Results: Fig. 2 presents the frequency response of a half-wave ZVS boost converter. The values of the resonant elements are L_r = 47μH and C_r = 13.3nF and the load resistance is R = 30Ω. The control system was designed using Unitrode's UC3864 resonant mode power supply controller.

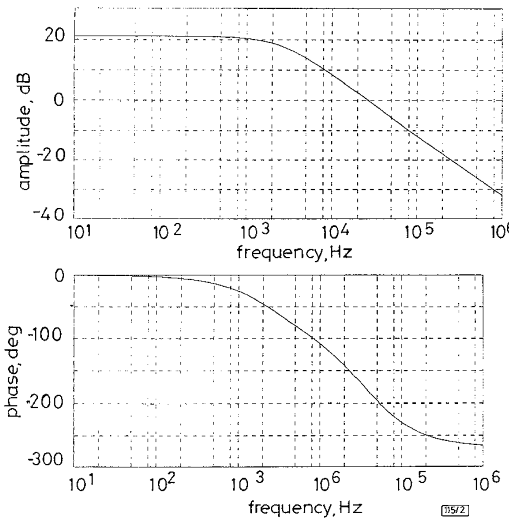

Fig. 2 *Frequency response of half-wave ZVS boost converter*

Conclusions: The method described in the Letter shows how to determine the mathematical expression of the transfer function of a quasi-resonant boost converter. It can be applied for each quasi-resonant DC/DC converter operating with continuous current. Knowing the control-to-output transfer function of the power circuit, the design of the feedback loop and compensation circuit is simpler, and better dynamic performances can be achieved. The algorithm can be implemented easily in computer simulation programs.

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Wien bridge based RC chaos generator

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Indexing terms: Chaos, Oscillators

A new circuit, which is formed by coupling a Chua diode with a Wien bridge oscillator in parallel, is presented. This circuit contains only resistors, capacitors and operational amplifiers. By choosing element values appropriately, this circuit is shown experimentally to exhibit various forms of chaotic behaviour.

Introduction: The study of chaotic behaviour in nonlinear dynamic systems has attracted great interest because of many possible applications in various fields of science. Since simple nonlinear circuits may exhibit such behaviour, the analysis and design of electronic circuits which generate chaotic signals has received a great deal of attention in recent years [1]. Most of the chaotic signal generators proposed in the literature contain inductors (see, e.g. [2]), which is inconvenient for various reasons. For example, inductors are less standard as compared to other circuit elements and have to be prepared separately in most applications. They are not as ideal as other circuit elements, and in terms of spatial dimensions they are bigger in size than the other circuit elements, unless the inductance is rather small. The circuits which contain capacitors instead of inductors are more convenient in this sense; however, most of such chaotic circuits proposed in the literature are rather complex (see [3] and the references therein).

In this Letter we propose a simple circuit which contains a Wien bridge and a three-segment piecewise linear resistor known as the Chua diode. We show experimentally that this circuit may generate various forms of chaotic signals.

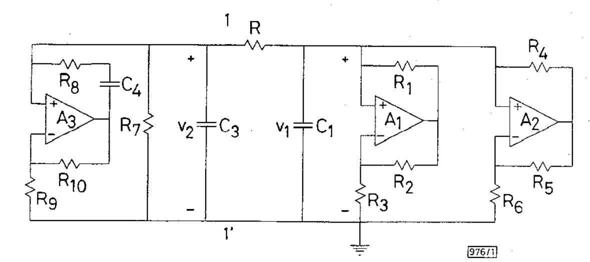

Fig. 1 *Wien bridge based chaos generator*

Proposed chaos generator: We consider the circuit shown in Fig. 1. In Fig. 1 the operational amplifiers and the associated resistances (R_1, ..., R_6) are used to realise the three-segment piecewise linear resistance called the Chua diode [2]. The circuit to the left of 1 – 1′ is a Wien bridge circuit. The resistor R is a potentiometer and can be used to tune the circuit to observe chaotic behaviour. This circuit is first proposed in [4], and for this reason, we used the same element labelling used in [4]. However, the mode of operation of the Wien bridge in this Letter is different than the one proposed in [4], which is described below.

Assuming that the operational amplifier A3 is ideal and operates in the linear region, the impedance $Z(s)$ of the Wien bridge circuit in Fig. 1 (i.e. to the left of 1 – 1′) can be found as

$$Z(s) = \frac{R_7R_9(sC_4R_8+1)}{s^2C_3C_4R_7R_8R_9+s(R_8R_9C_4+R_7R_9C_3-R_7R_{10}C_4)+R_9} \quad (1)$$

We note that all resistors and capacitors in this circuit are passive (i.e. resistances and capacitances are positive). A simple calculation shows that the impedance $Z(s)$ given in eqn. 1 is a positive real function (i.e. stable and $\mathrm{Re}\{Z(j\omega)\} \geq 0 \ \forall \ \omega \in \mathbf{R}$) if and only if the following condition holds:

$$R_8R_9 \geq R_7R_{10} \quad (2)$$

If eqn. 2 holds, then the impedance $Z(s)$ given above can also be realised by using only passive R, L and C elements. In particular, if the equality $R_8R_9 = R_7R_{10}$ holds, then the resulting impedance $Z(s)$ can also be realised by using a series combination of a resistor R_0 and an inductor L with a parallel combination of a capacitor C, with $R_0 = R_7$, $L = C_4R_7R_8$ and $C = C_3$. In this case, the circuit given in Fig. 1 is equivalent to the Chua oscillator [2, 4]. Since in this case the impedance $Z(s)$ is positive real, which is related to passivity, we call this mode of operation of the Wien bridge the 'passive mode'. It is known that the Chua oscillator generates chaotic signals [2], and it was shown in [4] that similar behaviour can also be observed in the proposed circuit when the Wien bridge operates in the passive mode.

In the Chua oscillator, the resist or R_0 represents the internal resistance of the inductor. In the ideal case the condition $R_0 = 0$ should hold, in which case the parallel/series combination of R_0, L and C becomes a harmonic oscillator. We note that this case is ideal and cannot be realised in practice. However, if the following condition is satisfied,

$$R_8R_9C_4 + R_7R_9C_3 - R_7R_{10}C_4 = 0 \quad (3)$$

then sustained oscillations can easily be obtained in the Wien bridge. For this reason we say that the Wien bridge operates in 'oscillatory mode' when eqn. 3 is satisfied. Since in this case the denominator of eqn. 1 is in the form $s^2 + \omega_0^2$, the oscillation frequency ω_0 (rad/s) is given by

$$\omega_0 = \frac{1}{C_3 C_4 R_7 R_8} \qquad (4)$$

We note that in the oscillatory mode, the impedance $Z(s)$ given by eqn. 1 is not positive real, and hence cannot be realised by using only passive elements. In the next Section we show experimentally that the proposed circuit can exhibit various forms of chaotic behaviour when the Wien bridge operates in the oscillatory mode.

Experimental results: For the Chua diode we choose the following parameters, which are taken from [2]: $R_1 = R_2 = 220\Omega$, $R_3 = 2.2\mathrm{k}\Omega$, $R_4 = R_5 = 22\mathrm{k}\Omega$, $R_6 = 3.3\mathrm{k}\Omega$, and A1 and A2 are operational amplifiers (AD712 or equivalent). To set the Wien bridge in oscillatory mode, for simplicity we choose $R_7 = R_8$ and $C_3 = C_4$. In this case, eqn. 3 reduces to $R_{10} = 2R_9$.

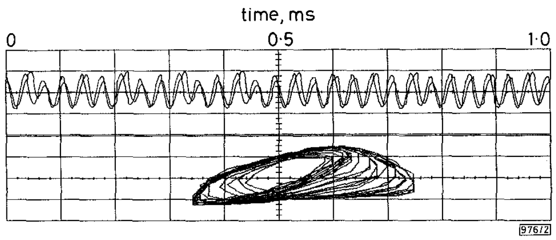

Fig. 2 *v_2–v_1 characteristics for C_1 = 33pF, R = 1890Ω*

Sensitivity:
Channel 1: 400mV/div
Channel 2: 100mV/div
Function 1: 60mV/div

We obtained chaotic behaviour for a large number of parameter values. However, we only report some of them here. We used a 2kΩ potentiometer for R and a 1kΩ potentiometer for R_{10}. The role of R_{10} is to tune the Wien bridge oscillator to oscillatory mode (i.e. to satisfy eqn. 3). In all these experiments, we first disconnect R, and change R_{10} till oscillations are observed for v_2. Note that these oscillations should be as close to a pure sinusoidal waveform as possible. Then, we connect and tune R to observe chaotic behaviour. We also note that the chaotic behaviour is very sensitive to R_{10}. Nevertheless, tuning to chaos can be achieved rather easily. We choose $R_7 = R_8 = R_9 = 100\Omega$, $R_{10} = 200\Omega$ and $C_3 = C_4 = 47\mathrm{nF}$. As explained above, R_{10} is a potentiometer and is used to tune the Wien bridge oscillator to the oscillatory mode. $R_{10} = 200\Omega$ is the theoretical value to obtain pure sinusoidal oscillations (see above); actual measurement is very close to this value ($R_{10} = 207\Omega$). The oscillation frequency is 33.87kHz in this case (see eqn. 4). Then we used R to obtain chaotic behaviour for various values of C_1 and R. For the parameter values stated above, we observed chaotic behaviour for various values of C_1 and R in the range $1\mathrm{pF} \le C_1 \le 470\mathrm{pF}$, $1345\Omega \le R \le 1890\Omega$. For the case $C_1 = 33\mathrm{pF}$, the waveforms of v_1 and v_2, and v_2 against v_1 characteristics are given in Figs. 2 and 3 for $R = 1890\Omega$ and $R = 1360\Omega$, respectively.

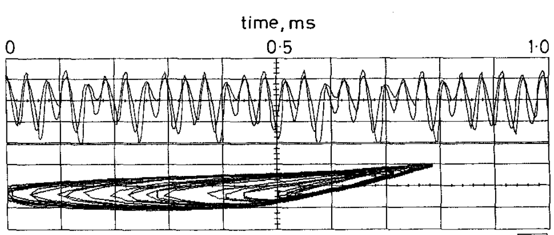

Fig. 3 *v_2–v_1 characteristics for C_1 = 33pF, R = 1360Ω*

Sensitivity:
Channel 1: 40mV/div
Channel 2: 10mV/div
Function 1: 14mV/div

Since we observed chaotic behaviour even for $C_1 = 1\mathrm{pF}$, which is the smallest standard capacitance available in our laboratory, we omitted C_1 in some experiments to see if we can still observe chaotic behaviour. Indeed, even if C_1 is not used, we observed chaotic behaviour in our experiments. For this case (i.e. C_1 is not used), Figs. 4 and 5 show the waveforms v_1 and v_2, and v_2 against v_1 characteristics for $R = 1840\Omega$ and $R = 1680\Omega$, respectively. Since a second-order autonomous system with continuous nonlinearity cannot exhibit chaotic behaviour, the observed chaotic behaviour when C_1 is not used, requires explanation. A possible explanation could be the existence of parasitic capacitances. Another explanation could be a possible hysterisis type nonlinearity occurring in some part of the circuit.

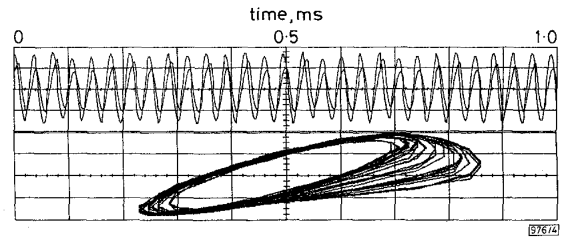

Fig. 4 *v_2–v_1 characteristics for R = 1840Ω (C_1 not used)*

Sensitivity:
Channel 1: 200mV/div
Channel 2: 40mV/div
Function 1: 36mV/div

In all the Figures we first observed the $v_2 - v_1$ characteristics in an analogue oscilloscope in the X - Y mode. Then the same Figure is obtained in a digitising oscilloscope (HP 54502A). After storing the screen in the memory of the oscilloscope, the screen is printed on a plotter (HP 7475A) by using an HB-IB bus. The signals above are v_1 and v_2 against time, and below are $v_2 - v_1$ graphics. Since the important information is the $v_2 - v_1$ graphics, we do not label the signals v_1 and v_2.

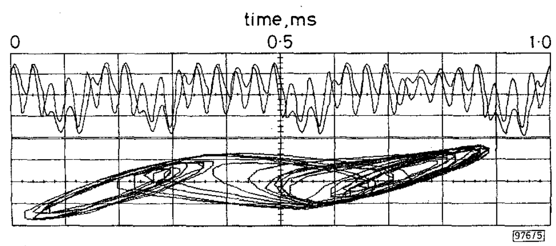

Fig. 5 *v_2–v_1 characteristics for R = 1680Ω (C_1 not used)*

Sensitivity:
Channel 1: 200mV/div
Channel 2: 40mV/div
Function 1: 36mV/div

Conclusion: In this Letter we have presented a new chaotic circuit. This circuit contains a Wien bridge coupled with a three segment piecewise linear resistor, known as the Chua diode. Since the proposed circuit does not contain an inductor, it may be more suitable for integrated circuit applications. We have shown experimentally that this circuit exhibits many types of chaotic behaviour. Since this circuit has more parameters which could be used for chaos tuning, it may be useful for various practical applications.

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