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Research Article

An Intelligent Solid State Switch for Starter Motor as an Alternate Solution to Solenoid with Contact Bouncing Issues

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Abstract

In this paper, a 0.8kW car starter motor is taken and the solenoid has been modeled to study the contact bouncing phenomenon that occurs in the solenoid . A mathematical model based simulation is carried out on Simulink for various operating conditions. Several simulations to eliminate contact bounce were conducted by varying parameters of the system. It was found that contact bouncing in the solenoid cannot be completely eliminated, but can only be reduced. The bounce occurs due to the characteristic properties of the springs and masses that operate the solenoid. Several alternate solutions were evaluated for the possibility to replace the solenoid as the switching component .In this paper, an intelligent solid state switch for the starter motor has been designed using a micro-controller based Mosfet gate drive. A schematic has been developed on OrCAD® and also a general simulation of the switch was conducted on LTSpice to show the capability of the Mosfet as an alternate solution to power the starter motor .Hence this investigation concludes that there is a possibility of developing a lighter and cheaper starter motor with a solid state switch that can be implemented in cars.

Keywords: *Starter motor concept, contact bounce simulation, intelligent solid state switch, contact bounce free starter motor design, Simulink mathematical model, OrCAD® Capture Design, LTSpice IV simulation.*

1. Introduction

A car starter motor is a device used for cranking the engine so that the engine can run. In engines the power stroke powers the remaining stroke till the next power stroke occurs. For starting the first cycle of a 4-stroke engine, the first two strokes are powered by the starter motor and when the engine runs, it stops.

The starter motor comprises of a DC electric motor (permanent-magnet type or series-parallel wound type) and also a solenoid mounted on the outer casing and a pre engaged type gear drive to mesh with the flywheel. When the key is inserted in the ignition and it is turned, then there is a starter relay that causes actuation of the solenoid, then the solenoid causes a pinion engagement mechanism that moves the pinion gear causing it to mesh with the ring gear that is mounted on the engine flywheel and hence the engine starts to crank. The solenoid also closes the gap between the contacts that enables a high current to flow from the battery to the starter motor to enable its rotation.

The electro-mechanical solenoid continues to be used in the starter motor as they are rugged, and can withstand harsh operating conditions and have remained the favored choice to actuate the starter motor.

The functions of the present day solenoid are:

Primary function: To create a temporary contact and hence act as a switch between the battery terminal and the motor terminal so as to supply the starter motor with the required amount of electricity to rotate it.

Secondary function: To engage the pinion gear of the starter motor with the ring gear on the flywheel via the Pinion engagement mechanism before the starter motor rotates and to reduce wear and tear of the gears.

Taking into consideration the main function that is switching power, there are other options like Transistors, Mosfets, IGBTs namely semiconductor devices capable of handling the operating conditions. There has been significant advancement in semi-conductor technology, making them versatile, rugged and suitable for high power switching applications.

In this paper the solenoid switch has been modeled to analyze the contact bouncing issues which can be overcome in the present solution. The solution

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leverages the advancements in semiconductor technology to create an intelligent solid state switch for the starter motor.It is designed, taking cost considerations and operating conditions into account.

2. Modeling & Analysis of the Solenoid

2.1 Construction of Solenoid Switch

A typical solenoid is switch is shown in Figure.1. There is a plunger of total mass M1 and at the front end of the plunger there is a projection referred to as supporting rod which has a hemispherical shaped end.

To the case of the solenoid, the end stop is fixed and this restricts the motion of the plunger beyond this point when the plunger comes in contact with the stop.

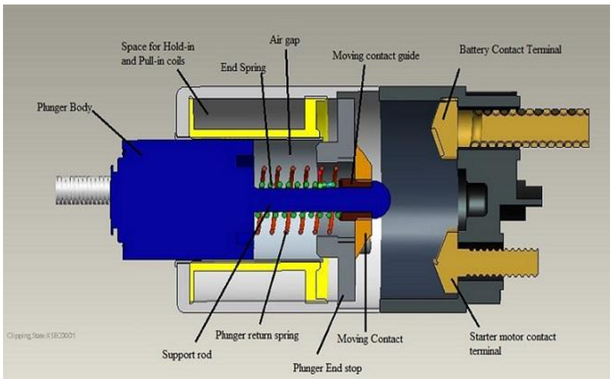

Fig.1 Cut sectional view of Starter solenoid

The air gap between the plunger and head stop provides a damping action to the motion of the plunger.

The moving contact of mass M2 is placed on the supporting rod. There is a guide between the support rod and the moving contact of negligible mass placed such that it is within the body of M2 and it has a small surface projection on the back and front sides of the moving contact to rigidly attach it to the moving contact.

The guide is free to move along the supporting rod and enables the moving contact to move along the supporting rod.

The plunger return spring is attached between the plunger and the plunger end stop. It has a stiffness of K1 and is used to bring back the plunger to its initial position when the solenoid is de-energized.

The end spring is attached between the guide of the moving contact and the plunger body. The spring has a stiffness K2 and the purpose of this spring is to apply a force to keep the moving contact in position when it comes in contact with fixed contacts of the battery and motor terminals and restrict the motion of the moving contact.

Above the solenoid plunger there are two sets of insulated wires that form the windings of the solenoid. One pair of windings is called the hold-in coil while the other is called the pull in coil.

2.2 Working of the solenoid

When the ignition key is turned to start position, the pull-in and hold- in coils are both energized and hence there is a force exerted by these coils on the plunger. This force is given by:

$$F = \frac{\mu \times A \times (Nt \times I)^2}{2 \times g^2}$$

Where

μ = Magnetic Constant i.e. $4 \times \pi \times 10^{-7}$ N/A^2

A= Area of the solenoid experiencing the force i.e. m^2

Nt= Number of turns of the solenoid coil

I=Current passing through the solenoid coils, i.e. A

g= Gap between the solenoid coils and the core i.e. m

The plunger starts to move inwards till the moving contact touches the fixed contact terminals. When the plunger starts to move towards the fixed contact terminals, the plunger return spring undergoes compression and exerts an opposing force to that exerted by the coils.

As the moving contact touches the fixed contact terminals the pull-in coils get de-energized and the hold –in coils only draw an electric current to keep the moving contact in touch with fixed contact terminals. As the moving contact comes in touch with the fixed terminal contacts the end spring undergoes compression. Due to inertia the plunger will keep bouncing for a small distance till it comes in contact with the plunger end stop.

2.3 Free Body Diagram representation

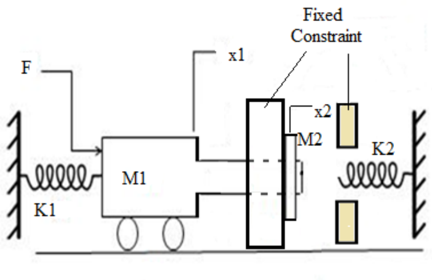

Fig.2 Free body diagram of solenoid

2.4 Mathematical model

The solenoid is modeled as a single degree of freedom system undergoing forced vibration when the solenoid is actuated. There are two states in which the vibration occurs.

First State

When the solenoid is actuated both masses M1 and M2 move forwards against the force exerted by the plunger spring K1. The equation is given by:

$$((M1 + M2) \times \ddot{x}1) + (C \times \dot{x}1) + (K1 \times x1) = F1$$

Also the frequency of vibration is given by $\omega = \sqrt{\frac{K1}{M1+M2}}$

Where $F1 = F_{pull\ in} + F_{hold\ in}$

Second state

When the solenoid moving contact has touched the fixed contacts, the pull-in coil is de energized and only the hold in coil exerts a force. They can move forward, but this happens against a force exerted by the plunger spring K1 and the end spring K2. The equation is given by:

$$(M1 + M2) \times \ddot{x}2) + (C \times \dot{x}2) + ((K1 + K2) \times x2) = F2$$

$F2 = F_{hold\ in}$

The frequency of vibration is given by $\omega = \sqrt{\frac{K1+K2}{M1+M2}}$

2.5 Simulation

A Mathematical equation based model is created and used to simulate the phenomenon of contact bouncing. The image shows the Simulink model that is developed and this model solves the equations for the different states and provides the output results for the contact bouncing occurring. The values of the springs and masses are calculated and the first simulation is done that shows the contact bouncing that occurs. Using this model many simulations were done by varying the values of the spring constants to obtain a solution with zero contact bounce.

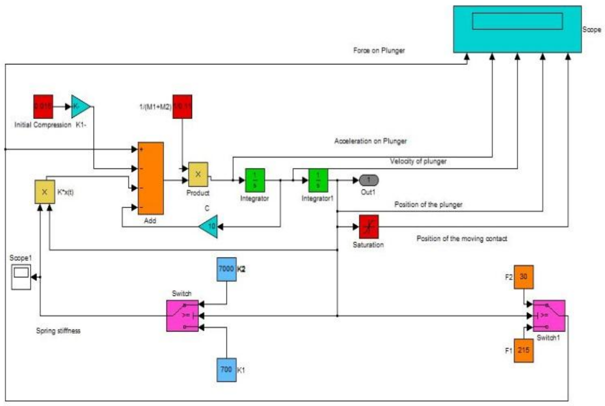

Fig.3 Simulink Model of Solenoid

2.6 Results

CASE I: This simulation shows contact bouncing using original values of the springs and masses in the solenoid. The contacts close within 65ms.

K1 = 900 N/m (plunger spring)
K2 = 10.9kN/m (end spring)
C1 = 10 Ns/m (Damping co-eff.)
M1 = 100g (plunger)
M2 = 10g (moving contact)
$F_{pull\ in}+F_{hold\ in}$=215N (Pull in & hold in coils combined force exerted on plunger)
$Fold_{in}$ = 30N (force exerted on the plunger by hold in coil)

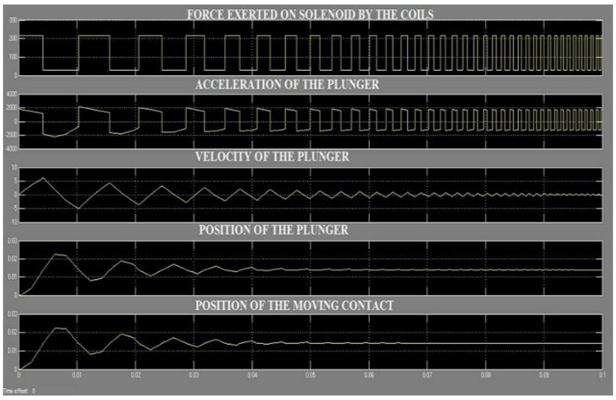

Fig.4 Case I output plot

CASE II: This simulation shows contact bouncing occurring, with a much shorter contact closing time.

K1 = 800 N/m (plunger spring)
K2 = 13kN/m (end spring)
C1 = 10 Ns/m (Damping co-eff.)
M1 = 100g (plunger)
M2 = 10g (moving contact)
$F_{pull\ in}+F_{hold\ in}$=215N (Pull in & hold in coils combined force exerted on plunger)
$Fold_{in}$ = 30N (force exerted on the plunger by hold in coil)

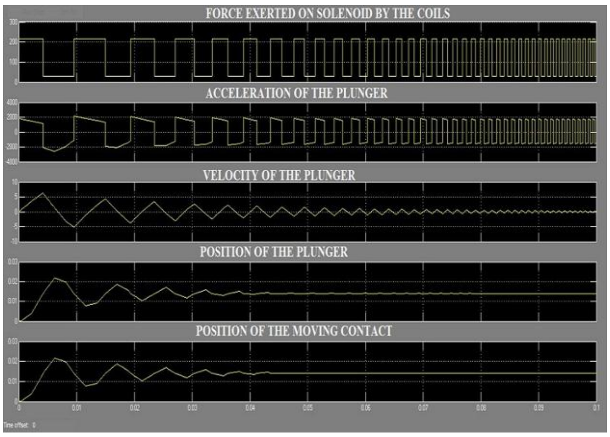

Fig.5 Case II Output Plot

CASE III: This simulation shows large contact bouncing occurring in the solenoid.

K1 = 700 N/m (plunger spring)
K2 = 7kN/m (end spring)
C1 = 10 Ns/m (Damping co-eff.)
M1 = 100g (plunger)
M2 = 10g (moving contact)
$F_{pull\ in}+F_{hold\ in}$=215N (Pull in & hold in coils combined force exerted on plunger)
$Fold_{in}$ = 30N (force exerted on the plunger by hold in coil)

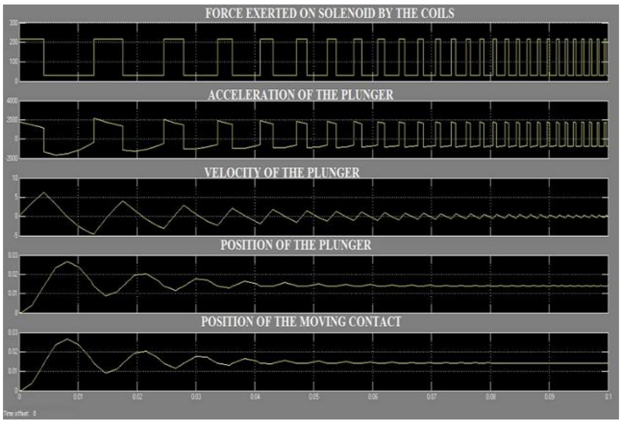

Fig.6 Case III output Plot

3. Solid State Solution

3.1 Introduction

As discussed in the last section the solenoids are prone to contact bouncing that cannot be eliminated but can be reduced. Keeping in mind the various functions that the solenoid performs, different solutions taking into consideration the space constraints, the response time, were evaluated namely linear actuators and linear motors. Each solution had drawbacks that made them infeasible to replace the solenoid. Solid state switches have response times in the range of a few 100ns and does not load the battery as much as the solenoid, is lighter and will occupy lesser space than the solenoid.

An intelligent solid state switch for the starter motor has been designed and simulated in LTSpice IV for having a comparative analysis of the performance with solenoid switch.

As per the literature study, there are many Mosfets that can handle the current requirements of the 0.8kW starter motor which is around 80-90A. A N channel Mosfet based circuit on H-bridge configuration is used to replace the solenoid.

This required the pre-engaged starter drive to be replaced with a Bendix drive so that the pinion gear on the starter motor could engage with the ring gear on the flywheel.This solid state switch can be used to power the DC starter motor.

3.2 High level Architecture

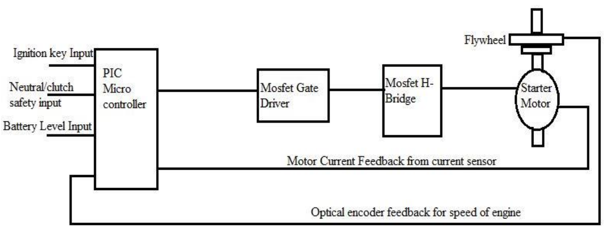

Fig.7 Block Diagram

3.3 Main components of the design

PIC16F877A

It is a powerful micro-controller with 256 bytes of EEPROM memory. It also has two pins to support PWM and is suitable for this design

HIP 4081

The HIP4081A is a popular N channel Full H bridge driver and it has the minimum requirements to safely operate the chosen Mosfets in this design.

IRFS 3004-7ppbf

Power Mosfet from International Rectifier and suits the all conditions of operation and can power the starter motor. Additionally, it can handle a continuous current of 280A (package limited).

ACS 758

The Allegro™ ACS758 family of current sensor ICs provides economical and precise solutions for AC or DC current sensing in the range of 50-200A.(digikey.com, 1995-2015) It can be used to provide a feedback on the current to the PIC micro-controller.

3.4 Schematic

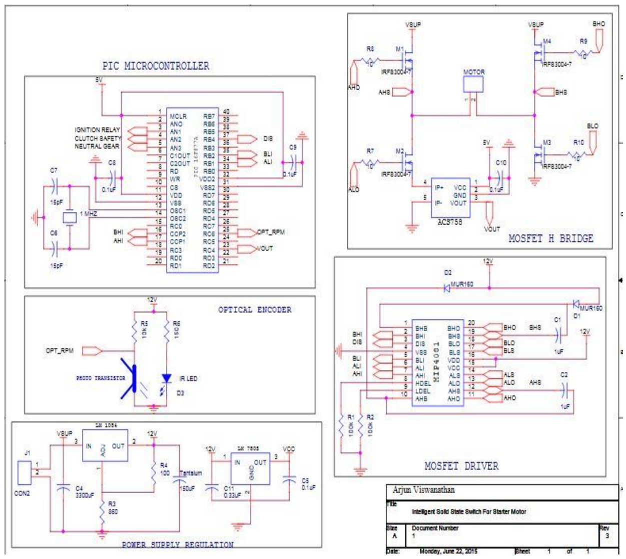

Fig.8 Schematic of Solid state switch

3.5 Working of the design

In this design, the starter motor needs to be rotated in the anti-clockwise direction so that, the Bendix drive can move backwards because of centrifugal force generated by armature's rotation. When the motor rotates in this direction the pinion engages the flywheel and transmits power to crank the engine.

As car key is turned to on, ignition relay sends a voltage to the PIC micro - controller. If either neutral relay also sends a voltage or the clutch relay sends voltage then the micro controller sends signal to cause the Mosfet driver to turn on the M4 and M2 Mosfets of the H-bridge so that the motor will start to rotate in the anti-clockwise direction and so meshing of gears is accomplished.

The optical encoder circuit is used to find the RPM of the flywheel so that when the RPM crosses a set limit, it can send a message to the micro-controller that tells it that the engine is on and can trigger the Disable pin of the Mosfet gate driver so all the Mosfets will be turned off and prevents the starter motor from cranking the engine and hence causes de-meshing of the pinion gear and the flywheel. Also, as the disable pin is turned on even if the ignition key is being tried to turn on , since the optical encoder has detected the engine has started ,it acts as a safety mechanism to prevent the starter motor from turning on .

Also, as an additional safety to prevent sudden large currents through the motor, an ACS 758 Hall Effect sensor has been used with the circuit so as to provide a current reading to the Micro-controller and hence can be used to regulate current through the motor.

3.6 Simulation of Solid State Switch

A simulation of the Mosfet H-bridge designed was done on LTSpice IV. The voltage between the gate and source is 12V, while the HIP4081 can supply up to 2.6A peak pull up current when the output is high. Taking into account the various inputs and outputs the model was generated and simulated.

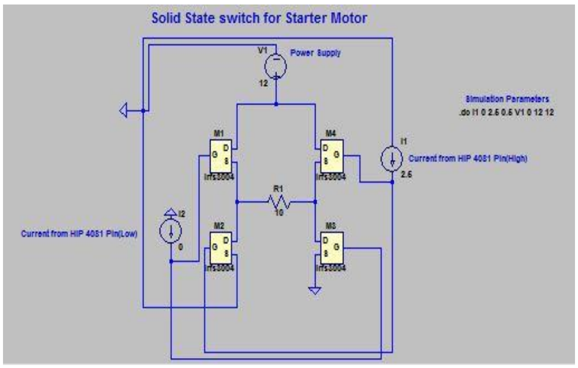

Fig.9 Simulation Schematic

4. Result of The simulation

The output graph indicates the current through the Mosfet's Drain pin against different values of current supplied at the gate pin of the Mosfet by the HIP4081 gate driver.

It is seen that it handles up to 270A of current when it is biased in the enhancement mode. The mosfet has a turn on delay time of 23ns and a rise time of 240ns. This means that the overall response time is better than the solenoid system.

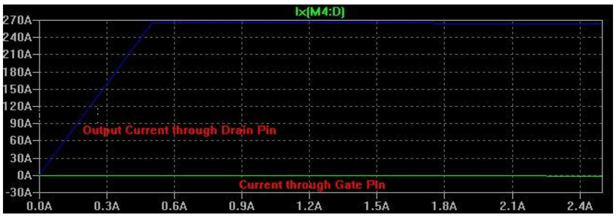

Fig. 10 Mosfet drain current plot

Conclusions

- Contact bouncing is an inevitable problem that occurs in the solenoid and results in the degradation of the contact.
- The solenoid's coils absorb significant current from the battery to actuate the solenoid and this increases the loading on the battery.
- The intelligent solid state switch designed leverages advancements in Mechatronics and power electronics fields to actuate the starter motor in a more efficient way by using a micro-controller.
- The solid state switch has a response time in ns whereas the solenoid has a response time in ms and also the solid state switch takes very little current from the battery to turn the starter motor on.
- The entire solid state switch will occupy lesser space than a solenoid.
- It can be programmed to perform additional functions like once the key is turned to an on position try a certain number of times to crank the engine ,and can also help in fault diagnosis in the starting system .

Future Work

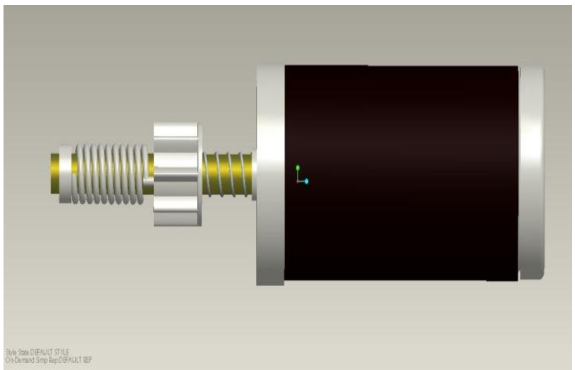

Fig.11 Proposed Bendix gear drive design

Since the intelligent solid state switch has been designed to use for the starter motor , the pre- engaged drive mechanism must be changed so that as the motor rotates , due to centrifugal forces the Bendix drive will engage with the flywheel. The Bendix design mechanism and the profile of the gear teeth must be designed and optimized to reduce gear clashing and friction to promote smoother engagement and increase the overall efficiency of the design. Also a further study to obtain the exact response time of the new system must be conducted.

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