Optimization Design of Transmit and Receive Coils for Active Induction Balance Metal Detection System

Sadiq, U. A.[123]; Ogohi, A[2];Audu, T. C.[2;] Ezeh, L. O.[2]; Oluyombo, O. W.[1,3]
National Space Research & Development Agency, Abuja, Nigeria[1]; Center for Satellite Technology Development, Abuja, Nigeria[2]; Electrical & Electronic Engineering Dept., University of Abuja, Nigeria[3];

Abstract- In an induction balance metal detector, there are two similar coils:Transmitter coil, which is the outer coil loopa coil of wire that carries electricity first in one direction and then in the other, thousands of times each second. Receiver coil on the other hand is the inner coil loop, which contains another coil of wire and acts as an antenna topick up and amplify frequencies coming from target objects in the ground.Most of the IB implementations presented in literature have some apparent drawbackswhen it comes to design ofsensing head for a metal detector. The sensing head needs tohave simple and compact geometry, high detection sensitivity, and pinpointing accuracy. Also, it must provide good precision accuracyso that the measureddata can be reliably computed.In this research, based on these requirements,the newly developed Firefly Optimization Algorithm (FOA) is proposed to solve the sensing coils optimization problem. The results obtained from experimental measurements showed that aluminum could achieve penetration depth of about 40 cm, followed byzinc, iron and steel. It was clearly seen that the developed FOA designed IB metal detector is capable of detecting both ferrous and non-ferrous metal target at considerable depth in both ground and underground conditions.

Keywords- Antenna, search coils, optimization, firefly, algorithm, metaheuristics, depth.

I. INTRODUCTION

Induction Balance (IB) metal detectors have been used for thedetection of metallic parts since the World War II and arenowadays considered a rather mature technology.However, in spite of recent developments in other metal detectiontechniques, induction balance metal detector still remains an area of active research (Sumbul and Tasdemir, 2011). Due totheir sensitivity, robustness and high-speed operation, they are practically theonly sensors that are currently used in humanitarian demining for close-indetection in the field (Sumbul and Tasdemir, 2011). Beat Frequency Oscillator (BFO) metal detector design uses a single search coilof wire. However, induction balance designs require two or more coils, and there are numerous ways to set up an induction balanced coil system, many of which have been used by metal detector manufacturers over the years(Sumbul and Tasdemir, 2011).

The method of partially overlapping two round coils to achieve induction balance was used by Alexander Graham Bell in his second attempt to locate President Garfield's bullet (1881), and possibly predates Bell by a few years. Figure 1 illustrates the different coils configurations, with the transmit (TX) and receive (RX) coils. The RX coil is slightly overlapped with the TX coil, so that part of the inner field of the TX coil goes through the RX coil, and part of the outer field of the TX coil also goes through the RX coil. The inner and outer fields of the TX coil are of opposite "polarity," so if the RX coil is precisely positioned, it is possible to get the effects of the opposing fields to cancel. This type of coil is often referred to as "coplanar" because the TX and RX coils lie in the same plane. Another common name for this configuration is the Double-O (or "OO") coil, Double-D, and Omega coils(Sumbul and Tasdemir, 2011).

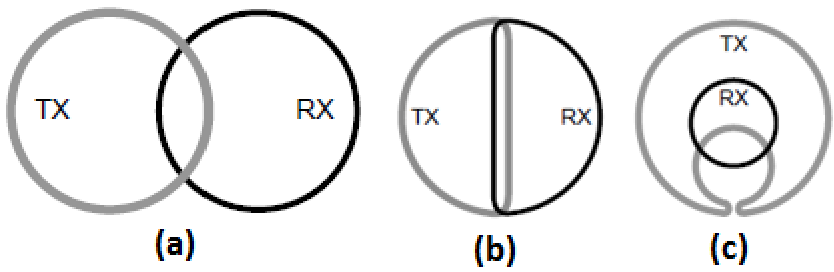

Fig.1: Induction Balance Coils Configurations (a) Double-O and (b) Double-D (c) Omega

In order to explore their benefits an efficient methodof primary field suppression (induction balance, IB) must be provided (Nelson, 2004). Thereare several IB methods that are normally used for design of metal detection system. Most these methods have some apparent drawbackswhen it comes to design ofsensing head for a handheld landmine detector withadditional model-based metal characterizationfeatures (Firdaus *et al.* 2014). Such sensor needs tohave simple and compact geometry, high detection sensitivity, highspatialresolution and pinpointing accuracy (Sumbul and Tasdemir, 2011; Firdaus *et al.* 2014). It also must provide good invariability ofthe measureddata so that the parameters of a model can be reliably computed (Firdaus *et al*. 2014).What allowed detectors to discriminate between metalswas the fact that every metal has a different phase response when exposed toalternating current (Candy, 2011). Scientists had long known of this fact by the time detectorswere developed that could selectively detect desirable metals, while ignoringundesirable ones (APH, 2006).

Metal detectors work on the principle of transmitting a time varying magnetic field and analyzing a return signal from the target object and environment (Moreland, 2006). The transmitted time varying magnetic field is usually at rates of fairly high-pitched audio signals (Nelson, 2004). The magnetic field is transmitted from a transmit coil when a varying electric current flows through it. The transmitter and receiver coils are usually the same. This changing transmitted magnetic field from the transmitter coil causes electric currents often called eddy currents, to flow in the metal targets (Sumbul and Tasdemir, 2011). These eddy currentsin turn generate a weak magnetic field, but their generated magnetic field is different from the transmitted magnetic field in shape and strength (Sumbul and Tasdemir, 2011). A simplified block diagram of the basic pulsed-EMI technique is shown in Figure 2.

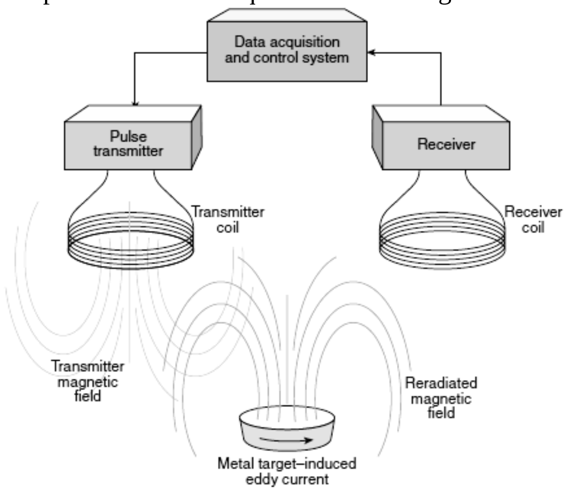

Fig.2: Two-Coils Metal Detection Principle (Hopkins, 2004)

As shown in Figure 2, the regenerated magnetic field from the eddy currents causes an alternating voltage signal at the receive coil. Since the deeply buried or small targets produce weak signals in the receive coil, there is need for the receive coil output voltage to be amplified to a reasonable level for matching the Analog-to-Digital Converter (ADC) or microcontrollerinput. Most metal detectors have the ability to discriminate metal target by selecting the desired properties of a seeking metallic target (Sumbul and Tasdemir, 2011). The properties that are usually selected are ferrous/non-ferrous and time constant (sometimes called conductivity) (Nelson, 2004; Sumbul and Tasdemir, 2011). A metal target is said to be ferrous target if it is attracted to a magnet, a non-ferroustarget if it is not attracted to a magnet. Metal detectors differentiate between different non-ferrous targets by measuring their magnetic field strength, which is a function of how well eddy currents flows in them, which in turn dependent on the conductivity of the non-ferrous target. This is the opposite of electrical resistance (Nelson, 2004; Sumbul and Tasdemir, 2011). High conductivity (low resistance) means easy flow of the eddy currents, while low conductivity (high resistance) means high eddy current friction (Nelson, 2004; Sumbul and Tasdemir, 2011).

II. OPTIMIZATION OF SENSING HEAD COIL DESIGN

Since it is necessary to construct the inductor for induction balance metal detector, this inductor is known as the search coil and is located at the end of the detector shaft. There are two conventional approaches to creating a search coil:Simply by winding a coil, for example,150 turns on a 155mm former. Then measure the inductance and calculate suitable values to use for C1 and C2, as the Colpitts oscillator (shown in Figure 3) is the transmit oscillator selected for this design.Second approach to search head inductor coil design is to specify an inductance for L1 to suit standard values for C1 and C2. Then wind L1 to match the specified inductance.

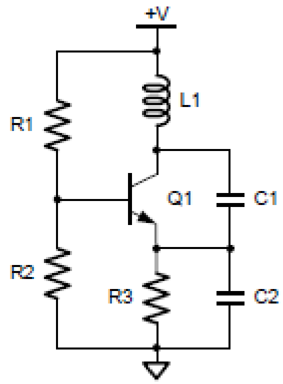

Fig.3: Typical Colpitts Oscillator Schematic

In this research, based on these requirements,the newly developed Firefly Optimization Algorithm (FOA) is proposed to solve the sensing coils optimization problem.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):

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

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

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:

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

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).

Define objective functions $f_1(x), ..., f_K(x)$ where $x = (x_1, ..., x_d)^T$
Generate initialize a population of *n*firefliesx_i $(i = 1, 2, ..., n)$.
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[-γr^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.

According to Brooks, the inductance of any air core coil can be approximated by the following equation (Wheeler, 1928):

$$\square = 400\square \times 10^{-9}\ \square\ \square^2\left(\left(0.5+\frac{\square^2}{48\square^2}\right)\ln\left(\frac{32\square^2}{\square^2}\right) - 0.84834 + 0.051\frac{\square^2}{\square^2}\right) \quad (1)$$

Where *L* is the inductance in Henries, *r* is the mean radius of the winding in meters, *l* is the coil length (which equals thickness c) in meters, and *N* is the number of turns.

This can be rewritten as(Wheeler, 1928):

$$\square = 400\square \times 10^{-9}\ \square\ \square^2\left(\left(0.5+\frac{\square}{12}\right)\ln\left(\frac{8}{\square}\right) - 0.84834 + 0.2041\square\right) \quad (2)$$

Where: *c* = *l* and *a* = *r*.

$$\square_1 = 400\square \times 10^{-9}\ \square\square^2\left(\left(0.5+\frac{\square}{12}\right)\ln\left(\frac{8}{\square}\right) - 0.84834 + 0.2041\square\right) \quad (3)$$

Therefore,

$$\square = \left(\frac{\square}{2\square}\right)^2 \quad (4)$$

In this research, variables to optimize are the inner radius (mm), the wire thickness (mm), and the required number of coil turns.

The coil thickness which is the cross-section of the coil (c) is calculated from (Wheeler, 1928):

$$\square = \sqrt{\square} \times \square\square\square\square\square\square\square\square\square\square\square\square\square\square \quad (5)$$

This assumes a square cross-section for the coil bundle. Therefore, the mean radius (a) is calculated from (Wheeler, 1928):

$$\square = \square\square\square\square\square\square\square\square\square\square\square + \frac{\square}{2} \qquad (6)$$

This implies the inner radius plus half of the cross-section of the wire bundle.

Therefore, in order to ease the problem of high dimensionality, four design variables were identified and are presented in Table 1. The geometry constraints and operating limits are shown in Table 2.

Table 1: Search Coil Design Variables and Ranges

Variables	Range	Unit
Inner Radius (x_1)	0.05 – 0.15	m
Wire Thickness (x_2)	0.0001 – 0.0005	m
Number of Coil Turns (x_3)	10 – 500	-
Total capacitance, (x_4)	200 - 800	pF

Table 2: Search Coil Design Constraints

Variables	Range	Unit
Mean Radius, *a*	≤ 0.5	m
Coil thickness, *c*	≤ 0.01	m

These design variables were represented as:

$$\square = [\square_1, \square_2, \square_3, \square_4] = \begin{bmatrix} \square\square\square\square\square\ \square\square\square\square\square\square \\ \square\square\square\square\ \square\square\square\square\square\square\square\square\square\square \\ \square\square\square\square\square\square\ \square\square\ \square\square\square\square\ \square\square\square\square\square \\ \square\square\square\square\square\ \square\square\square\square\square\square\square\square\square\square\square\square \end{bmatrix}^{\square} \qquad (7)$$

While the geometry constraints and operating limits were represented as:

$$\square(\square) \le 0 \Leftrightarrow \begin{cases} \text{Mean Radius} \le 0.5 \\ \square\square\square\square\ \square\square\square\square\square\square\square\square\square \le 0.01 \end{cases} \qquad (8)$$

The parallel combination of C1 and C2 is calculated as (Hagen, 2009).:

$$\square_{\square} = \frac{\square_1\square_2}{\square_1 + \square_2} \qquad (9)$$

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

$$\square_2 = 35\square_1 \qquad (10)$$

Using the total capacitance (CT) of the parallel combination of C1 and C2 in equation (1), substituting C2 with 3*C1 to obtain equation (11):

$$\square_{\square} = \frac{35\square_1}{36} \qquad (11)$$

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:

$$\square\square\square\square\square\square\square\square\ \square_{\square}(\square) = \frac{1}{2\square\sqrt{\square_1\square_{\square}}} \qquad (12)$$

III. SEARCH COIL 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 Pro 64-bit personal computer. The optimization of the transmit oscillator was then run to simultaneously find the critical parameters of the transmit coil inductance L1 (coil inner radius, wire thickness, and number of turns), and the total capacitance of the series capacitors C1 and 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 Search Coil Parameters and Total Capacitance.

Parameters	FOA Results	Unit
Inner Radius (x_1)	114.0199	mm
Wire Thickness (x_2)	0.612	mm
Number of Coil Turns (x_3)	105	nF
Total capacitance, C_T (x_4)	405.43	pF
Mean Radius, *a*	117.165	mm

Coil Thickness, c	6.29	mm
Coil Inductance, L	6.246	mH
Resonant Frequency, f_r	99.994	kHz

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 resonant frequency of approximately 100 kHz is obtained from the FOA results. This will be achieved from 105 turns of wire wound on 22.8 cm former with 0.612 mm wire thickness.

IV. EXPERIMENTAL SETUP FOR SEARCH COIL OPTIMIZATION DESIGN

In order to verify whether the circuit can detect ferrous and non-ferrous metal, a prototype search coils were developed based onthe predicted FOA design results (Table 3)as shown in Figure4. The experimental set up is shown in Figure 5. Four metal plates with standard size of 10cm x 15cm were used as test specimens. The metal was of different types, comprising ferrous metal: iron and stainless steel and also non-ferrous metal: aluminum and zinc. An operational induction balance circuit will sound a tone as system initialization. A beep tone is produced when a metallic material is near the detector coil. Metal detection test were carried out based on ground and undergroundconditions. The aim of these initial tests was to simulate metal detection in condition of metal landmines component, when located either on the ground (as detonator) or buried underground (as explosive).

Fig.4: Search Coils Alignment

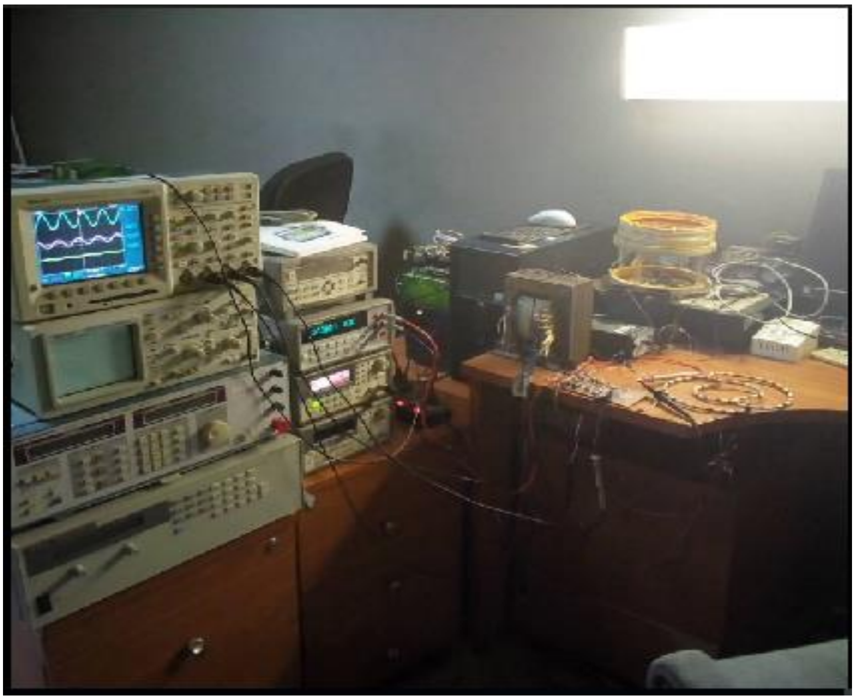

Fig.5: Experimental Setup for the Search Coils Testing for Induction Balance

The induction balance metal detector was developed based on the proposed FOA design and was experimentally validated using the standard values of electronics component. The performance of the prototype induction balance metal detector was then tested with different level of sensitivity to determine the sensitivity that produced the maximum depth of metal detection. Table 3 shows the ground and underground test results for four different metallic objects investigated.

Table 4: Maximum Depth Obtained with Ferrous and Non-Ferrous Metals

Material	**Test Medium**	**Maximum Depth (cm)**
Ferrous Metals		

Steel	Ground	29
	Underground	26
Iron	Ground	31
	Underground	32
Non-Ferrous Metals		
Zinc	Ground	35
	Underground	33
Aluminium	Ground	40
	Underground	38

From the table, it is clearly observed that aluminum produced the maximum depth with respect to ground and underground tests conducted when compared to zinc, steel and iron. Both ferrous and non-ferrous tests confirmed that aluminum could achieve penetration depth of about 40 cm, followed byzinc, iron and steel. It was clearly seen that the developed FOA designed IB metal detector is capable of detecting both ferrous and non-ferrous metal target at considerable depth in both ground and underground conditions. In addition, non-ferrous metallic target produced higher conductivity at low resistance that could allow eddy current to flow easily whereas ferrous has low conductivity which implies that it has high eddy current friction (Candy, 2011). Non-ferrous metal exhibits maximum conductivity values compared to ferrous metal (TIBTECH, 2014). Thus, it can be proven that non-ferrous metals have excellent conductivity that is associated with considerable penetration depth with respect to air and ground.

V. CONCLUSIONS

This paper has presented the results of the search coil optimization design problem by using the proposed firefly optimization algorithm (FOA). A prototype IB metal detector was developed based on the optimization design results and was capable of detecting both ferrous and non-ferrous materials. Analysis of the ground and underground penetration distance was carried out based on the measurements obtained. During experimental and field measurements, it was observed that IB metal detector is capable of detecting non-ferrous metal at higher penetration depth than ferrous metal target with respect to ground and underground conditions, which confirmed their high conductivity properties.

VI. REFERENCES

[1]. P. H. Guide (2006): Making a Fast Pulse Induction Mono Coil, vol. 1.0, no. December, pp. 3–9.

[2]. Candy, B. (2011): Metal Detector Basics and Theory Introduction, (2011), pp. 4–12.

[3]. Carlos, A., Coello, C. (2000): Use of a self-adaptive penalty approach for engineering optimization problems. Computers in Industry 41(2), 113–127.

[4]. Firdaus, A., Zaidi, A., Cherng, Y. W., Munir, H. A., & Zaidi, N. H. A. (2014): Design and Development of Sensing System for Mines Detector Robot. Key Engineering Materials, 594, pp. 924-929.

[5]. Hagen, J. B. (2009): Radio-Frequency Electronics: Circuits and Applications. CambridgeUniversity Press, New York, 2nd edition.

[6]. Kazemzadeh-Parsi, M. J. (2014): A Modified Firefly Algorithm for Engineering Design Optimization Problems. IJST, Transactions of Mechanical Engineering 38(M2), 403-421.

[7]. Lewis S.M, and Cratsley C.K. (2008): Flash signal evolution, mate choice and predation in fireflies. *Ann Rev Entomol*. 53(2):293-321.

[8]. Moreland, C. (2006): Induction Basics Magnetic fields, pp. 2–4.

[9]. Nelson, C. V. (2004): Metal Detection and Classification Technologies, Johns Hopkins APL Technical Digest, p. 25.

[10]. Ray, T., and Liew. K. M. (2003): Society and Civilization: An Optimization Algorithm Based on the Simulation of Social Behavior. IEEE Transactions on Evolutionary Computation 7, 386-396.

[11]. Sümbül, H. and Taşdemir, M. (2011): An Experimental Comparison of Induction Balance Systems and Pulse Induction Systems, pp. 16–18.

[12]. TIBTECH (2014): Conductive Materials or Metal Conductivity - TIBTECH innovations -. [Online]. Available: http://www.tibtech.com/conductivity.php. [Accessed: 10-May-2014].

[13]. Wheeler, H. A. (1928): Simple Inductance Formulas for Radio Coils, Proc. I.R.E., vol 16, pp 1398-1400.

[14]. Yang, X.S. (2013). Multi-objectives firefly algorithm for continuous optimization. *Engineering Computation*, *29*/175–184.

[15]. Yang, X.-S. (2008): Nature-Inspired Metaheuristic Algorithms. Luniver Press.