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Realization of Direct Linear Relation Between Control Voltage and Resonance Frequency of the LC Voltage Controlled Oscillator

Abstract- *The main problem of traditional LC (L represents the inductance, and C represents the Capacitance) Voltage Controlled Oscillators VCOs, is the non-linearity relation between the tuning control voltage and output resonance frequency, which is caused by two following reasons: the first one is the inverse and non-linear relation between the tuning control voltage and produced capacitance of the used varactor diode in the VCO circuit, and the second is the inverse and non-linear relation between the capacitance value of the used varactor diode and the output resonance frequency. In this paper, a proposed circuit has been designed and implemented to solve this problem and realize a direct-linear relation between the tuning control voltage and output resonance frequency for the LC Voltage Controlled Oscillator that utilize the varactor diode as a voltage controlled capacitance. The proposed circuit has been realized using Logarithmic, Inverting, Ant-Logarithmic, and Difference Amplifiers, which they are characterized by their simplicity and low cost. The theoretical and practical results of testing the proposed circuit had been presented using MATLAB software package. The proposed work has been practically tested by 21 measurement points, whereas, it has exhibited stimulant results that supports the successfulness of its design and performance.*

Keywords: *Difference Amplifier, Inverting Amplifier, Logarithmic Amplifier, Tuning Control Voltage, Varactor Diode.*

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1. Introduction

Most FM (Frequency Modulation) communication systems, have voltage controlled LC tuning circuits, they utilize the varactor diodes for tuning and frequency modulation processes, whereas, these diodes are used as voltage controlled capacitors [1]. LC Voltage Controlled Oscillator (VCO) composed from two main parts: Class C amplifier, and positive feedback circuit. The class C amplifier consists of a single-stage FET (Field-Effect-Transistor) or BJT (Bipolar-Junction-Transistor), which biased to amplify the tops of the HF signal wave. In most cases, the feedback circuit is composed from parallel LC resonance circuit, the capacitor of this resonance circuit is represented by varavtor diode, which is controlled by variable reverse bias voltage to change the capacitance values in a specific range (in range of tens or hundreds of pico-farad *pf*) [2]. The first problem in these LC VCOs is the inverse non-linear relation between capacitance value of the capacitor and output frequency of the Voltage Controlled Oscillator. The second problem is the inverse non-linear relation between the applied reverse bias voltage and capacitance value of the varactor diode [3]. These problems cause a non-linear relation between the applied reverse bias voltage of the varactor diode and resonance frequency of the Voltage Controlled Oscillator [4]. There are several models of LC VCO circuits, one of mostly used LC VCO circuit has been illustrated in Figure 1, As which illustrates a circuit involves a single-stage class C amplifier, which consists of a FET and Gate biasing resistor R_b, and an RFC (Radio Frequency Chock) that acts as a high frequency load for the FET. The RFC presents a high impedance load at the drain of the FET at high frequencies, which is suitable for increasing the gain of FET. This circuit also consists of a positive feedback circuit composed from the tapped inductor L_p, and the varactor diode D_v. The varactor diode D_v is controlled by the tuning control voltage V_t, which is applied across this diode for presenting a capacitance variation range.

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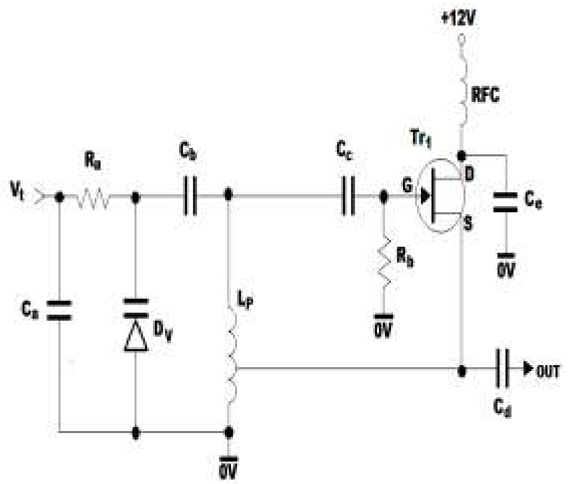

Figure 1: An example of LC VCO circuit diagram

The capacitor Cb (where, C_b>>C_V) is used as an isolator, which it isolates the tuning circuit (composed from C_a, R_a, D_v) from the circuit of the inductance L_p of the oscillator circuit. The resonance frequency of this parallel LC tuning circuit can be calculated as follows [5,6,7]:

$$f_r = \frac{1}{2\pi\sqrt{L_P \cdot C_V}} \quad (1)$$

where,

f_r: Resonance frequency (in Hz).

L_P: Inductance of the tapped inductor (in Henry).

C_V: Capacitance of the varactor diode (in Farad).

As shown from Eq.1, if the inductance value of the inductor L_P is constant, the relation between the capacitance of the varavtor diode and resonance frequency is inverse and non-linear, which is the first problem. The relation between the tuning control voltage and capacitance value of the varactor diode can be calculated as follows [6,8,9]:

$$C_V = \frac{C_o \cdot N}{(V_D+V_t)^m} \quad (2)$$

where,

C_o: Capacitance of the varactor diode at zero tuning voltage.

N: Parameter and generally equals (1).

V_t: Tuning voltage (in Volt).

V_D: Diode junction barrier voltage (in range 0.5-0.6 Volt).

m: Factor depends on material structure of the varactor diode (in range 0.35-0.5).

By substituting Eq.2 in Eq.1, the following formula can be obtained:

$$f_r = \frac{(V_D+V_t)^{\frac{m}{2}}}{2\pi\sqrt{L_P \cdot C_o \cdot N}} \quad (3)$$

By proposing a constant value for the inductance L_P, one can conclude the following proportionality:

$$f_r \propto (V_D + V_t)^{\frac{m}{2}}$$

As shown in Equation (3), the relation between the tuning control voltage and resonance frequency is non-linear, which is not suitable for high accuracy VCO circuits, whereas, the linearity is the essential condition between the tuning control voltage and output resonance frequency for LC VCO circuits that used in frequency modulation circuits. In this work, a proposed circuit has been designed and implemented to solve the mentioned troubles of the traditional LC VCO circuits. The proposed circuit converts the non-linear relation between the tuning control voltage of the varactor diode and resonance frequency to pure linear relation that required for good frequency modulation process. This proposed circuit consists of four stages: Logarithmic, Inverting, Anti-logarithmic, and Difference amplifiers. At the beginning, the tuning voltage will be processed by the logarithmic amplifier to present a logarithmic tuning voltage, then the resultant signal will multiplied by a (-2/m) by an Inverting amplifier, then the last resultant voltage will be processed by an Anti-logarithmic amplifier, and then the final resultant signal of this stage will be processed by a Difference amplifier to cancel the effect of the junction barrier voltage of the varactor diode. The proposed circuit constructed from four OP/Amps (Operational Amplifiers), two diodes, and several resistors, therefore, it can be characterized by the following features: Simplicity, low cost, good performance and efficiency.

2. Previous Related Works

There are several previous works had related the utilizing the varactor diodes in voltage controlled oscillator (VCO) circuits with producing various ranges of frequencies, and they had proposed different kinds of VCO designs. These works are briefly discussed as follows:

In 2014, Ali *et al*. [5] had proposed a design of a high frequency Voltage Controlled Oscillator VCO utilized for data communication as an ultra-speed clock. This design has used the varactor diode as a voltage controlled capacitor, and the proposed oscillator has been designed as a Colpitt circuit model, which had presented high-speed clock with frequency range (800-1500) MHz with reverse bias voltage range (0-25) Volt applied across the varactor diode. This work has not solved the problem of the non-linearity relation between the tuning control voltage and output frequency of the VCO circuit. In 2015, Abhay Kumar *et al*. [10] had proposed a Voltage Controlled Oscillator with three stages, which based on 0.18 µm thickness CMOS. The presented tuning frequency is at range (0.5-4.7) GHz, while the controlling applied voltage is at range (0.5-1.8) Volt. In this work, a linear relation between the applied controlling voltage and output frequency has been achieved for the proposed oscillator using processing circuits such as, multiplier, divider, etc. The main characteristics of the proposed design for this work are low power consumption, and low phase noise. In 2016, Byron Murphy [11] had presented a design and realization of high frequency Phase-Looked-Loop that has been utilized for beam forming of the phase antenna array. The proposed circuit had been used for applications of frequency 30GHz and more. This circuit consists of four Voltage Controlled Oscillators VCOs with a tuning range of 10%, phase control of 417 degrees, and a resolution of 10 degrees. The proposed circuit has been realized using ST Microelectronics 65 nanometers design kit, and simulated using Cadence Virtouso software package. This work had utilized the varactor diode as a variable controlled capacitor, and has not converted the relation between the applied voltage and the produced capacitance to linear form. In 2016, Qirollari *et al*. [12] had presented a design of high accuracy Voltage Controlled Oscillator used for radio frequency applications. This oscillator can be tuned with different center frequencies in the range of (1.56-1.96) GHz. This design had used the varactor diode for tuning the proposed oscillator, where it has not solved the problem of non-linear relation between applied tuning voltage and output frequency. The design of this work has been simulated in the computer using Keysight's Advanced Design System (ADS), and it has been characterized by its high accuracy and low cost.

3. Proposed Circuit Design

The complete circuit diagram of the proposed circuit has been illustrated in Figure 2, as shown in this figure, the proposed circuit involves four OP/Amps (Operational Amplifiers) type LM358, and they had been connected as logarithmic amplifier, Inverting, Anti-logarithmic amplifier, and Difference amplifiers.

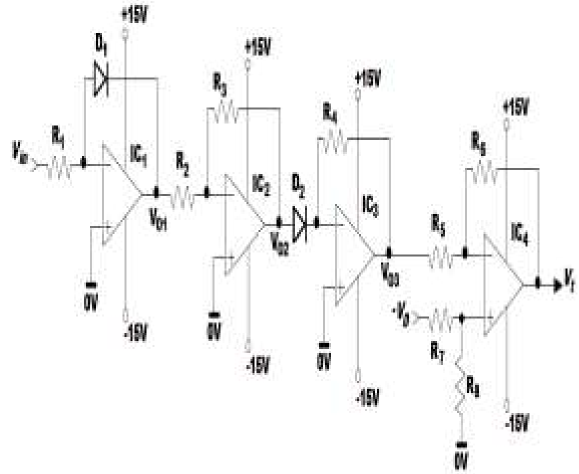

Figure 2: Complete circuit diagram of the proposed system

The input voltage has been applied to the inverting input of the Logarithmic amplifier IC1, which it constructed from the Op/Amp, and diode D_1 connected across the input and output of the Op/Amp as a negative feedback. The output voltage of this stage has been calculated as follows [14]:

$$V_{o1} = \left(\frac{-KT}{q}\right) . ln(\frac{V_{in}}{I_s . R_1}) \quad (4)$$

where,

V_{in}: Input voltage of the proposed circuit (in Volt).

K: Boltzmann Constant equals 1.38×10^{-23} J/K.

V_{o1}: Output voltage of the logarithmic amplifier (in Volt).

T: Temperature (in Kelvin).

q: Electron charge equals 1.6×10^{-19} Coulomb.

The Diode type is 1N4007 has been used for D_1, so, from data sheet of this diode the saturation reverse current I_s = 50nA, and resistance of R1 can be set to 10MΩ. So Eq. 4 has been rearranged to the following express:

$$V_{o1} = \left(\frac{-KT}{q}\right) . ln(\frac{V_{in}}{0.5}) \quad (5)$$

The last output voltage V_{o1} has been applied to input of the inverting amplifier (Multiplier) IC_2, the gain of this amplifier G can be expressed as follows [15,16]:

$$G = \frac{-R_3}{R_2} = \frac{-2}{m} \quad (6)$$

where,

m: factor depends on the material structure of the varactor diode.

The output voltage of the Amplifier IC_2 is expressed as follows:

$$V_{o2} = \left(\frac{-2}{m}\right)\left(\frac{-K.T}{q}\right) ln(\frac{V_{in}}{0.5}) \quad (7)$$

so,

$$V_{o2} = \left(\frac{K.T}{q}\right) ln(\frac{V_{in}}{0.5})^{\frac{2}{m}} \quad (8)$$

The output voltage V_{o2} has been applied to input of the Anti-logarithmic amplifier IC_3, which it consist of diode D_2 (1N4007 type), this diode connected to input of this amplifier. The output voltage V_{o3} of this amplifier can expressed as follows:

$$V_{o3} = -I_S . R_4 . exp(\frac{q}{K.T} . \frac{K.T}{q} . l\,n(\frac{V_{in}}{0.5})^{\frac{2}{m}}) \quad (9)$$

so, when R_4 is set to 1MΩ,

$$V_{o3} = -(0.05\ (\frac{V_{in}}{0.5})^{\frac{2}{m}}) \quad (10)$$

The output voltage V_{o3} has been applied to the inverting input of the Difference amplifier IC_3, therefore, the output voltage of this stage V_{o4} has been expressed as follows:

$$V_t = V_{o4} = \frac{R_6}{R_5} . (0.05)(0.5)^{\frac{-2}{m}} . (V_{in})^{\frac{2}{m}} - \left(1+\frac{R_6}{R_5}\right)\left(\frac{R_8}{R_7+R_8}\right) . V_D \quad (11)$$

Using the Diode SVC 704 as a varactor diode for this proposed circuit, one can read (from data sheet) the factor m of this diode which equals to 0.5, and by setting R_6 to 1.25kΩ, R_5= 1kΩ, R_7=1.5kΩ, and R_8=1.5kΩ, the output voltage V_t can be expressed as follows:

$$V_t = V_{o4} = (V_{in})^4 - V_D \quad (12)$$

By substituting Eq. 12 in Eq. 3, and m=0.5 (from data sheet of the varactor diode), the following expression can be obtained:

$$f_r = \frac{((V_D + (V_{in})^4 - V_D))^{0.25}}{2\pi\sqrt{L_P . C_o}} \quad (13)$$

Finally, by setting Co=100pf, and diode barrier voltage=0.6, the resonance frequency can be expressed as follows:

$$f_r = \frac{V_{in}}{2\pi\sqrt{100\times10^{-12}\times L_P}} = \frac{15.916\times10^3\times V_{in}}{\sqrt{L_P}} \quad (14)$$

Whenever, L_P has a given value, the following proportionality can be expressed as follows:

$$f_r \propto V_{in}$$

The proposed circuit, and the LC VCO circuit, have been implemented on single Printed Circuit Board (PCB), which has been as shown in Figure 3. As illustrated, two LM358 ICs has been used in this circuit, each IC consists of two Op/Amps, so there are four Op/Amps in this circuit. The length of the coil L_P equals 1cm, and the diameter of the same coil equals 0.5 cm, this coil has been tapped after 1 turn, so it has been formed as (1turn+ 4 turns), the total turns equal 5 turns, so the inductance of this coil equals 0.0617µh (which has been measured by digital LC Meter).

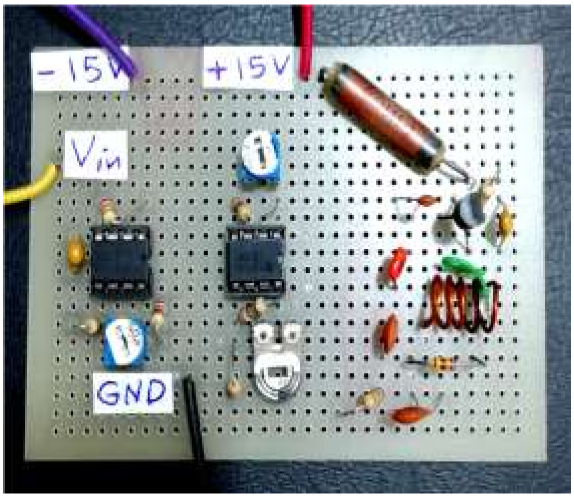

Figure 3: The Implementation of the proposed and LC VCO circuits onto printed circuit board

4. Results and Discussion

The relation between the tuning control voltage and resonance frequency has been plotted according to Eq.3, this Equation related to the LC VCO circuit shown in Figure 1, the tuning control voltage was in range (0-16) Volt, the inductance of L_P=0.0617µH, and the parameter m=0.5 (from data sheet). This relation has been illustrated in Figure 4, which is considered the theoretical relation between the tuning voltage and resonance frequency of the LC VCO circuit without connecting the proposed circuit.

It is clear from this figure, the relation between the tuning voltage and resonance frequency without connecting the proposed circuit, is non-linear (which is the mentioned problem), note this relation has been plotted according to Eq. 3.

The LC VCO circuit shown in Figure 1 has been implemented and utilized for testing the characteristics of the proposed circuit. The following components has been set for this circuit: The transistor Tr_1 is 2N4416 type, the capacitors C_a=C_b=C_e=0.01µf, C_c=22pf, C_d=0.001µf, and the resistors R_a=R_b=100kΩ, and the inductance of the RFC=1mH, L_P=0.0617µH, and finally, the varactor diode is SVC 704. This LC VCO circuit has been tested without connecting the proposed circuit, whereas, the practical relation between the tuning voltage and resonance frequency of this circuit has been illustrated in Figure 5. As observed, the curve-line of this relation is so similar to that of theoretical relation shown in Figure 4, with existence of several slight deviations that has been occurred due to the following reasons:

1. Poor accuracy of the measurement devices.
2. Propagation phenomenon that occurs at high frequencies.
3. Mutual inductance between electronic components.
4. Stray capacitance between electronic components.

The relation of Figure 5 has been plotted within 17 measurement points in range of tuning voltage (0-16) Volt with 1 Volt step, as observed, this relation supports Eq. 3.

The output of the proposed circuit of Figure 2 has been connected to the input of the LC VCO circuit of Figure 1. The applied tuning voltage (Vin) was in range (0-2) Volt. The theoretical results of connecting the propose circuit to the input of the LC VCO circuit has been shown in Figure 6, note this figure has been plotted according applying of Eq. 16, as seen from this figure, the relation between the tuning voltage and resonance frequency became pure linear with applying a tuning control voltage in range of (0-2) Volt, this curve-line proofs that Eq. 16 is true and exact. As a comparison, one can observe from Figure 6, that the curve-line starts from zero tuning voltage and resonance frequency while the curve-line of Figure 4 is not, this has occurred due to the possibility of staring the tuning voltage from zero value, while in Eq. 3, when the tuning voltage starts from zero value, the varacter diode has a reverse barrier voltage (=-0.6 Volt) across its junction, so the resonance cannot starts from zero value, while in Equation (16) the tuning voltage can starts from zero value because it consists of an additional voltage (+0.6) that cancels the reverse barrier voltage of the varactor diode. The practical results of connecting the proposed circuit to the input of the LC VCO circuit has been shown in Figure 7. As seen from this figure, the curve-line of this relation is so similar to that of theoretical results of Figure 6 with existence of several deflections that occurred due to the above-mentioned reasons. The shape of the curve-line of Figure 7 proofs and supports the successfulness of the concept, design, and performance of the proposed circuit when it compared with that of Figure 5.

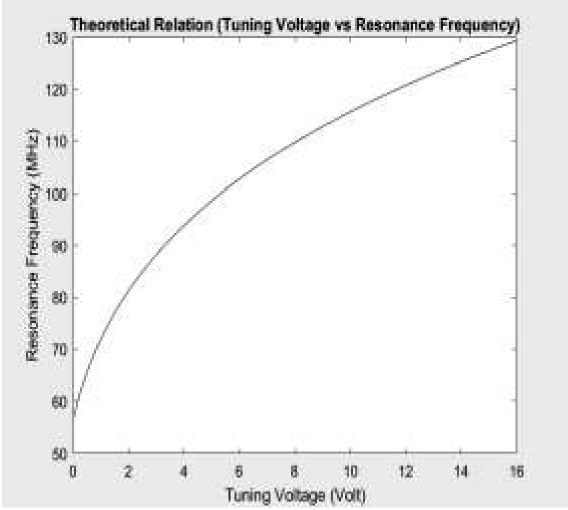

Figure 4: Theoretical relation between tuning voltage and resonance frequency without connecting the proposed circuit

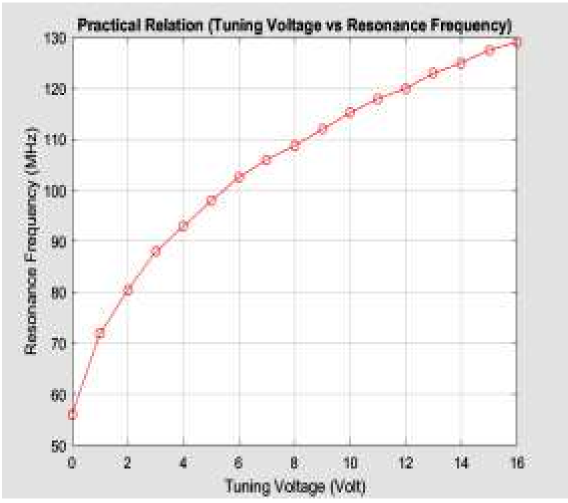

Figure 5: Practical relation between tuning voltage and resonance frequency without connecting the proposed circuit

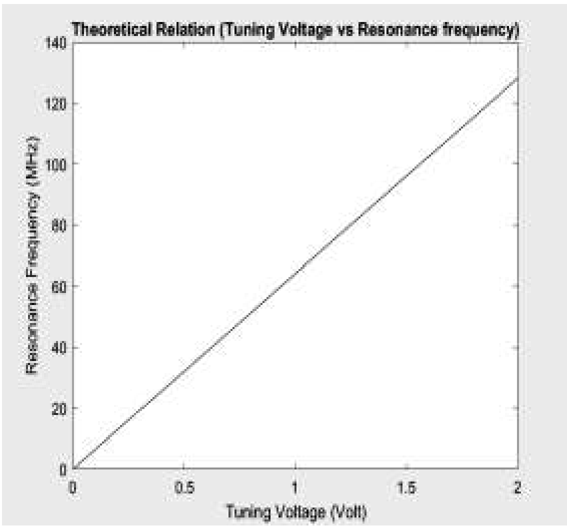

Figure 6: Theoretical relation between tuning voltage and resonance frequency with connecting the proposed circuit

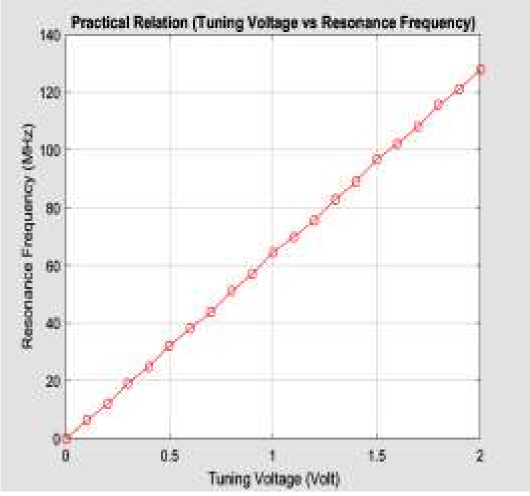

Figure 7: Practical relation between tuning voltage and resonance frequency with connecting the proposed circuit

5. Conclusions

The inverse non-linear relation between tuning control voltage and resonance frequency of the LC VCO circuit can be converted to direct linear relation using Logarithmic, Inverting, Anti-logarithmic, Difference, etc. amplifiers. Generally, any inverse non-linear relation between two voltage elements can be successfully converted to direct linear relation using these amplifiers. The concept of the proposed circuit depends upon the exponential relationship between forward current and applied voltage of the ideal diode that make the possibility of changing the operational amplifier to Logarithmic or Anti-logarithmic amplifiers. The Inverting amplifier can be utilized as an analog multiplier, which it can multiply any given analog voltage with a specific factor, whereas, this factor represents the Gain of this amplifier. In this work, the proposed circuit acts as an Analog Computer, which it performs an analog processing operation using operational amplifiers, whereas, the tuning control voltage has been analogy processed to make it directly and linearly varies with resonance frequency using specific OP/Amps. Using the proposed design, a stimulant result has been presented in this paper by obtaining a direct linear relation between a tuning control voltage in range (0-2) volt with the resonance frequency in range (0-140)MHz.

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