequency controlled power amplifier to improve the controller's efficiency in terms of speed and better results. The objective of this work is to control the operating frequency. Feedback control method is used by using proportional integral derivative controller (PID), proportional integral (PI) and voltage controlled oscillator (VCO) to reduce the phase shift and settling time. The Bode plot and Nyquist stability criterion analyses show that the developed power amplifier frequency controller is stable and perform well to improve the controller efficiency.*

Streszczenie. W artykule opisano wzmacniacz mocy używany w technice bio-implantów. Wzmacniacz klasy E z operacją ZVS przekształca stałe napięcie na napięcia AC. Kontrola częstotliwości tego napięcia ma ważne znaczenie ponieważ częstotliwość może się zmieniać przy obecności elementów L, C w układzie. W pracy opisano metode kontroli częstotliwości tego napięcia. ***Kontrola częstotliwości wzmacniacza mocy wykorzystywanego do zasilania bio-implantów***

Keywords: Biomedical implanted devices, Frequency control, PID controller, class-E power amplifier, voltage controlled oscillator (VCO)
Słowa kluczowe: wzmacniacz mocy klsy E, bio-implanty, kontrola częstotliwości

Introduction

Recently, various biomedical implanted devices are powered inductively using wireless inductive coupling. The bio-implanted device system is composed of two coils: one implant integrated and isolated inside the human body, the other located outside the body. The device is magnetically coupled and uses the radio frequency (RF) short-range communication to harvest a low power to the system. Power amplifier (PA) used as a power driver in these circuits [1]. The main problem for power amplifier is the resonant frequency control. The goal is to monitor and control the transmitted signal frequency of the power amplifier by using a frequency control technique. The stability of the RF signal gives a high readability for DC voltage at the implant device in terms of the distances from the reader coil. Power transfer efficiency of inductive coupling link from both sides is to be tuned to the same resonant frequency f_o. The used capacitors or inductors in the circuit can create misalignment or change in distance between the coils which is caused carrier frequency shift. Introducing artificial intelligent (AI) control technique, the transcutaneous energy transmission system can keep the optimum state with constant output voltage. Adjusting the important design parameters the duty ratio and frequency of the driving signal and the supply voltage is an important issue [2]. Fig. 1 shows the biomedical power amplifier with feedback control system. It contains two most important circuits in which first one is power circuit and second one is control circuit used to control the pulse which is providing for power switching. The supply of wireless power to biomedical implants begins with power amplifier (PA), which supply energy at a particular frequency to an antenna or coil. Switched power amplifiers have been a popular choice to drive inductive power links for implantable electronics due to their ability to minimize losses at high frequencies [3]. The power amplifier increases the incoming signal to the desired power level that drives the transmitting circuit. power amplifiers are used widely in transcutaneous power systems because of their simplicity (they consist of only one transistor), high efficiency, wide frequency bandwidth and simple control circuitry. PID controller used to reduce the phase shift of class-E power amplifier and control the output voltage by adjusting switching frequency.

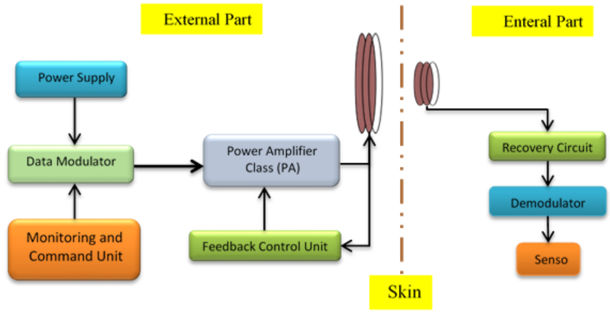

Fig. 1. Biomedical power amplifier with feedback control system.

Power Amplifier Design

The simple power amplifier consists of a CMOS transistor as a switch, a shunt capacitor and a choke inductor. The shunt capacitor (C) is used for soft switching in non-ideal CMOS, so there is no overlap between voltage and current. A choke inductor (LC) is used to keep supplied current constant DC flows through the amplifier. The shunt capacitor is connected in parallel with the series load network of the transistor is adjusted to a known frequency to fix the current of the supply source and convert the digital input into a sinusoidal output with zero DC [4]. Since the power amplifiers are used in biomedical implants many analyses and considerations have been made to develop the design of the power amplifiers to make it more practical. One of these the power amplifier design was the infinitely loaded quality factor (Q). The Q of the output circuit LC must be high to ensure the output current and output voltages consist of only the fundamental harmonics [5]. The formulas below are used to design power amplifiers as follows [6].

$$P_o = \frac{2}{1+\frac{\pi^2}{4}} \cdot \frac{V_{CC}^2}{R} \tag{1}$$

(2) $$Q \leq \frac{\omega L}{R}$$

(3) $$C_S = \frac{1}{\omega_o R_L\left[\frac{\pi^2}{4}+1\right]\left[\frac{\pi}{2}\right]} = \frac{1}{\omega_o (5.447\, R_L)}$$

(4) $$C_P = C_s \left[\frac{5.447}{Q}\right]\left[1 + \frac{1.42}{Q-2.08}\right]$$

For the design of Class-E power amplifier, we have used the parameters shown in Table 1 [7] and applied for the PID controller to correct the phase shift.

Table 1. power amplifier parameters

	DC voltage supplied (v)	RFC Inductor (µH)	Primary Inductor (µH)	Primary Capacitor (pF)	Load Resistor (Ω)	Shunt Capacitor (pF)	Resonance Frequency (MHZ)
Symbol	V_s	L_{ch}	L	C_2	R_{load}	C_1	f_o
Value	3.3	30	4.92	33.11	2.2	51.5	13.56

Proportional Integral Derivative (PID) controller

Proportional integral derivative (PID) control is the most used control scheme today. It is expected that over 90% of control loops works with PID control technique. PID controller consist of three common parameters that explain most of control problems. First proportional term (P) responds immediately to the current error. Second integral term (I) harvests zero steady-state error in tracking a constant set-point. Integral control allows the complete rejection of constant disturbances and filters higher frequency sensor noise, so it is slow in response to the current error. Plants with significant dead time, the effects (P) and (I) control activities are hardly characterized in the current error. This situation may lead to large transient errors when PI control is used. Derivative action (D) combats this problem by basing a portion of the control on an estimation of future error [8]. Figure 2 shows the PID controller terms.

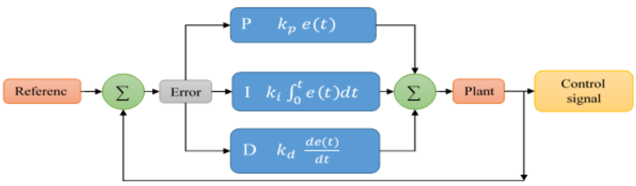

Fig. 2. PID controller for power amplifier

By tuning these three factors in the PID controller procedure, the controller can provide control action designed for specific process requirements. The response of the controller can be described in terms of the responsiveness of the controller to an error, the degree to which the controller overshoots the set point and the degree of system oscillation [9-10]. The proportional, integral, and derivative terms are summed to calculate the output of the PID controller. Defining *H* (*t*) as the controller output, the final form of the PID system is as follows.

(5) $$H(t) = K_p\, e(t) + K_i \int_0^t e(t)\, dt + K_d \frac{d}{dt} e(t)$$

Voltage Controlled Oscillator (VCO)

A voltage controlled oscillator is implemented for monitoring the RF transmitter using the feedback control techniques. Following is the design of a simple control system to auto-correct the RF signal using VCO frequency that offers the stability of output power of the power amplifier as shown in Fig. 3. It provides constant voltage at the implant device [10]. This method is simple to implement for reducing the RFID reader Hardware. The feedback system consists of an amplifier for the RF signal passed through a square circuit (multiplier) filtered at the center frequency. The RF signal is converted into the digital signal, and captured transmit signal into the digital form. The phase comparator is used to compare the digital transmitted signal with respect to the fundamental transmit pulse signal by VCO.

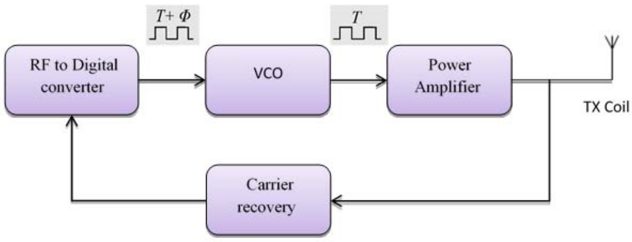

Fig. 3. Voltage controlled oscillator for power amplifier

Results and Discussion

The simulation has been assembled by Matlab-Simulink R2013a. Fig. 4 shows the results from closed loop control power amplifier simulation. The results are obtained by fine-tuning PID parameters (K_P=*0.5*, K_i=1, K_D=12) manually. The results showed that the phase shift of the output signal was reduced from 20ns to 15ns after using PID controller. The settling time reduced from 7 µs. to 3 µs.

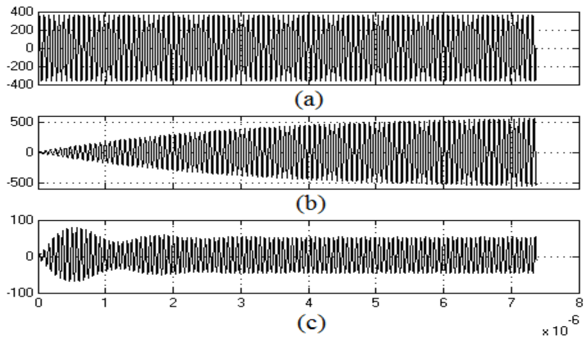

Fig. 4. Output waveforms of Class E power amplifier (a) reference output voltage (b) output voltage without controller (c) output voltage with PID controller

Figure 5 shows the output voltage of transcutaneous Class-E power amplifier with PI controller. The use of PI co-ntroller with (K_P=*1*, K_i=1, K_D=0) reduced the phase shift from 20 ns to 11 ns. The settling time is also reduced to 0.7 µs.

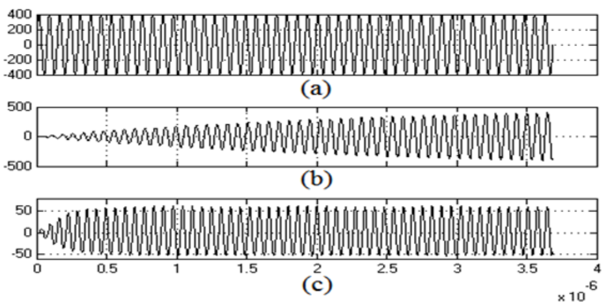

Fig. 5. Output waveforms of class-E power amplifier (a) reference output voltage (b) output voltage without controller (c) output voltage with PI controller

Fig. 6 shows the VCO controller result for the power amplifier. The obtained results from voltage controlled oscillator (VCO) shows that there is no phase shift in the output voltage. However, the settling time is still 20 ns with distortion.

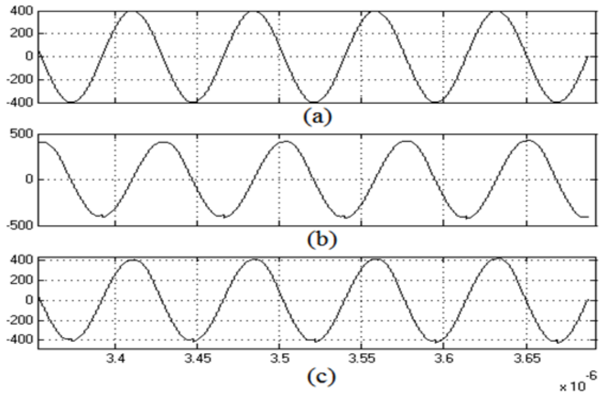

Fig. 6. Output waveforms of class-E power amplifier (a) reference output voltage (b) output voltage without controller (c) output voltage with VCO

To analyze the performance of the developed system Bode plot and Nyquist stability criterion are discussed, respectively. Bode plots are the most widely used means of displaying and communicating frequency response information. Wide range of frequencies and gains are used to measure the stability of a system as shown in Fig. 7. In general the stability conditions of the bode plot are gain margin at -180^0 phase should be greater than zero and phase margin at 180^0 phase and 0 dB should be greater than zero. However, the system should not have any poles or zeros in the right hand of the s-plan (RHP). Fig. 7 shows the Bode plot on magnitude and phase margin of PID controller in hand of the s-plan (RHP). Fig. 7 shows the Bode plot on magnitude and phase margin of PID controller in which a phase margin of -90.7^0 at f = 1.09e7 rad/sec, 90.7^0 at 5.62e9 rad/sec and a gain margin of ∞, because the phase does not cross the -180^0. Thus, it could be concluded that the frequency response of the PID controller is stable.

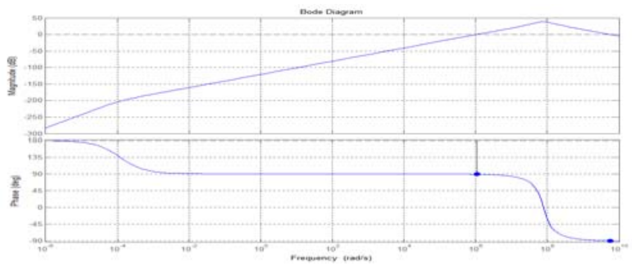

Fig. 7. Bode plot on magnitude and phase margin of PID controller.

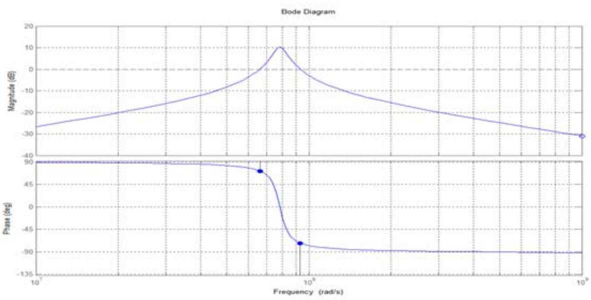

Fig. 8. Bode plot on magnitude and phase margin of VCO controller.

Fig. 8 shows the Bode plot on magnitude and phase margin of VCO controller in which a phase margin of 107^0 at f = 9.29e7 rad/sec and -108^0 at f = 6.61e7 and a gain margin of 57dB at 3.14e10. Thus, it also could be concluded that the frequency response of the VCO controller is stable.

Similarly, the Nyquist stability criterion is a test for system stability. By altering the gain of the system, if any of the poles move into the RHP then the system would become unstable. The Nyquist criteria, however, can tell us things about the frequency characteristics of the system. For instance, some systems with constant gain might be stable for low-frequency inputs, but become unstable for high-frequency inputs. Also, the Nyquist criteria can tell us things about the phase of the input signals and the time-shift of the system. The Nyquist diagram is basically a plot of G (j* w) where G(s) is the open-loop transfer function and w is a vector of frequencies which encloses the entire right-half plane. When studying feedback controls, we are not as interested in G(s) as in the closed-loop transfer function.

$$\frac{G(S)}{1+G(S)} \tag{6}$$

If 1+ G(s) encircle the origin, then G(s) will enclose the point -1. In the closed-loop stability, no closed-loop poles (zeros of 1 + G(s)) should be in the right-half plane. Therefore, the behavior of the Nyquist diagram around the -1 point in the real axis is very important.

Fig. 9 shows the Nyquist diagram on magnitude and phase margin of PID controller in which a phase margin of -90.7^0 at f = 1.09e7 rad/sec, 90.7^0 at 5.62e9 rad/sec and a gain margin of ∞ because the phase does not cross the -180^0.

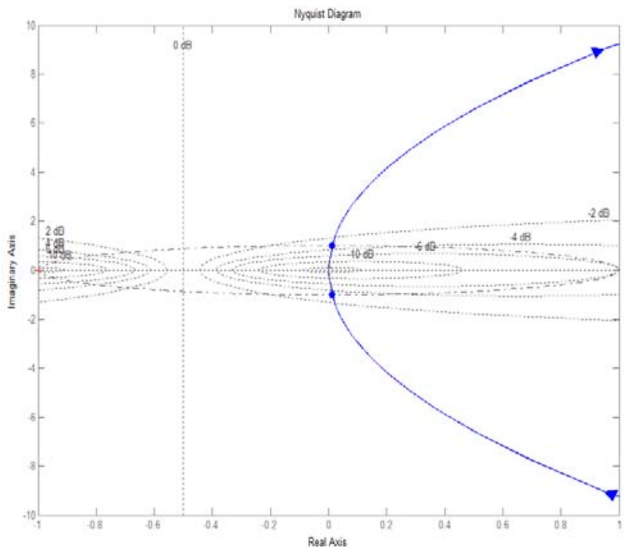

Fig. 9. Nyquist diagram on magnitude and phase margin of PID controller.

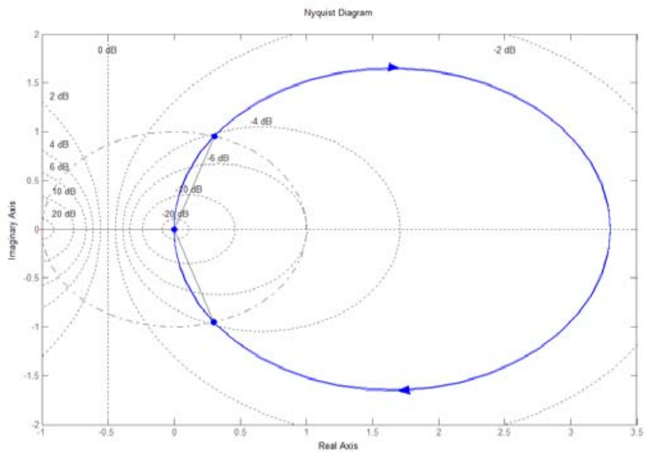

Fig. 10. Nyquist diagram on magnitude and phase margin of VCO controller.

Fig. 10 show the Nyquist diagram of discrete time VCO controller of phase margin of 107^0 at f = 9.29e7 rad/sec and -108^0 at f = 6.61e7 and a gain margin of 57dB at 3.14e10. It can be seen that both Fig. 9 and Fig. 10 are stable in frequency response using PID and VCO feedback controller.

Conclusion

This paper deals with PI, PID, VCO controllers for class-E power amplifier operated with standard frequencies used in biomedical wireless telemetry devices and suitable for inductive coupling links. The operating frequency according to industrial, scientific and medical (ISM) radio bands is considered as 13.56 MHz's. The simulated circuit explained that the phase shift of the output waveform is created due to the inclusion of capacitors and inductors in the power amplifier design. The results showed that phase shift and settling time is reduced with the feedback control system. Moreover, the Bode plot and Nyquist stability criterion analyses show that the developed frequency controlled amplifier is stable system in operation with implanted devices. The improved version of the feedback control system could use in real applications.

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