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Simulation and Modelling of Solenoid in Switch Gear

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Abstract **- Switchgear protection plays a vital role in modern power system network, right from generation through transmission to distribution end. The current interruption device or switching device is called circuit breaker in** switchgear protection **system. A switchgear has to perform the function of carrying, making and breaking the normal load current like a switch and it has to perform the function of clearing the fault in addition to that it also has provision of metering and regulating the various parameters of electrical power system. The breaking of mechanism or tripping is carried out by solenoid. So, in this paper the detail design of solenoid according to the temperature, resistance, reluctance, magnetic field and current density. This paper gives idea about the force generated in solenoid according to given condition. It also determine the maximum force require to break the mechanism and also useful to design the spring opposing the plunger for particular current and voltage condition. It also determine increasing temperature, dissipation of heat according to which we can design a solenoid. We also give idea about the value engineering of product. It also helps to determine the required force by considering various parameter and help in cost effectiveness.**

Keywords — Solenoid, force, magnetic field, reluctance.

INTRODUCTION

Solenoid is electromagnetic device in which a coil is wounded around the steel rod and the current passes through the coil because of magnetic field induce in the steel rod and it moves in and out. The current running through the coil generates magnetic potential difference across air gape.This magnetic potential difference produces an attractive force between the opposing core and plunger, which moves the plunger to cause tripping mechanism in switch gear product.

Solenoid valve is combination of coil and moving plunger i.e. core or armature. It is mounted inside the U-frame in switch gear product.

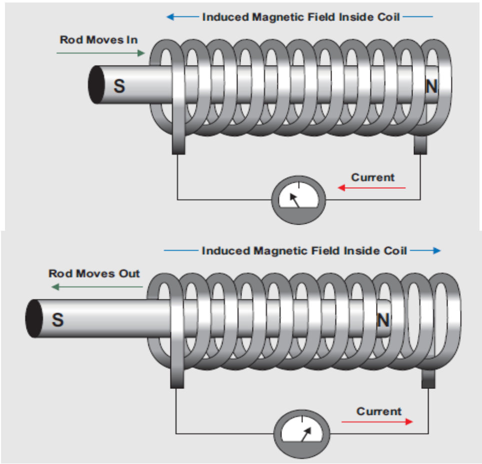

Figure 1 : Induce Magnetic field direction according to current direction

There are various types of solenoid valves used in industrial applications. The 2-way solenoid valve has one inlet and one outlet pipe connection. They are used to allow or shutoff fluid flow. The normally open type valve is open when de-energized and closed when energized. The 3-way valve has three pipe connections (pressure, cylinder, and exhaust port) and two orifices. The normally closed 3-way type valve applies pressure through the cylinder port when the solenoid is energized and exhausts pressure through the exhaust port when the solenoid is de-energized. The internal pilot operated solenoid valve has a pilot and bleed orifice that enables this valve to use line pressure to assist the valve in its operation. This pilot solenoid valve is suited for high or moderate flow and quick exhaust applications in power plants.

Previous study based on Solenoid

Many previous studies related to the design and development of SOVs have been performed. Tao et al. [3] proposed an optimal design method for the magnetic field of the solenoid valve by considering the effects of three soft magnetic material properties and geometries on the performance of the solenoid valve. Their design method can achieve a larger magnetic force and lower power consumption only by adjusting the structural parameters of the solenoid, such as the number of coil windings and the coil length.

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Yehia [2] introduced a detailed design for a solenoid valve without a diaphragm for a selected size. He focused on the design of the valve body and did not address the process of the coil design, which is a core part of the design of a solenoid valve. Sung [4, 5] have developed a design program for ON/OFF type solenoid actuators. Their design summarized 22 input parameters and 18 design parameters based on electromagnetic theories, experimental values, and their experiences. He proved the propriety of his design program by experiments with manufactured prototypes, because a theoretical verification of the design has not considered yet. Kajima [6] focused on the electrical circuits that he had developed for the purpose of energizing the solenoid valve in an effort to develop high-speed solenoid valves. Kajima and Kawamura [7] performed simulations and tests based on a mathematical model to develop a high-speed solenoid valve. They demonstrated the effects of design parameters, such as the solenoid dimensions and the number of coil turns, on the switching time. Vaughan and Gamble [8] presented a method for predicting the electromechanical behaviours of solenoid actuated proportional valves, paying particular attention to solenoid modeling. This model predicted both the dynamic and static responses, such as those in the current and the plunger position of the valve, to voltage inputs.

Ferreira et al. [9] proposed a semi-empirical model for predicting the spool position and flow-rate in a hydraulic proportional valve. A nonlinear dynamic model of a pneumatic proportional pressure valve was formulated to analyze and design valves with similar structures by considering the mechatronic structure of this type of valve and the integration of electronic, pneumatic, and mechanical devices [10]. Two models of a pneumatic PWM (pulse width modulated) solenoid valve for engineering applications were proposed by Ye et al. [11],which also analyzed the instantaneous and equivalent mass flow rates across the valve. Recently, Liu et al. [12] presented a method to design the parameters of the direct action solenoid valve based on computational intelligence. They focused on obtaining the biggest electromagnetic force by optimizing the design parameters and showed that the current is the most important parameter affecting the electromagnetic force. Most previous work on solenoid valve has focused on the static and dynamic behaviours of solenoid actuators and only on its design, especially the coil and plunger. There are not enough technical studies that describe the whole range of the design process for SOVs. Moreover, suitability check of the design has not been considered into design process and has been performed only by experiments which are time- and expenses-consuming works.

Characteristics of Solenoid coil

The main electrical characteristic in solenoid is inductor i.e. inductance which opposes any change in current. Because of which current does not reach a maximum level immediately when solenoid energized. A solenoid's main electrical characteristic is that of an inductor, in that it possesses inductance, which is the characteristic that opposes any change in current. This is why current does not immediately reach a maximum level when a solenoid is energized. Instead, the current rises at a steady rate until it is limited by the DC resistance of the solenoid. An inductor (in this case a solenoid) stores energy in the form of a concentrated magnetic field. Whenever current is present in a wire or conductor, a magnetic field, however small, is created around the wire. With many turns of wire wound into a coil, such as in a solenoid, the magnetic field becomes very concentrated. This electromagnet can be used to control a mechanical valve via an electrical signal. As soon as the solenoid is energized, the current increases, causing the magnetic field to expand until it becomes strong enough to move the armature. The armature movement increases the concentration of the magnetic field as the armature's own magnetic mass moves farther into the magnetic field. Remember, a magnetic field changing in the same direction of the current creating it induces an opposing voltage into the windings.

Because the magnetic field quickly expands when the armature strokes, it causes a brief reduction in the current through the solenoid windings. After the armature strokes, the current continues on its normal upward path to its maximum level. The result is current waveform in figure

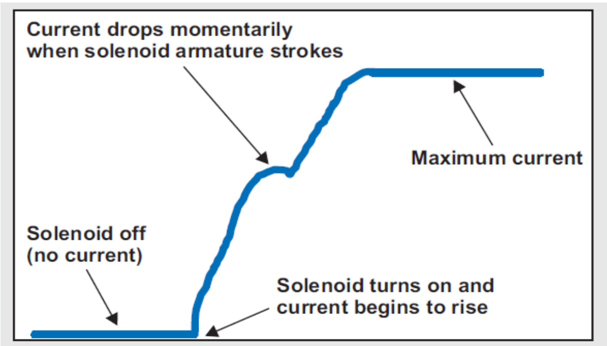


Figure 2: Current waveform

The force applied to the armature is proportional to the coil's change in inductance with respect to the armature's change in position. The same force is also proportional to the currentflowing through the coil.

Therefore,… $Force = Q * V * \mu_o * N * I$ ………………….equation 1

Where Q is the charge of the passing point charge, V is the velocity of the point charge, the μ_0 is $4\pi \times 10^{-7}$, N is the number of turns in the solenoid coil, and I is the current running through the solenoid.

Design of solenoid

The main objective is to design and develop a solenoid for switch gear with linear motion. The main aspect of designing the solenoid in switch gear is to obtain the electromagnetic force at the condition of high current or short circuit and leakage condition to trip or breaking the mechanism at high voltage connection. Also the design is in such way that the temperature rise and power loss condition is low. For this we have to consider various condition such as reluctance, inductance and resistance in coil. An electromagnetically inductive coil is wounded around the moving plunger. We use mild steel as a plunger

Solenoid Structure

The solenoid consists of coil, movable plunger, spring, fixed support and U frame casing as shown in the figure. The electromagnetically inductive coil is wound around the plunger. We use mild steel as a plunger. When current flows inside the wound coils an electromagnetic force induced by the magnetic field inside the solenoid. Because of this electromagnetic force plunger moves in linear motion in solenoid.

Working and theoretical Calculation

As we know the current passes through the coil and an electromagnetic force induced inside the solenoid but at normal current the magnetic field produce is much lesser force as compare to the force exerted by opposing force by spring.

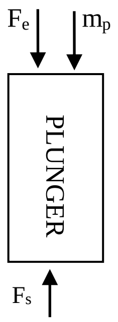
$$F_s > F_e + m_p g \,.$$

Whereas Fs is spring force, Fe is electromagnetic force, m_p is mass of plunger and g is acceleration due to gravity.

But as current increases at a certain limit the magnetic field increases.

This magnetic field induce EMF on plunger. And hence the force of plunger Increases because of which it moves in linear motion on downward side.

$F_s < F_e$



For theoretical calculation we have to consider some other terms to determine the exact force acting on plunger

Electric Resistance of coil

As design consideration view to obtain maximum force and good response curve at given power consumption. Then at given power consumption we have to determine the current rating *I* and resistance of coil R. Then according to ohm's law for given power consumption *P* and applied rating voltage V.

$$P = V * I \qquad \text{....... equation 2}$$

$$I = \frac{V}{R} \qquad \text{........ equation 3}$$

Resistance define as,

$$R = \frac{\rho}{A} l \qquad \text{....... equation 4}$$

ρ is resistivity of material, ***A*** is area of cross section of coil, ***l*** is length of coil. Resistivity of material is defined. As length of coil increases resistance increase, and as area increase the flow of current density increase which reduces the resistance. This determines the length of coil, number of winding and the attraction force of solenoid.

Temperature rise

According to current and rated voltage condition, we have to determine the temperature rise in coil. Because at the time of high rated current and extreme overheating of coil with consequent softening of material occurs. Which damage internal mechanism and connection in switch gear. It also heats up the switch gear which is very dangerous as safety point of view.

How to determine the temperature rise t_r,

$$t_r = \frac{Q}{Sm} \qquad \text{..................equation 5}$$

Whereas, ***Q*** is amount of heat added to the coil in Joule, ***S*** is specific heat of the coil material (J/kg/K), ***m*** is the mass of coil in kg.

$$Q = PT \qquad \text{.......equation 6}$$

T is the time for which the power is dissipated in the coil.

$$P = I^2 R \qquad \text{............equation 7}$$

$$P = I^2 \frac{\rho}{A} l$$

By substituting equation we get,

$$t_r = I^2 \frac{\rho}{ASm} \qquad \text{............equation 8}$$

Considering D is density in kg/m^3

$$t_r = I^2 \frac{\rho}{ASm} l = \frac{\rho}{SD} \left(\frac{I}{A}\right)^2 \qquad \text{............equation 9}$$

So, by considering all this condition we have to choose the material which is essential for considering design purpose of solenoid and gives the exact force for tripping the mechanism.

Actual Design of solenoid

According to the product rating the conditions are mentioned for B, C and D curve product. By considering product current rating the solenoid force is design. Select material for coil as our requirement. And then by considering required temperature of coil according to product and substituting values in above equation to determine the cross sectional area of coil A_c. By assuming resistance in milli ohm, we can calculate length of coil.

$$R = \frac{\rho}{A} l$$

From this equation we can determine the total length of wire l_w. Accordingly we have to assume diameter of plunger D_p on the basis of our assembly of solenoid in switch gear. As we know we required less force, hence diameter of plunger is less.By taking radial clearance r_c across plunger and define the diameter of coil D_c. From length of coil, diameter of coil and considering single layer of turn we easily define number of turns N_t.

i.e. $l_w = \pi \left(D_c + n_{layer} * d_w\right) * N_t d_w$ coil wire diameter.

Then magneto motive force of coil ***mmf***,

mmf of coil = ampere x number of turns

= A x N

= AT

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As we know that force ***F*** in solenoid is,

$$F = \frac{B^2 A_p}{2\mu_0}$$

…….equation 10

$$B = \frac{mmf}{R_T A_p}$$

………equation 11

Whereas, ***B*** is magnetic flux density in solenoid, $\boldsymbol{A_p}$ is area of plunger, $\boldsymbol{\mu_0}$ is permeability of air, $\boldsymbol{R_T}$ is total reluctance produced in solenoid. As reluctance increases magnetic flux density decreases because of which force decreases. So by considering reverse engineering we can achieve the force required to operate the solenoid. Total reluctance means the reluctance develop because of casing, plunger and air gape medium of coil and plunger.

$$\text{Reluctance, } R = \frac{l}{\mu A}$$

Whereas, ***l*** is length of material or medium path of reluctance, ***μ***is permeability of medium may be its material or air medium, ***A*** is area of material or medium. So, it is easily define that as material is more permeable reluctance decrease. As consider that permeability of steel material as compare to air is more. So, we have to say that force generated by core type solenoid is more as compare to air core type solenoid. By taking some trial and error then considering the reluctance medium we have to achieve the exact force required for switch gear.

Therefore, $R_T = R_{radgap} + R_{plunger} + R_{stroke} + R_{case}$

……………..equation 12

By substituting values in above equation we easily calculate the force acting on the solenoid. Accordingly we have to design the spring which oppose the solenoid force below the rating of switch gear.

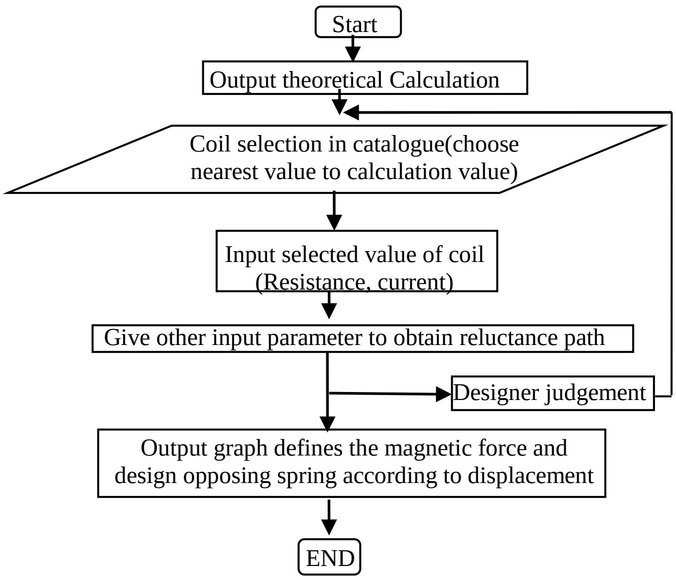
Design Process

Specification of product according to given condition are as follows.

Table 1: Material Properties

Items	Target Performance
Supply Voltage	240V
Resistance of coil	1 milli ohm
Temperature of coil	5 to 8 kelvin

Showing the flow chart of development design process which is design according to the above equation and which is needed to judge the fact whether the final design parameters are proper for manufacturing the product.



Theoretical calculation

As we consider the temperature of coil is 5 to 8 kelvin and by specifying the current and voltage rating value and using above formulae we determine the power dissipated, magnetic field, number of turns, reluctance, force generated and also idea about to design the spring opposing the plunger at specific current where the mechanism not trip. The theoretical calculation gives idea about the working and also helpful for proper design of product.

By considering first parameter of changing the displacement of plunger because of which air gape changes and we determine the force obtaining in solenoid. And second parameter by changing current condition, number of turns of coil and determining the force.

By considering condition of first parameter and temperature in coil upto 5 to 8 kelvin an obtain result are as follows.

Table 2: Displacement vrs Force

Displacement of plunger (mm)	Force obtain (N)
2.8	12.15
3	10
3.5	8.03
3.8	6.89

By considering same condition with constant displacement of plunger and considering second parameter and obtain result are as follows.

Table 3: Current and Number of turns vrs Force

Current (Ampere)	Number of turns of coil	Force (N)
470	3	3.5
630	4	10.7
750	5	20.9

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By considering both the parameter and obtaining result of force are as follows.

Table 4: Displacement, Current, Number of turns vrs Force

Displacent of plunger (mm)	Current (Ampere)	Number of turns of coil	Force (N)
3	470	3	3.5
3.5	630	4	8.03
3.8	750	5	13.4
4	750	5	12.23

From this calculation we can easily determine the force by changing various parameter according to our requirement.

Analysis Result of JMAG :

JMAG is simulation software for electric device design and development. It accurately grasps complex physical phenomena inside of equipment and performs high speed analysis. It incorporates analyse a wide range of physical phenomenon that includes complicated geometry, various material properties, electromagnetic field sand force generated by solenoid.

The cut section model of solenoid with covering U-Frame are as follows:

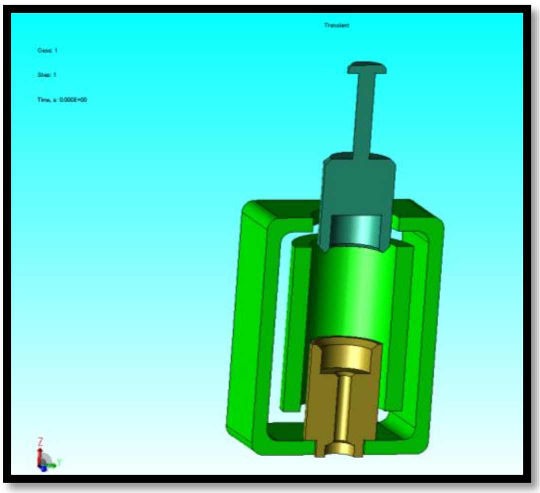
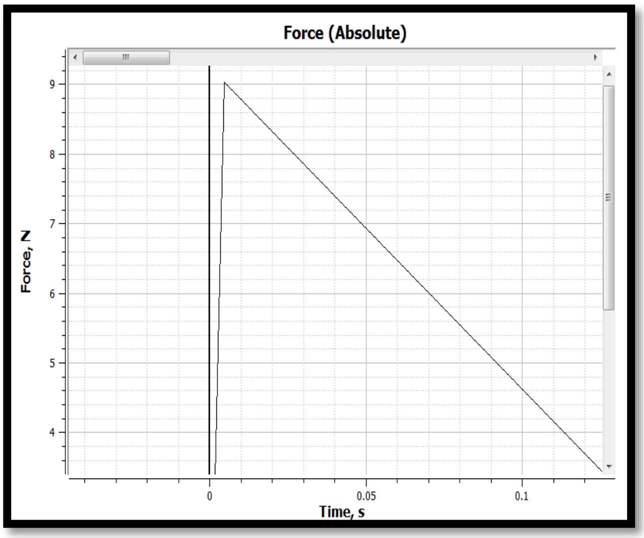
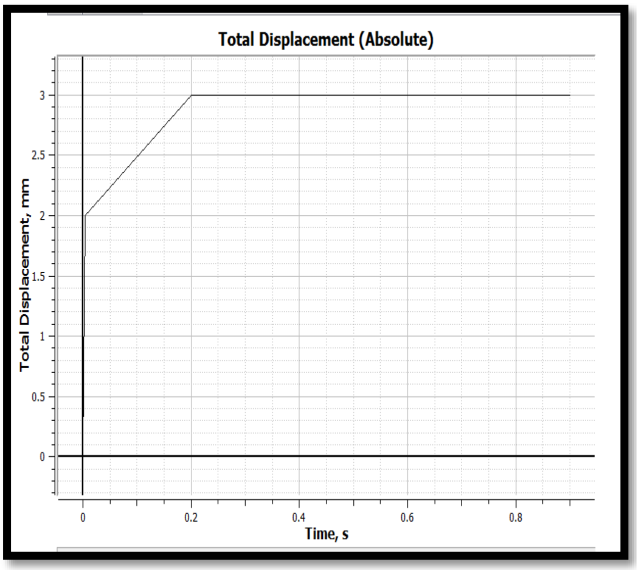


Figure 3: Solenoid cut section model with U-frame

The result according to the parameters and considering the required condition are as follows. By considering first parameter showing displacement of plunger and by which the force generated



Graph 1: Force vrs Time



Graph 2: Displacement vrs Time

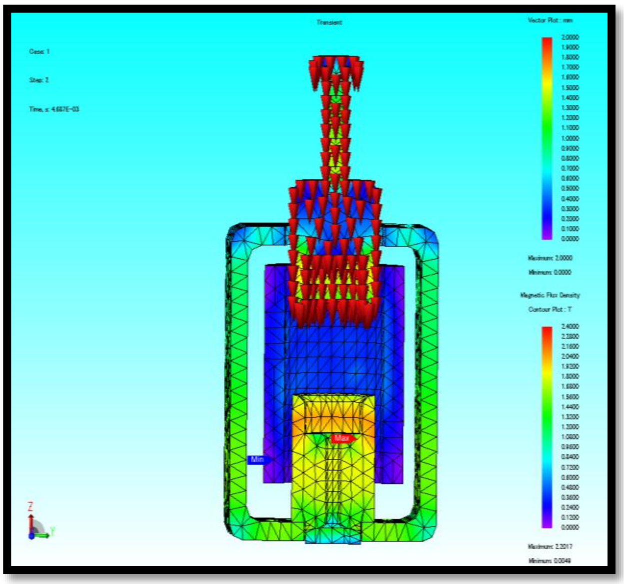


Figure 4: Showing vector and contour plot distribution of Displacement and Magnetic flux density with meshing

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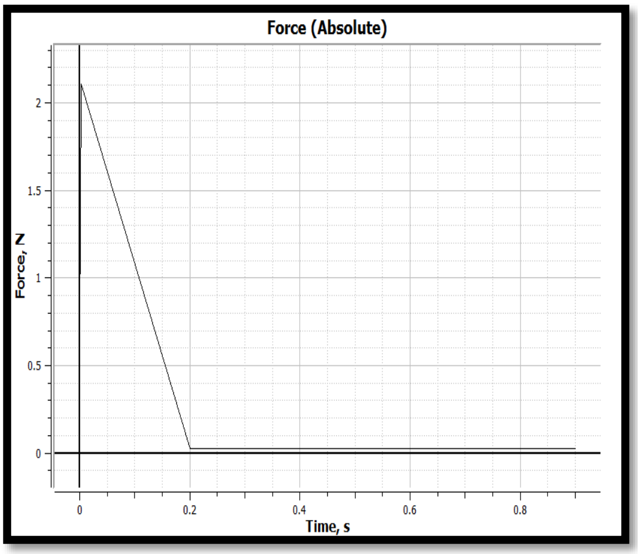
First parameter analysis shows the total displacement of plunger by required condition of current. So, by changing various parameter accordingly force and displacement remains unchanged and maintaining temperature of coil according to switch gear product.

By considering second parameter we have to consider number of turns and current value. The turns and current condition is such that the resistance in coil maintain properly because of which the product can pass in other test also and have generate the required force to trip the mechanism with constant displacement.



Graph 3: Force vrs time

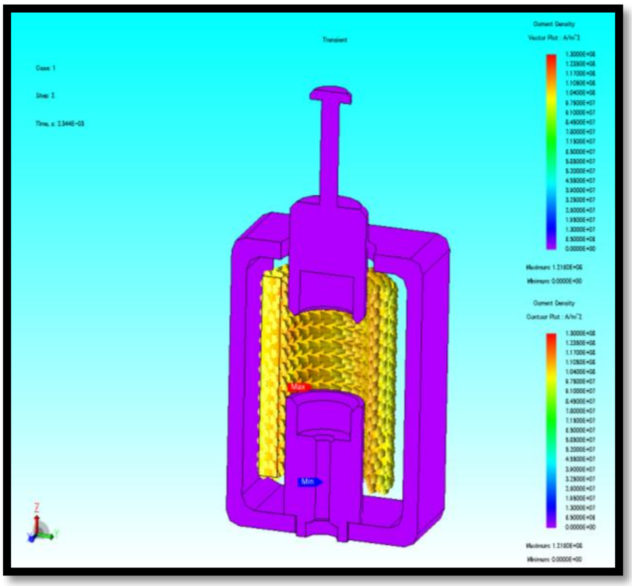
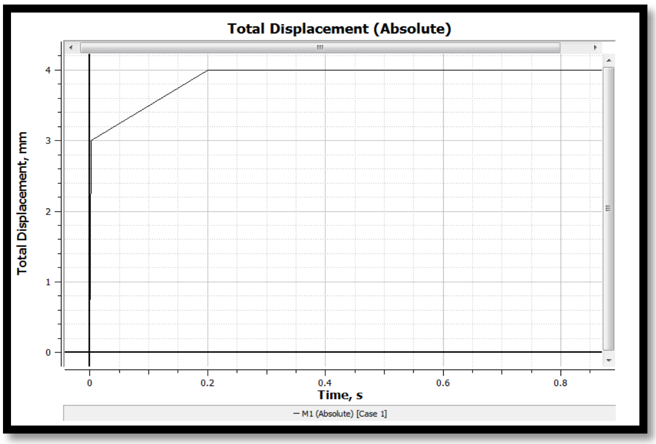
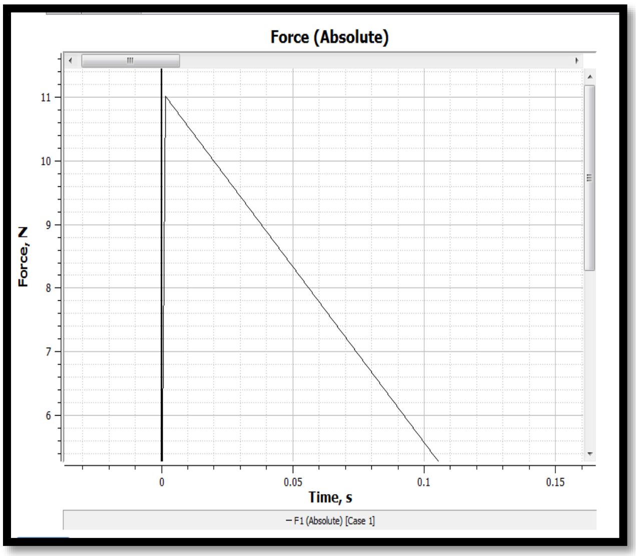


Figure 5: Vector and contour plot of current density

By considering third parameter the analysis result are as follows.



Graph 4: Displacement vrs Time



Graph 5: Force vrs Time

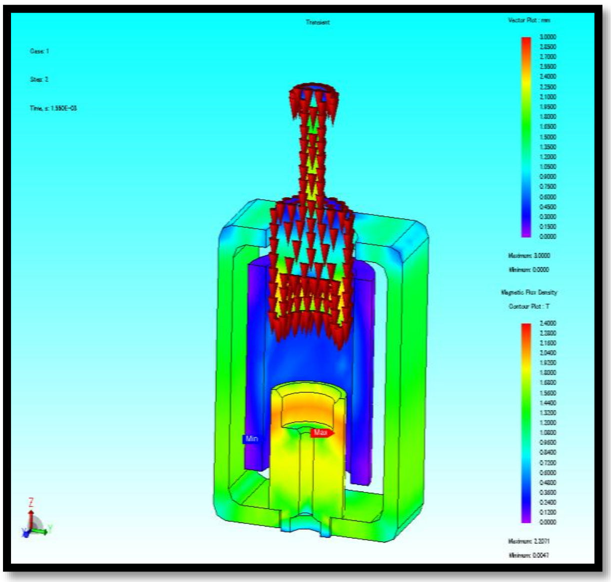


Figure 6: Vector and contour plot of Displacement and magnetic flux density

This result shows that the theoretical and analytical result are nearly more similar. So, according to this we can design a solenoid which give required force to operate the tripping action in mechanism. Accordingly we design a solenoid according to the current condition and considering other parameter.

CONCLUSION

The first objective of design a solenoids is to determine the design parameters that yield the maximum attractive force and good response characteristic at given power consumption and allowable temperature range. We have suggested a detail design procedure and verification method of solenoid for convenient use in switch gear. By comparing the theoretical and analytical result we easily determine various parameter to design the solenoid. It also determine the tripping time of solenoid and it works according to the given standard of product by considering the rated current and voltage supply. It also help to design the opposing spring in solenoid which works at specific current rate. By changing the material and other parameter obtaining the same force by considering rated current and voltage value because of which we can approach towards value engineering and cost effectiveness of material. So, this paper gives whole study to determine and develop a better design of solenoid.

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