Optimization Design of Colpitts Oscillator for Active Induction Balance Metal Detection

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Abstract- There are numerous combinations of inductor and capacitors that will produce the required resonant frequency in Colpitts oscillators. However, not all these combinationswill produce a functional Colpitts oscillator.The Colpitts oscillator circuit proposed in this paper is the Bipolar Junction Transistor (BJT) common-base Colpittsoscillator.A portion of the collector voltage is returned back to the emitter via the capacitor divider in order to create feedback. One important factor to be considered in Colpitts oscillator design is the by considering the amount of feedback as this is always affected by the ratio of the capacitor divider. The assumption that the capacitor divider is equal in value does not lead to an optimal design for the Colpitts oscillator. This is because the amount of feedback from the capacitive divider may be too large, which usually causes the circuit to produce an output waveform that is not a clean sine wave.UsingOptimization approach proposed in this research, optimal circuit elements can be determined.The paper presents the optimization design and simulation of a Colpitts oscillator for induction balance metal detection by finding its critical parameters such as the resonant capacitors and the coil, which could produce optimal output characteristics.Using the Firefly Optimization Algorithm (FOA) approach proposed in this research, optimal circuit elements were obtained.Validation of the FOA results was carried using the NI Circuit Design Suite 11.0 from the National Instruments.FOA predicts the output current amplitude of 42.3 mA at a frequency of 99.994 kHz, output voltage amplitude of the oscillator was12.1V. With standard values of electronics components, simulation results measured11.8 V output voltage, which deviates from the FOA values by about 0.29% and 2.48% for resonant frequency and output voltage respectively, close to the expected FOA estimate.

Keywords- Optimization, Firefly, Colpittsoscillator, Induction balance metal detection.

I. INTRODUCTION

Arrangement of coils, where transmit and receive coilsare set up to minimize the magnetic coupling between the transmit and receive coils is referred to as induction balance. Very Low Frequency (VLF) principle metal detector is the best type to discriminate metallic target as it sends out a constant magnetic fieldfrom one coil (Transmit coil) while receiving it in another coil (Receive coil)(Connor and Scott,1998).Any changes in the phase of the received magnetic field is an indication of its proximity to electromagnetic target. The amplitude of the magnetic field signal determines the depth and size of the target(Autors, 2004).

Metal detectors allow the security personnel to screen individuals that may be carrying weapons or contraband that contain metallic components. Metal detectors can be walk-through or handheld models and are commonly used at checkpoints in airports, schools, courthouses, prisons, and military installations. Walk-through metal detectors can be indoor or outdoor models. The outdoor models are weatherproof and are often used at temporary venues, such as concerts or sporting events. Indoor models are typically installed at a fixed location and can however be moved if needed (Rocker, 1999). Handheld metal detectorsare more commonly used as a secondary means of screening in conjunction with walk-through metal detectors.The handheld modelsare used for pinpoint screening when the alarm in the walk-through metal detector has been triggered. However, they can be used as a primary screening device. Handheld metal detectors are weatherproof, portable, and cost less than walk-through metal detectors.

Virtually all standard metal detectors are designed based on the induction balance principle. There are two coils in the search head with one coil (transmitter coil) driven by the oscillator while the second coil (receiver coil) is used to pick up the signals from the transmit coil. These two coils are arranged in an overlapping fashion as shown in Figure 1, so that the receiver coil is very loosely coupled to the transmitter coil. When an electromagnetic target is in close proximity to the search head (transmit &receive coils), the magnetic field pattern of the transmit coil is disturbed, and thus the coupling between the transmit and receive coils will be increased. This technique is by far more sensitive than the beat frequency oscillator (BFO) type of metal detector, but it has the disadvantage that careful alignment of the coils is required (Rocker,1999).

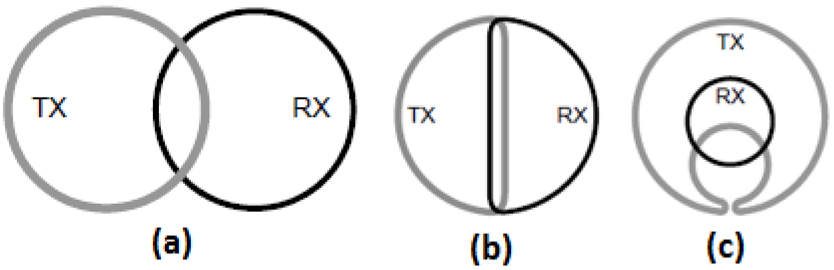

Fig.1: Induction Balance Coils Configurations (a) Double-O and (b) Double-D (c) Omega

Moreover, with the IB technique, lower frequencies can be employed without compromising sensitivity. In order to avoid “skin effect”, the frequencies used by IB detectors are lower than that of BFO(up to 100 kHz) metal detectorsand are as low as 1.5kHz to as high as 90kHz (Gaudin *et al*, 2003). The higher the frequency the more pronounced the skin effect becomes. Skin effect arises when current with a high frequency flows in a conductor and starts to become noticeable above 100kHz. If the magnetic field generated by the transmitter coil only penetrates the metal target to a shallow depth, then the true nature of the target may be misinterpreted and ferrous objects can be mistaken for non-ferrous, and vice-versa. This implies that the ability of the IB to distinguish between good and bad buried objects is compromised. Therefore, the highest recommended frequency we can specify is 100kHz. This is why IB detectors are also commonly referred to as VLF (very low frequency) (Autors, 1997).

There are numerous combinations of inductor and capacitors that will produce the required resonant frequency in Colpitts oscillators. However, not all these combinations will produce a functional Colpitts oscillator due to analytical approach of determining the circuit elements (Mayaram, 2000; Palumbo *et al*, 2009).

Colpitts oscillator design requires an amplifier while the amplifier circuit isprovided by a bipolar junction transistor. BJTs are easily available and their characteristicsare well known. Similar oscillators can certainly be constructed using field-effecttransistors but their variety makes the BJT a simpler choice to form a basis for analysis (Robert *et al*, 1999; Neamen, 2009). Also, the operational amplifier could be chosen as the active component, but the harmonic output in the megahertz frequency range cannot be guaranteed by using commonop-amps (Smith, 1986; Rohde and Apte, 2016; Lee and Lee, 2016). The choice of Colpitts oscillator over the Hartley oscillator is a matter of practicality.The Colpitts oscillator uses two capacitors and one inductor against only one capacitor and two inductors for the Hartley,while capacitors are more readily available than inductors (Nomura and Aoyagi, 2006). All thesefactors score the choice of Colpitts oscillator circuit design used in this study (Smith, 1986).

The main aim of this research is to employ a metaheuristic optimization approach, which is firefly optimization algorithm (FOA) to optimize the design of a Colpitts oscillator for induction balance metal detection by finding its critical parameters such as the resonant capacitors and the coil, which could produce optimal output characteristics.Using the Firefly Optimization Algorithm (FOA) approach proposed in this research, optimal circuit elements can be determined. The Colpitts oscillator circuit proposed in this paper is the Bipolar Junction Transistor (BJT) common-base Colpitts oscillator (Hagen, 2009).

II. OPTIMIZATION OF COLPITTS OSCILLATOR DESIGN

The schematic diagram of the Colpitts oscillator is shown in Figure 2. In this oscillator, the tuned circuit consists of L1, C1 and C2. A portion of the collector voltage is returned back to the emitter through the capacitor divider formed by C1 and C2, in order to create feedback. The parallel combination of C1 and C2 is calculated as(Hagen, 2009).:

$$C_T = \frac{C_1 C_2}{C_1 + C_2} \qquad (1)$$

Therefore, there is a rule-of-thumb which specifies that C2 is approximately equal to 35 times C1.
That is(Hagen, 2009).:

$$C_2 = 35C_1 \qquad (2)$$

Using the total capacitance (CT) of the parallel combination of C1 and C2 in equation (1), substituting C2 with 3*C1to obtain equation (3):

$$C_T = \frac{35C_1}{36} \qquad (3)$$

As stated earlier, the inductance L1 in parallel with the series combination of capacitive divider C1 and C2 forms the resonant circuit (Hagen, 2009).

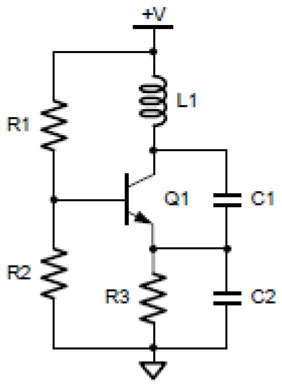

Fig.2: Typical Colpitts Oscillator Schematic

The resonant frequency of the transmit oscillator is calculated using (Hagen, 2009):

$$f_r = \frac{1}{2\pi\sqrt{L_1 C_T}} \qquad (4)$$

If a standard RF inductor with a value of 4.7mH is chosen, then the capacitance CT can be calculated from the following equation:

$$C_T = \frac{1}{\omega^2 L_1} \qquad (5)$$

$$C_T = \frac{1}{(2\pi f_r)^2 L_1} \qquad (6)$$

Where: frequency (f) is measured in Hertz (cycles per second), ωis the angular frequency measured in radians.

In this research, FOA has been used to design the required Colpitts transmit oscillator design.Firefly Optimization Algorithm (FOA) is a new nature inspired algorithm developed by Yang in 2008 based on swarm intelligence and inspired by the social behaviours of fireflies for solving optimization problem (Yang, 2008). This algorithm is based on bioluminescence principle. The rhythmic flash, the rate of flashing, and the amount of time between flashes form part of the signal system that brings both sexes together (Lewis & Cratsley, 2008). The mathematical formulation of the algorithm is based on the fact that; all fireflies are unisex and therefore can communicate with anyone else (Kazemzadeh-Parsi, 2014), the attractiveness between fireflies is therefore determined by the level of brightness of the individual firefly, and the brighter firefly light attracts other fireflies (Carlos & Coello, 2000). The objective function of the problem depends on the brightness of a firefly (Ray & Liew, 2003). FOA aims to find an optimal solution to optimization design problem.

It is a known fact that the light intensity at a particular distance from the light source obeys the inverse-square law. The light intensity l decreases as the distance r increases in terms of $l \propto 1/r^2$. Furthermore, the air absorbs light, which becomes weaker and weaker as the distance increases. These two combined factors make most fireflies visible to a limited distance, usually several hundred meters at night, which is good enough for fireflies to communicate with one another. The flashing light can be formulated in such a way that it is associated with the objective function to be optimized, which makes it possible to formulate optimization algorithm. The algorithm starts by placing the fireflies in random locations. The locations of a fireflies correspond to the values of the parameters for the objective function to be solved. The multiple objectives optimization problem in this research using FOA is implemented with the following steps (Yang, 2013):

1. Initializing number of fireflies, n, biggest attraction β_0, absorption coefficient of light intensity γ, step size factor α, and maximum number of iterations or generations t_{max}.
2. Initializing the positions of fireflies randomly, the values of objective functions of fireflies were set as their maximum brightness of fluorescence I_0.
3. Calculating relative brightness and attractiveness of fireflies belonging to the population. The direction of movement depended on the relative brightness of fireflies. An expression for this maximum brightness of fluorescence is (Yang, 2013):

$$I = I_0 \times e^{-\gamma rij} \qquad (7)$$

$$\beta = \beta_0 \times e^{-\gamma rij} \qquad (8)$$

where β_0 is the maximum attractiveness at r = 0, γ is the absorption coefficient of the light intensity, and r_{ij} is the spatial distance between fireflies I and j. The attractiveness of a firefly was proportional to its brightness and they both decreased with distance.

4. Updating the spatial positions of fireflies. Random perturbations were injected into the firefly with the best position. The updated equation is:

$$x_i = x_i + \beta \times (x_j - x_i) + \alpha \times (rand - 0.5) \qquad (9)$$

where x_i, x_j represent the spatial positions of firefly $i$and j, respectively. α is the step size factor. *rand* is random factor distributed uniformly in [0,1].

5. Recalculating the brightness of fireflies according to the updated positions.
6. Returning to Step 3 until the search precision was met or the maximum number of generations was achieved.

The pseudo code of the FOA is given below (Yang, 2013).

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Define objective functions $f_1(x), ..., f_K(x)$ where $x = (x_1, ..., x_d)^T$
Generate initialize a population of nfirefliesxi $(i = 1, 2, ..., n)$.
Light intensity $I_i$ at $x_i$ is determined by $f(x_i)$.
Define light absorption coefficient γ.
while (t<MaxGeneration)
for i = 1: n (all n fireflies)
        for j = 1: n (all n fireflies) (inner loop)
        if $(I_i<I_j)$
                Move firefly I towards j.
        End if
        Vary attractiveness with distance r via $\exp[-\gamma r^2]$
        Evaluate new solutions and update light intensity.
        Enf for j
        End for i
        Rank the fireflies and find the current global best g.
        End while
        Processes results and visualization.
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As shown in Figure 2, the tuned circuit consists of L1, C1 and C2, which form the desired resonant frequency of the Colpitts transmit oscillator. Therefore, in order to ease the problem of high dimensionality, three design variables were identified and are presented in Table 1. The geometry constraints and operating limits are shown in Table 2.

Table 1: Transmit Oscillator Design Variables and Ranges

Variables	**Range**	**Unit**
Coil inductance (x_1)	1 – 10	mH
Feedback Capacitor, C1 (x_2)	250 – 800	pF
Emitter Capacitor, C2 (x_3)	1 – 10	nF

Table 2: Transmit Oscillator Design Constraints

Variables	**Range**	**Unit**
Resonant frequency, f_r	≤ 100	kHz
Total Capacitance, C_T	≤ 800	pF

These design variables were represented as:

$$X = [x_1, x_2, x_3] = \begin{bmatrix} Coil\ inductance, L1 \\ Feedback\ capacitor, C1 \\ Emitter\ capacitor, C2 \end{bmatrix}^T \qquad (10)$$

While the geometry constraints and operating limits were represented as:

$$g(x) \leq 0 \Leftrightarrow \begin{Bmatrix} \text{Resonant frequency} \leq 100 \\ Total\ capacitance\ \leq 800 \end{Bmatrix} \qquad (11)$$

The optimization design of the transmit oscillator problem was formulated by defining the minimum resonant frequency of the Colpitts transmit oscillator for the induction balance metal detector as the objective function as:

$$Minimize\ f_r(x) = \frac{1}{2\pi\sqrt{L_1 C_T}} \qquad (12)$$

III. COLPITTS OSCILLATOR OPTIMIZATION DESIGN RESULTS

The Firefly optimization algorithm was written in Matlab environment and the results were obtained by running the developed program on a 1.60 GHz Intel® Celeron® CPU Windows 10 Pro64-bit personal computer. The optimization of the transmit oscillator was then run to simultaneously find the transmit coil inductance L1, feedback capacitor C1 and emitter capacitor C2. Data for the transmit oscillator primary design variables when displayed on the screen to show their iterative process as well as the plots for the oscillatory trend in the iterative process was observed which was caused by the randomization parameter of the FOA. This results in the final circuit elements for the metal detector transmit oscillator as shown in Table 3. The standard values for these circuit elements are as well presented in Table 3.

Table 3: The Predicted FOA Results for Colpitts Oscillator Circuit Components.

Parameters	**FOA Results**	**Unit**
Coil inductance, L1 (x_1)	6.246	mH
Feedback Capacitor, C1 (x_2)	417.0155	pF
Emitter Capacitor, C2 (x_3)	14.595	nF
Total capacitance, C_T	405.4318	pF
Resonant frequency, f_r	99.994	kHz
Output voltage, V_{pp}	12.1	V
Output Current, I_{pp}	42.3	mA

In the firefly optimization algorithm, the total capacitance of the series capacitors C1 and C2 and the resonant frequency of the tuned circuit are all constrained to the operational limit.The optimization problem is to obtain the optimal values of the coil inductance, and the capacitive divider C1 and C2 while meeting these constraints.As shown in Table 3, the optimal field coil current of 42.3 mA is obtained from the FOA results while the amplitude of theoutput voltage of the transmit oscillator is 12.1 V. These results were validated using standard values of resistors and capacitors from National Instruments Multisim Software.

IV. COLPITTS OSCILLATOR HARDWARE SIMULATIONS

The software that was used for the simulations was based on the NI Circuit Design Suite 11.0 from the National Instruments (NI, 2010). Figure 3 is the circuit diagram for the Colpitts oscillator with the available standard component values. The simulated output waveform obtained with these circuit components is displayed in Figure 4. It can be seen that the change in the capacitive divider C1 and C2 did not alter the resonant frequency and the output voltage significantly as presented in Table 4.The waveform is still saturated and the maximum value isapproximately 12 V, though there is less fluctuation in the circuit.

Table 4: Comparison of the Simulation Results with FOA Prediction and Standard Values.

Parameters	**FOA Results**	**Standard values**	**Deviation (%)**

Coil inductance, *L1*(mH)	6.246	6.246	0.00
Feedback Capacitor, *C1* (pF)	417.0155	390	6.47
Emitter Capacitor, *C2* (nF)	14.595	12	17.78
Total capacitance, C_T (pF)	405.4318	377.72	6.83
Resonant frequency, f_r (kHz)	99.994	99.70	0.29
Output voltage, V_{pp}(V)	12.1	11.8	2.48
Output Current, I_{pp} (mA)	42.3	30.8	27.18

Table 4 shows the output characteristics of the simulated circuit with the FOA and the available standard components. Theoutput voltage amplitude of the oscillator with the FOA predictions is much larger than that of the standard values by just 2.48%, though the C1 and C2 capacitorsare significantly smaller.

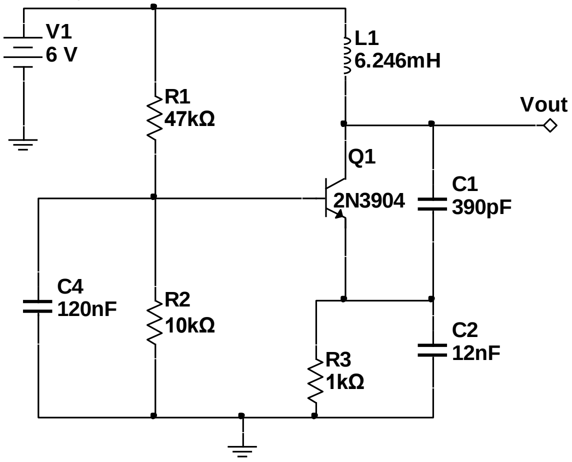
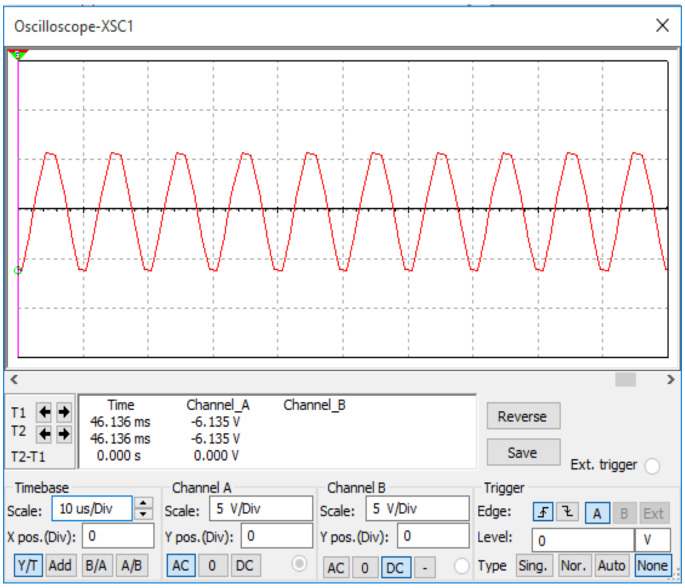


Fig.3: Colpitts Oscillator Circuit Diagram



	Time	Channel_A	Channel_B
T1	46.136 ms	-6.135 V	
T2	46.136 ms	-6.135 V	
T2-T1	0.000 s	0.000 V	

Timebase
Scale: 10 us/Div
X pos.(Div): 0

Channel A
Scale: 5 V/Div
Y pos.(Div): 0

Channel B
Scale: 5 V/Div
Y pos.(Div): 0

Trigger
Edge: A
Level: 0 V

Fig.4: Oscilloscope Waveform for Colpitts Oscillator Simulation

Therefore, the proposed firefly optimization algorithm prediction for the chosen Colpitts oscillator and standard values simulation agree that the Colpittsoscillator circuittopology produces oscillation. The simulated circuit with the standard values exhibited lower components values with respect to the FOA predicted values and its simulated output characteristics with respect to the voltage amplitude, resonant frequency, and excitation current amplitude were also lower than that of the FOA-specified circuit characteristics. However, the deviation in the FOA predicted values did not significantly alter the resonant frequency and the output voltage of the designed Colpitts oscillator.

V. CONCLUSION

The optimization design and simulation of a Colpitts oscillator for induction balance metal detection is presented in this paper. Now days, metal detecting system are becoming very important role in securing live and properties of civilian and military. This research aimed to employ FOA, a metaheuristic optimization approachto optimize the design of a Colpitts oscillator for induction balance metal detection. The critical parameters of the Colpitts oscillator such as the resonant capacitors and the coil inductance, which could produce optimal output characteristics were obtained.Using the Firefly Optimization Algorithm (FOA) approach in this research, optimal circuit elements were determined.FOA predicts the output current amplitude of 42.3 mA at a frequency of 99.994 kHz, output voltage amplitude of the oscillator was12.1V. With standard values of electronics components,simulation results measured11.8V output voltage, which deviates fromthe FOA values by about 0.29% and 2.48% for resonant frequency and output voltage respectively, close to the expectedFOA estimate.

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