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Computer aided design of an electromagnetic ignition coil for high speed benzine engines

***Abstract**. In this study, since it can be analyzed in term of practically and easily in application, a 15 kV ignition coil was designed, and analyzed in electromagnetic way. In order to benefit from this design in automotive industry, it has been determined an ignition coil construction here. Magneto static designing of the ignition coil have been done as 3 dimensional analytical way with help of finite elements methods (Ansoft Maxwell V12 program). By this way, electrical and magnetic parameters and quantities have been calculated; the static magnetic data obtained have been commented. In this design, the effects of using different electromagnetic materials such as nanocrystalline, amorphous and enni55 as core of the ignition coil have been explored. By using Ansoft–Simplorer program, different types of ignition coil cores could have been obtained. It has been inferred that more accurate dynamic analyzing conclusions for the ignition coil would result in the calculation.*

***Streszczenie.** W artykule zaprezentowano projekt 15 KV cewki zapłonowej z przeznaczeniem do silników benzynowych. Projekt wykorzystuje obliczenia magnetostatyczne wykonane z pomocą metody elementów skończonych. Uwzględniono zastosowanie różnych materiałów jak materiałów nanokrystalicznych czy amorficznych. Przedstawiono różne koncepcje projektu cewki. (**Komputerowe projektowanie cewki zapłonowej do silników benzynowych**)*

Keywords: Electromagnetic ignition coil design, nanocrystalline, amorphous and enni55 embedded core designs.
Słowa kluczowe: cewka zapłonowa, metoda elementów skończonych.

Introduction

Electric, solar-powered and alternate fuel vehicles may be the wave of the future, but for now most automobiles run on gasoline, which they burn in an internal combustion engine to convert into motion. For combustion to take place, a spark is needed to ignite the fuel mixture in the engine. The vehicle's ignition system is designed so that a 12 volts battery can generate very high voltages required to create such a discharge. The heart of this system is a device called an ignition coil.

There are some commercial CAD systems for magnetic studies, and more than existing ones are being used by major industrial companies for several application aims. When the capacities of such software are changing, their methodologies and purposes are similar [1].

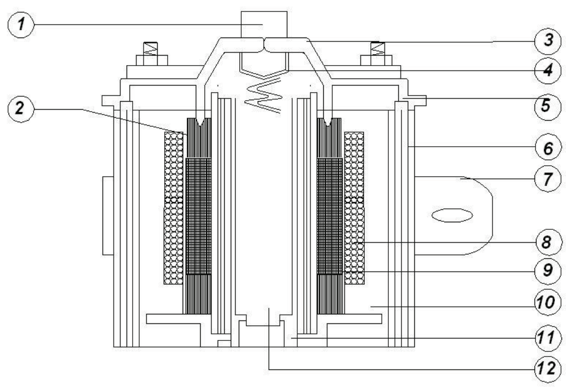
As known, there are three types of ignition systems, and are called as magnetogenerator, classical ignition with battery, and electronics one. The electronics ignition system is an innovative type and is used at vehicles instead of classical ignition systems [2]. This ignition system has a normal coil which takes place in all modern automobiles. Regarding to the case, it has been required to design a coil for such ignition systems. In order to obtain the best results amongst the current, voltage values of the ignition coil, the core materials of the coil have been modified.

In this study, ignition coil is being examined for producing voltages at a shorter period as structural. To realize this aim, the 3D model is constructed by using a commercial simulation packet of Ansoft–Maxwell v11. This coil has been designed in electromagnetic aspect; the designed ignition coils has been analyzed and modelled with using different electromagnetic materials; finally, efficiency of the designed coil has been showed by simulating its magnetic field dispersions. The magnetic properties of the designed ignition coil and its parameters have been determined by using of Ansoft Maxwell 3D software [3].

Ignition coil Design Principles

An ignition coil consists of two transformer windings sharing a common magnetic core. It contains both primary and secondary winding circuits.

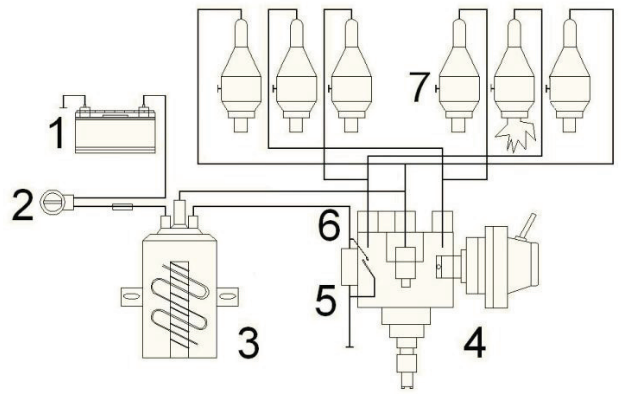
Conventional coils used in earlier model automobiles have been utilised larger cylindrical coils in conjunction with distributors. The secondary winding on these coils are wound directly onto the laminated iron core and connected electrically to the centre tower in the cap of the ignition coil. Figures 1–2 demonstrate an ignition coil structure and an ignition system.



1- High-tension connection on the outside, 2- Winding layers with insulating paper, 3- Insulating cap, 4- High-tension connection on the inside, 5- Case, 6- Mounting bracket, 7- Metal plate jacketing (magnetic), 8- Primary winding, 9- Secondary winding 10-Sealing compound, 11- Insulator, 12- Iron core

Fig.1. General view of an ignition coil structure

Since the high-voltage is applied to the core, the core must be insulated by the cap and an additional insulator is inserted in the base. The primary winding is located near to the outside around the secondary winding. The primary current, which is switched on and off by a switching device (maybe a distributor, Darlington transistor, MOSFET or IGBT, depending on the application) flows through the primary winding. As the switch is turned on, current flowing through the primary winding causes a magnetic field that magnetises the iron core. When the switch opens its contact, the voltage flips from positive-negative to negative-positive. In doing so, a voltage spike is induced on both primary and secondary side [4, 17].



1- Battery, 2- Ignition and starting switch, 3- Ignition coil, 4- Ignition distributor, 5- Ignition capacitor, 6- Contact breaker, 7- Spark plugs, Rv ballast resistor for boosting the starting voltage (not always fitted)

Fig.2. General view of ignition system

In a transistorised ignition system (TSI), the coil stores energy as well as acting as a voltage transformer. This case results relatively high coil inductance, limited switching rate for charging, thick but short connecting cables, and long burning time. Hence, very high engine speed cannot be achieved with these coils and power output may be below optimum value [5].

Laminations manufactured from silicon steel are traditional material for transformers, cores etc. New amorphous laminations and nanocrystalline materials have much lower losses than laminations, but they are expensive and the technology of manufacturing is more difficult [6]. Amorphous and nanocrystalline magnetic materials, in terms of combined induction and permeabilities are now competitive with SiFe bulk alloys, and the above mentioned Fe-Co alloys [7].

In this study as a basis, an ignition coil labelled as MK140 was chosen as a high-performance coil [8]. The geometrical shape of the core has been kept as constant and the design and simulations have been done for three different core materials. The primary and secondary number of turns also has been kept as constant. The ignition time goes down when the engine speed is up. Therefore the ignition voltage has been selected as 15 kV for a short time and different core materials.

Analysis and modelling of the designed ignition coil

Electromagnetic characteristic of the designed ignition coil has been determined by using finite element method (FEM). Moreover the induced voltages and total magnetic fluxes have been calculated by using 2D or 3D finite elements method (FEM) too.

Magnetostatic field solver carries out 3 dimensional analyses by Finite Element Method. The system modeled is divided to tetrahedral and the obtained finite element mesh is composed. In solution process error is reduced by refining the mesh through iterations. The solver writes the completed solution into a file and performs an error analysis. In an adaptive analysis, it refines the tetrahedral with the highest error, and continues to the solutions until the designated criterion is met. As a result, inductance values are calculated, current density, magnetic field intensity, magnetic flux density, forces are obtained in both magnitude and vector quantities [9]

Value of a linear inductance which occurred in a coil is directly proportional with total magnetic flux and the current passed through conductor. According to Faraday's Law, voltages amongst terminals of an inductor equal to derivative of total flux linkages as in time. These declarations can be expressed as shown in equations (1–2).

(1) $$\lambda = L.i$$

(2) $$v = \frac{d\lambda}{dt} = L.\frac{di}{dt}$$

where: λ – flux, L – inductance, i – current flowing.

There seems a certain coupling between two adjacent wrapped up coils regarding to their physical configurations and circulation speed of currents. This coupling between two adjacent wrapped up coils rises up related with windings wrapped up on end (successively), and direction of magnetic flux which made by soft iron material. However such soft iron material eliminates linearity of magnetic flux inside the coil with iron core.

In order to determine the characteristics of the electromagnetic field created, Maxwell equations are used. The Equation (3) given below is written as one of Maxwell Equations.

(3) $$\nabla \times \left[\frac{1}{\mu_r \mu_o} \nabla \times A \right] + \sigma \frac{\partial A}{\partial t} = J_o$$

where: A – magnetic vector potential, J_0 – applied current.

Air gap flux density can be obtained from curl of magnetic vector potential [10]. Since finite element softwares have a basic instruction set and they have ability in calculating of flux density from potential solution, magnetic flux density can be calculated as shown in Equation (4).

(4) $$B = \nabla \times A$$

where: ∇ – Divergence.

But, when magnetic core saturation is considered at lamination materials, it is understood that the materials must have high saturation to increase efficiency. Consequently, saturation limits the efficiency of machine to be designed.

Coil inductance is related with the energy stored in the magnetic field. The energy is related with the current flowing through coil, and it is given in Equation (5).

(5) $$W_m = \frac{1}{2} L i^2$$

where: W_m – magnetic field energy.

The Maxwell 2D computes inductances associated with a structure by simulating the magnetic field that arises when various voltages and currents are applied. Then, by computing the energy stored in those fields, and then it can compute the necessary inductances. This inductance is given in Equation (6).

(6) $$L = \frac{2W_m}{i^2}$$

In order to compute inductances by using this method, B flux density and H field intensity associated with distribution of currents must first be computed. The magnetostatic field simulator which computes the magnetic vector potential at all points in the problem region can perform this task. The magnetostatic field simulator produces a solution for the magnetic vector potential $A_z(x, y)$. The equation is below as given in Equation (7).

$$J_z(x,y) = \nabla \times \left[\frac{1}{\mu_r \mu_o} (\nabla \times A_z(x,y)) \right] \quad (7)$$

where: $A_z(x, y)$ – the z component of the magnetic vector potential, $J_z(x, y)$ – the DC current density which flows in the direction of transmission, μ_r – the relative permeability of each material, μ_o - the permeability of free space.

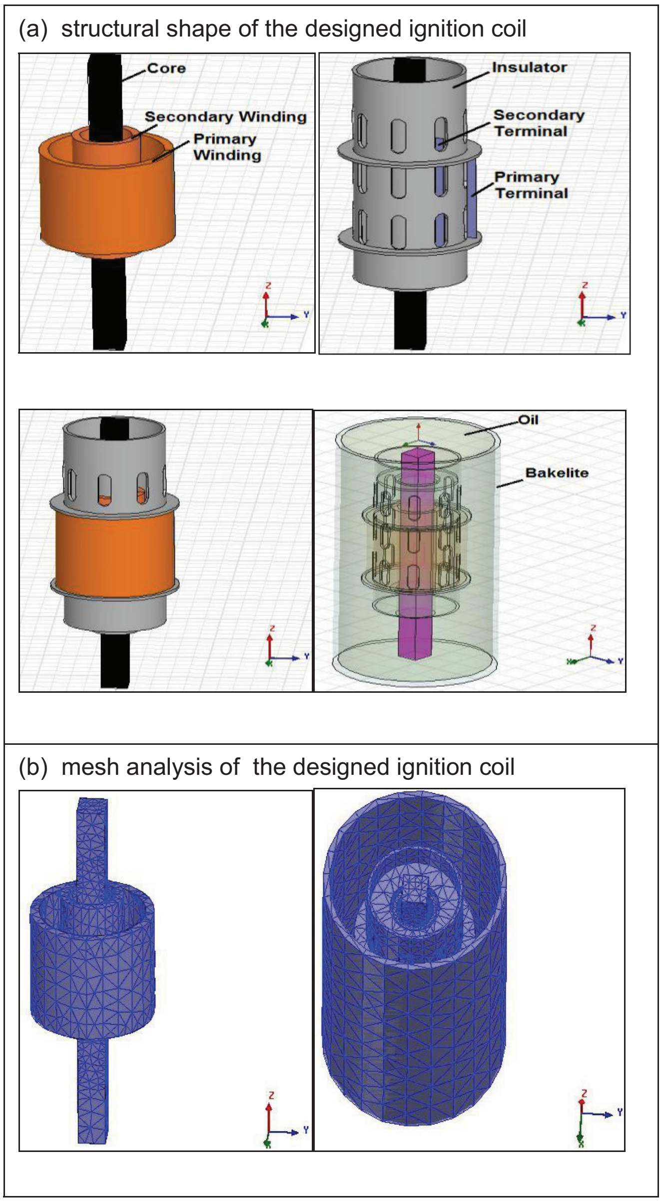


Fig.3. The physical shapes and mesh views of the designed induction coil.

The transient solver allows us to analyze the magnetic fields, energy, force, power loss, core loss, and flux of a model at various time steps of a solution over a specified period of time. For solid conductors fed by a current source, the total current is known, but the source component is unknown. The transient solver computes the current source based on the following circuit equation for the n conductor [11].

$$\iint_{\Omega_C} \left(-\sigma \frac{\partial A}{\partial t} + j_s \right) \partial\Omega = \iint_{\Omega_C} j_t \partial\Omega = I_t \quad (8)$$

where: Ω_c – the width cross-section of the n_{th} conductor, I_t – the total current value, J_s – the source component, J_t – the total current density.

Finite elements method can be determined that model is sub–divided to geometrical pieces and differential equations are written and the equations are solved for all of them. Simulations have been performed at ratio of 1 % error, and the model consists of 64575 finite elements approximately.

The physical shapes and mesh views of the designed induction coil obtained by finite elements method is shown in figure 3.

The designed ignition coil can be modeled by electronic simulation software (Simplorer©). In this software the parameter exchanges are clearly arranged, so the different system quantities can be linked easily and quickly. Using this program diverse dynamic regime of the motor can be easily studied. It can be useful during design stage, or for testing different core variants [12]. This powerful tool is used to describe power electronic control algorithms. Fast and stable simulation algorithms reduce design time and provide reliable results [13, 14]. To support this choice, SIMPLORER offers several experimental analysis algorithms [15].

Belonging to the ignition system in software, the circuit for dynamic performance analysis method is shown in figure 4.

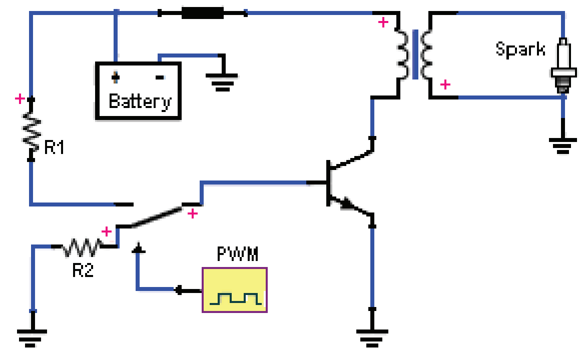


Fig.4. The designed ignition system model by Simplorer.

The FEM analysis is the most precise method for determining secondary voltage, primary current and response time [12]. Parameters of the designed ignition system are shown in Table 1. By using this parameter, ignition coil can be designed.

Table 1. Main parameters of designed Ignition Coil

PARAMETER		VALUE
$V_{battery}$	Voltage	14 V
	r_{in}	0.01Ω
R_1	Resistance	33 Ω
R_2	Resistance	330 Ω
R_p	Primary resistance	3.5 Ω
R_s	Secondary Resistance	9440 Ω
Wire	Resistance	$1.27e^{-003}$ Ω
N_s/N_p	Winding ratio	75
Spark	R_{on_diff}	-2 Ω
	t_{don}	$5e^{-005}$ s
	i_{sus}	1 A
	state	-1

It has been seen that rising time of current been changed since that different materials are being used in design and simulations. Therefore the PWM values (period and dc) used for driving the transistor in figure 4.

In order to make dynamic simulations for ignition system, magneto static analysis has been done. The driver part of the system consists of a voltage source (the automotive battery, nominally 14 volts) and a controlled switch. The switching device is commonly an IGBT. However, this simple switch will not suffice, because the large voltage that develops in the secondary is transformed by the coil to the so-called "flyback voltage" in the primary. The fly-back voltage may be over 1000 volts. IGBTs used for ignition can withstand no more than approximately 600 V across the emitter-collector ports. The transistor parameter was selected as shown in Table 2. Thus, the transistor would be protected against the fly-back voltages [16].

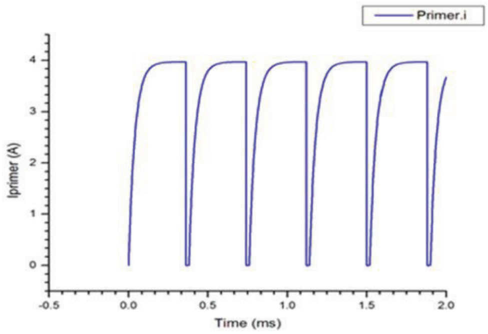
Table 2. The transistor parameter values for analysis.

Description	Value	Unit
TAU_{BE}	$1e^{-008}$	s
TAU_{BC}	$1e^{-008}$	s
A_{CONV}	10	cm^2
$SIGMA_{RAD}$	$5.7e^{-012}$	$W\_per\_m^2\ kel^4$
A_{RAD}	10	cm^2
V_{BREAK_BE}	500	V

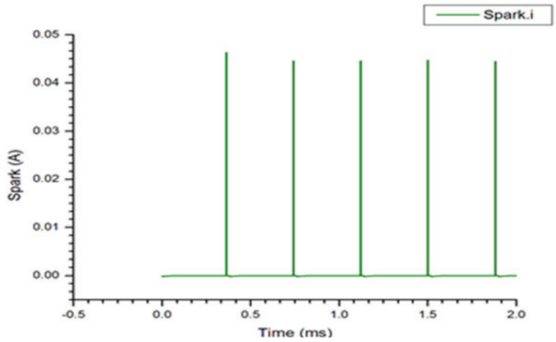
The transient solution options in Simplorer have been stated below:

- Integration equation and local cut-off error have been defined as 1%, since that it's especially useful for investigating energy problems.
- Maximum error value of current and voltage is 0.0001.
- Analog/Digital synchronization has been selected as Hybrid. This simulation option controls the synchronization strategy used. Although each of the strategies below will yield correct results, correctly selecting the best synchronization strategy for the system to be simulated, will yield the fastest simulation.

a)



b)



c)

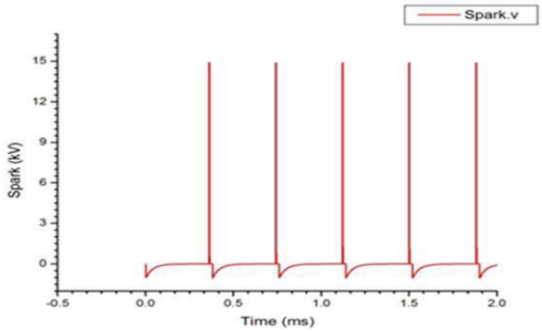
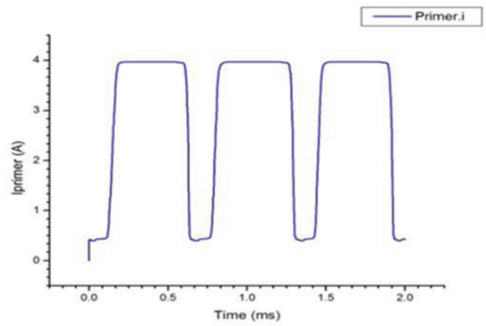


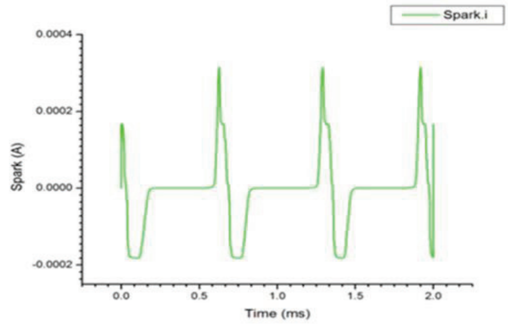
Fig.5.The graphics of I_{primer} versus time; spark current versus time; spark voltages versus time, if material Enni is used.

In the figures 5, values of ignition current, ignition voltage and primary current for Enni55 material have been given. The PWM values in the design and simulations made for Enni55 are given as Period 0.38 ms and dc (duty cycle) 0.95. The PWM values for Nanocrstalline material have been defined as Period 1μs and dc (duty cycle) 0.95. The PWM values for Fe based amorphous material have been defined as Period 1μs, and dc (duty cycle) 0.95.

d)



e)



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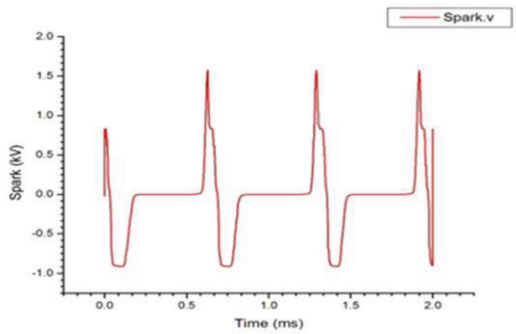

Fig.6.The graphics of I_{primer} versus time; spark current versus time; spark voltages versus time, if material Nanocrystalline is used.

The lamination of this Enni material is 0.1mm. When the primary current is cut off, the spark is occurred. Figures 6–7 give graphics of primary and spark currents and voltages versus time (materials Nanocrstalline and amorphous are used).

It is shown that maximum output voltage is at secondary voltage from the figure 6. There hasn't been an instantaneous drop at secondary voltages. The output voltage is being given when the primary current is raised and down.

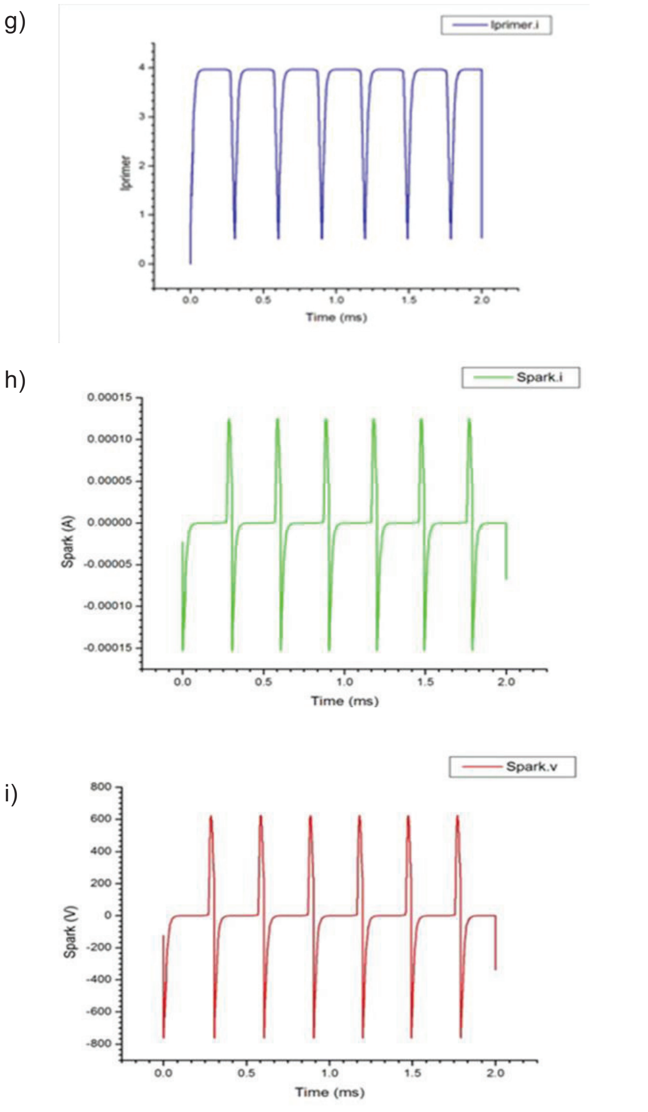

Fig.7. The graphics of I_{primer} versus time; spark current versus time; spark voltages versus time, if material Amorphous is used.

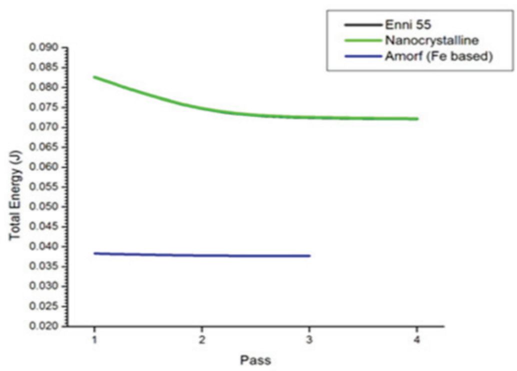

Fig.8. The total energy amounts for 3 types of material.

The total energy amounts obtained for all types of material in magneto static solution has been given as shown in figure 8.

On condition that number of turns is being kept, flux linkages at coil are changed. Regarding to these change, inductance value is decreased. As result of this, energy amount has been decreased. Hence, the secondary voltages have been presented decrement tendency too. The decrement at secondary voltages has been limited by primary current.

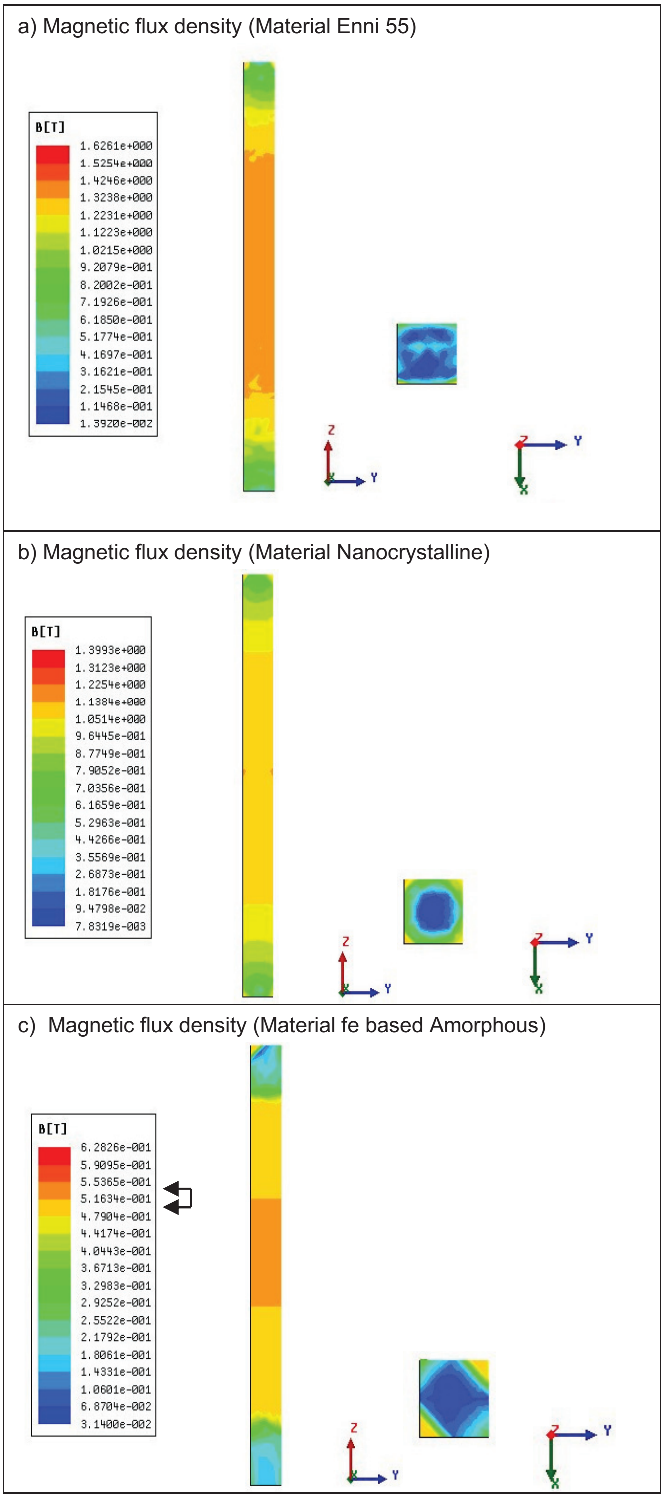

Fig.9. Finite elements analysis results

Despite to saturations observed at some areas of the design, it can be said that magnetic saturation is occurred in a specific region as shown in figure 9 (c). Nevertheless the design is in applicable limits.

Results and Discussion

In this study, the magnetic parameters of an ignition coil have been determined and shown for the designed electromagnetic model. The calculations have been done with help of finite elements, and the parameters which affect the ignition coil performance have been brought to design when needed. It has been obtained that this ignition coil which uses different metallic cores produces great arcs in a short time. If the system voltage is low or the engine speed (RPM) is high, the charging of the ignition coil begins earlier than normal time.

Conclusions

In this study, electromagnetic analysis of an ignition coil has been performed. According to the analysis results, the designed ignition coil has been given good performance when different core materials are used.

It has been seen that primary current, secondary current and voltage are obtained as regularly at the selected switching frequencies. If the switching frequencies are changed, the output current and voltage values are changed pretty much.

It has been inferred that Enni material can be used in ignition coils, since that the secondary voltage which has a core made from Enni material gives approximately 15 kilo Volts. Both FEM and Simplorer analyses result that material Enni55 is suitable for ignition systems in higher speed engines. It can be said that materials Nanocrstalline and Amorphous are useful for alternating current ignition systems (ACI).

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