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V. M. Murugesan, G. Chandramohan, M. Senthil Kumar, R. Rudramoorthy, L. Ashok Kumar, Rambabu Palla

Analysis of Automobile Starter Solenoid Switch for Improved Life

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Original scientific paper

The purpose of this paper is to present an experimental study of simple geometries representing the electrical contact in automotive connectors when current passes through them. The starting system is designed to provide the vehicle operator with a convenient, efficient and reliable means of cranking and starting the internal combustion engine used to power the vehicles and all of its accessory systems from within the safe and secure confines of the passenger compartment. The starting system consists of two separate circuits, high amperage circuit (150A - 350A) and low amperage circuit ($<$ 20A). Since foresaid circuit involves high current low voltage system, the starter motor solenoid contact will observe high current at their contacts. So this high current makes pitting effect and lead to increase in solenoid contact resistance. Due to increased contact resistance the starter motor may not produce sufficient torque and leads to overloading of battery due to successive attempts. In order to overcome this problem, a new model for solenoid switch contact has been developed using finite element modelling method ANSYS Parametric Design Language to reduce the internal resistance of the battery due to overloading because of increased contact resistance at the solenoid contact points. The obtained results are useful for finding a compromise between the electrical and mechanical aspects for a power connector and to help manufacturers to decrease the weight and the electrical contact resistance of their connectors.

Key words: Starting system, Solenoid, Contact resistance, Battery, Cranking

Analiza prekidača startera solenoida automobila. U ovom članku namjera je prikazati jednostavnu eksperimentalnu analizu električnog kontakta u automobilskim kontaktima kada vode struju. Sustav za paljenje je dizajniran je kako bi osigurao vozaču praktičan, učinkovit i pouzdan način paljenja motora s unutarnjim izgaranjem. Sustav za paljenje sastoji se od dva odvojena kruga, krug s jakom strujom (150 A - 530 A) i slabom stujom ($<$ 20A). Kako spomenuti krug podrazumijeva krug s jakim stujama i niskim naponom, kontakt solenoida će na krajevima davati velike iznose stuja. Ta će struja uzrokovati povećanje otpora kontakta. zbog povećanog otpora kontakta starter možda neće proizvesti dostatan moment što će dovesti do preopterećenja baterije. Kako bi se riješio navedeni problem, razvijen je novi model kontakta solenoida koristeći modeliranje konačnim elementima (ANSYS Parametric Design Language). Dobiveni rezultati korisni su kako bi se pronašao kompromis između električnih i mehaničkih aspekata i kako bi se pomoglo proizvođačima da smanje težinu i otpor konektora električnog kontakta.

Ključne riječi: sustav za paljenje, solenoid, otpor kontakta, baterija,

1 INTRODUCTION

In the coming years, the need for electrical energy in a vehicle will rise at an ever faster face. An increasing demand for electrical energy systems from the large amount of electrical equipment which has become an integral part of every modern day vehicle. The main function of automobile starting system is to supply cranking torque to the crank shaft of internal combustion engine until a sustainable RPM is achieved. The cranking torque provided by the starter motor is a linear or quadratic function of the current flowing through the starter motor winding via starter solenoid [4].In most of the starter motor design a pull-in solenoid is used for engaging the pinion to the ring gear of the fly wheel. The pull-in solenoid is suitable for low armature travel and high pull-in force. Once the pinion is engaged with the fly wheel the total accumulated voltage is applied to the electric starter motor [1-2]. The starter motor must be ready at all times to crank the engine, and during its course of life must successfully complete thousands of starting operations. Also the starter motor incorporates several features to create reliable, efficient, compact, light weight and powerful unit. The DC series wound starter motor has four electromagnetic field coils wound around four pole shoes and four brushes contact the motor commutator. Starter failure sources are either mechanical or electrical. Wear, seizure or fractures of moving parts come under mechanical sources of failures, short or interrupted circuit and contact resistance increases come under the electrical source of failures [1-2].The common electrical faults of starting system are battery fault, brush fault, armature fault, short circuit fault, open circuit and solenoid contact resistance fault[6].

The low voltage in automotive applications requires carbon brushes with very low contact resistance, which is particularly necessary for starter motors, which carry peak current densities of 1000A/cm^2 [7]. Due to increased contact resistance at the solenoid contact points and brush commutator points, the current drawn by starting system with brush fault is less than the current drawn by the starting system in normal or healthy condition. In this condition the engine will take long cranking time for starting. This will results in accelerated wear of commutator brushes and therefore accelerates the release of lead from the commutator brushes.

Due to high current at the solenoid contact points, pitting effect occurs, also conventional starting circuit doesn't contain any battery monitoring system, when the battery voltage is low; driver may go for further attempt to start the engine which leads to uneven wear in the solenoid contacts. This leads to increase in solenoid switch contact resistance. If the contact resistance of the power contacts increases, the losses increase and the starter output drops. The starter end-of-life is reached when the output is not sufficient for minimal cranking speed of the combustion engine. Thus contact resistance of the starter power contact is very important for reliable cranking.

It is very difficult to use the starter motor effectively due to malfunctioning of solenoid switch because of its damaged contact points (pitting) and wear, and it is needed to use the starter continuously until the engine is started [6]. This affects the battery life, starter motor armature and pinion finally results with vehicle idle, affecting actual purpose of the vehicle [8-9].The foresaid problem can be improved by redesigning the solenoid switch contact points and by minimizing electrical contact resistance of the solenoid power contact points by new contact geometry using Finite Element Modelling (FEM).

2 MEASUREMENT OF VOLTAGE DIP AND CRANKING CURRENT ON CONVENTIONAL CRANKING SYSTEM

The method of measuring voltage dip and peak cranking current during cranking using "Voltmeter" and "Tong tester" on a vehicle which is fitted with old and new starter motors are shown in Figure 1. Experiments were conducted on a test vehicle after attaining the engine operating temperature for all cranking attempts. Hence, mechanical resistance is assumed as constant in all attempts. The time interval followed between each attempt is 5 seconds.

Fig. 1. Measurement of voltage dip and peak cranking current with old and new starter motor

Initially the old starter motor was fitted on the vehicle and the values of peak cranking current and voltage dip were measured. Then the old starter motor was replaced by new starter motor on the same vehicle, and corresponding peak cranking current and voltage dip were measured during cranking. In this experiment, a tong tester and a current transformer (sensor) were used to acquire peak cranking current data during cranking.

The wiring diagram of starting system indicating measuring points are shown in Figure 2.

The measured values of voltage dip and peak cranking current during cranking on a vehicle which is fitted with old and new starter motors are shown in Table 1 and Table 2.

3 COMPARISON OF VOLTAGE DIP DURING CRANKING WITH BATTERY OPEN CIRCUIT VOLTAGE ON A VEHICLE FITTED WITH OLD AND NEW STARTER MOTORS

Comparison of voltage dip during cranking with battery open circuit voltage on a vehicle which is fitted with old and new starter motors is shown in Figure 3.

It is observed that in conventional starting system during cranking, open circuit voltage of the battery drops (voltage dip) and peak cranking current is increased. In

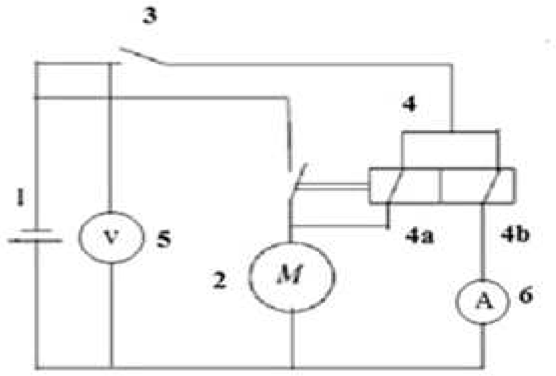


Fig. 2. Wiring diagram of starting system indicating the measuring points (1. Battery, 2. Startermotor, 3. Starter-switch, 4. Solenoidswitch, 4a. Pull-inwinding, 4b. Hold-inwinding, 5. Voltmeter, 6. Tong tester)

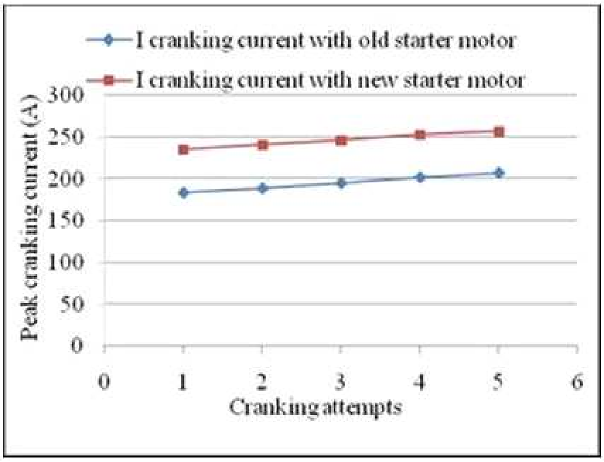


Fig. 3. Voltage Dip Comparison

Table 1. Measured values of voltage dip and peak cranking current with old starter motor

Cranking attempt	Battery open circuit voltage(V)	Voltage dip during cranking(V)	Peak cranking current(A)
1	12.52	10.57	184.00
2	12.18	10.36	189.00
3	12.00	10.09	195.00
4	11.98	09.87	202.00
5	11.85	09.67	207.00

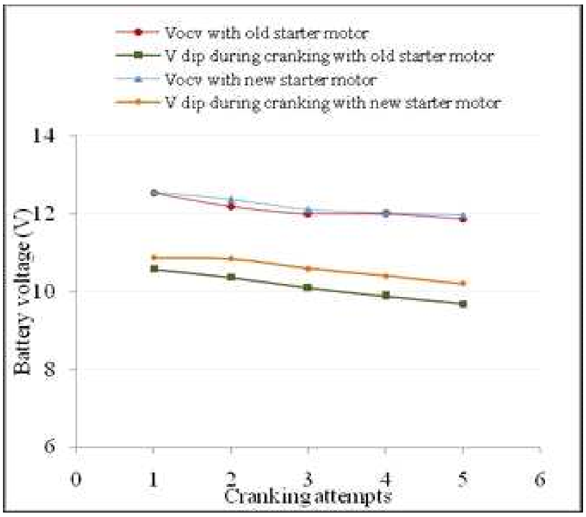


Fig. 4. Peak Cranking Current Comparison

Table 2. Measured values of voltage dip and peak cranking current with new starter motor

Cranking attempt	Battery open circuit voltage(V)	Voltage dip during cranking(V)	Peak cranking current(A)
1	12.55	10.87	235.30
2	12.35	10.84	241.00
3	12.10	10.58	246.00
4	12.02	10.40	253.00
5	11.97	10.20	257.00

case of starting system with old starter motor the voltage dip is more when compared to the starting system fitted with new starter motor. Thereby affecting the battery life by consuming heavy current. Suppose, if the driver doesn't hold the cranking key properly to start the engine, this reduces battery voltage at the same time current drawn by the starter motor is increased. This results in faster battery discharge. At the same time starter motor heating loss (I^2R) will occur, this reduces the solenoid life. In this condition old battery discharges quickly than new battery [5].

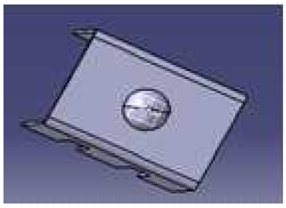
4 COMPARISON OF PEAK CRANKING CURRENT DURING CRANKING ON A VEHICLE WHICH IS FITTED WITH OLD AND NEW STARTER MOTORS

The comparison of peak cranking current during cranking on a vehicle which is fitted with old and new starter motors is shown in Figure 4.

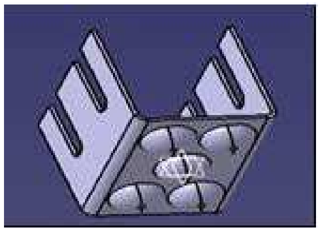
It is recorded that conventional starting system with old starter motor draws less current due to increased contact resistance when compared to the same fitted with new starter motor because there is no contact resistance.

5 MODELING OF NEW SOLENOID CONTACT GEOMETRY

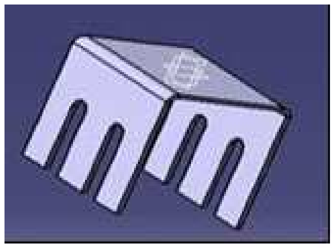
Using CATIA V5R20 modelling software the solenoid contact geometry model has been developed. The U-shaped samples were made with a sheet having 12.5mm width, 16mm height and 20mm length. One sample has plane part or lower part and the sphere part or upper part with one contact point and another sample has plane part or lower part and the sphere part or upper part with five contact points with the same thickness. In general the contact resistance for sphere / plane contact was lower than that of the cylindrical / plane contact and plane / plane contact. Therefore, the U-shaped sample with spherical shape contact is selected. Types of contact point geometry are shown in Figure 5.



(a) One spherical type contact point



(b) Five spherical type contact point



(c) Flat type contact point

Fig. 5. Types of contact point

6 MATERIAL USED FOR SOLENOID CONTACT

The selected material for two contact samples is high copper alloy (C19210) which has good mechanical and thermo-electrical properties. The thermal, electrical characteristics and mechanical properties of high copper alloy (C19210) are given in Table 3 and Table 4.

Table 3. Thermal and electrical characteristics of high copper alloy C19210

Composition	Thermal conductivity (W/mk)	Electrical Resistivity (Ωmm)	Electrical Conductivity (%IACS)
CuFeP	350	1.88×10-5	91

Table 4. Mechanical characteristics of high copper alloy C19210

Yield stress σ_e (MPa)	Young modulus E(MPa)	Vickers hardness HV	Tensile strength σ_m(MPa)
322	0.5×105	100-130	360

7 FINITE ELEMENT MODELLING

Finite Element Analysis (FEA) is a numerical method which provides solutions to problems that would otherwise be difficult to obtain. Since finite element analysis is a computer simulation technique used in engineering analysis. Finite element models were developed with the finite element Multiphysics code (ANSYS) in order to calculate the transient numerical values of contact resistance and contact temperature.

8 INDIRECT COUPLING METHOD

Numerical contact resistance and contact temperature values were calculated using indirect coupling program. This program is written in a macro file by a scripting language called ANSYS Parametric Design Language (APDL) in order to automate the coupling between the mechanical and thermo-electrical fields.Using APDL interface it is possible to pass commands to the commercial software package, such as modeling the structure, meshing the model, applying the boundary conditions on the model, solving the problem, saving the deformed structure and changing element types and boundary conditions. The indirect coupling method begins by importing in the finite element pre-processor the geometric model of the two contact samples created by the CAD software CATIA V5R20. The material properties of the two contact samples are then specified. In order to study the mechanical behavior of contact samples under indentation loading, the previous geometric model is meshed with tetrahedral structural solid elements (Solid187-3D-10 nodes) with degrees of freedom: displacements Ux, Uy and Uz according to the three axes X, Y and Z respectively.

Then mechanical boundary and contact conditions are applied to this meshing model. The deformed structure is saved and the mechanical elements (Solid187-3D-10 nodes) are replaced by the coupled field solid elements (Solid227- 3D-10 nodes) with degrees of freedom, temperature and voltage. Then, thermo-electrical boundary and contact conditions are applied to this deformed structure. The numerical values of electrical contact resistance and contact temperature are calculated. The algorithm for solving the thermo electro-mechanical problem using the indirect coupling method is shown in Figure 6.

Due to symmetry of the loading or boundary conditions, materials and geometry, only a half of the contact samples are meshed in order to reduce modelling efforts. Tetrahedral structural solid h-element type with ten nodes is used to mesh the structure. This element is characterized by quadratic interpolation functions within the element is used in order to increase the accuracy of finite element findings. A free meshing type is used to mesh the model. The model with one contact point is meshed with 28783 elements and 52364 nodes while the model with five contact points is meshed with 43471 elements and 79380 nodes. Using the h-refinement method, the contact zones are refined in order to get better results.

For mechanical boundary conditions, a pressure corresponding to a contact force of 100 N is applied to the upper surface of the spherical contact part; the lower surface of the plane part is embedded and the displacements Ux, Uy and Uz according to the three axes X, Y and Z of coordinate system are null. Due to the symmetric config-

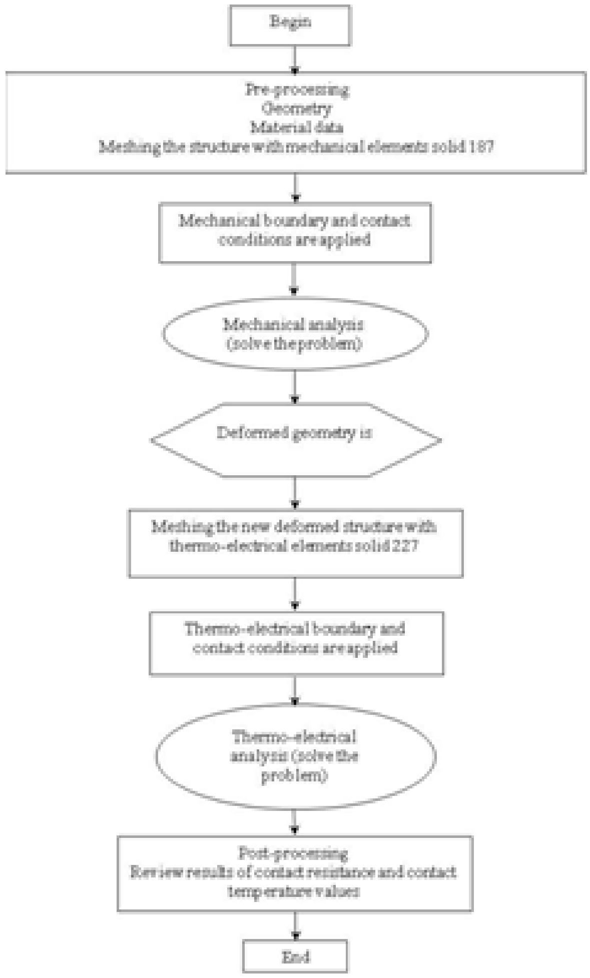


Fig. 6. Algorithm for Solving Thermo electro - Mechanical Problem Using indirect coupling method

uration of the contact samples, symmetry boundary conditions are applied on the symmetric surfaces of contact samples. So, a displacement constraint Uz = 0 is applied on the two parallel surfaces to the plane XY, and a displacement constraint Ux = 0 is applied on the two parallel surfaces to the plane YZ. For thermo-electrical boundary conditions, the upper extreme surface of the spherical part is submitted to total electric current I which is equal to 200 A. The calculated voltage values of nodes set attached to this surface are forced to be the same during analysis for each time step. For this reason, a coupled voltage is applied to this extreme surface. Zero voltage is applied to the lower extreme surface of the plane part.

To solve numerically the heat conduction equation, an appropriate boundary and initial conditions will be stated:

1) In the first condition, temperature function of time should be applied in the two extreme surfaces of the two contact samples

2) Second condition: The two parts of contact sample were fixed in the Teflon insulator supports. Therefore, zero heat fluxes are applied to the sample surfaces which are in contact with this insulator. This second condition can be formulated mathematically as follows:

$qx + qy + qz = 0$

Where qx, qy and qz are heat fluxes dissipated in x,y and z directions respectively.

3) Third condition: In order to take into account the heat exchange with the outside, natural air convection with a film coefficient of 5 W/m^2K and an air temperature of 22°C is applied to the sample surfaces exposed to the air.

The third condition is verified at any point (x, y, z) and at any instant t, it can be formulated mathematically as

$qx + qy + qz = qc$

Where qc is total heat flux dissipated

4) For the fourth condition, the initial temperature distribution in the contact samples at the initial time t = 0 should be specified before analysis:

$T(x, y, z, 0) = T0 = 22°C.$

9 CONTACT CONDITIONS

9.1 Mechanical Contact Conditions

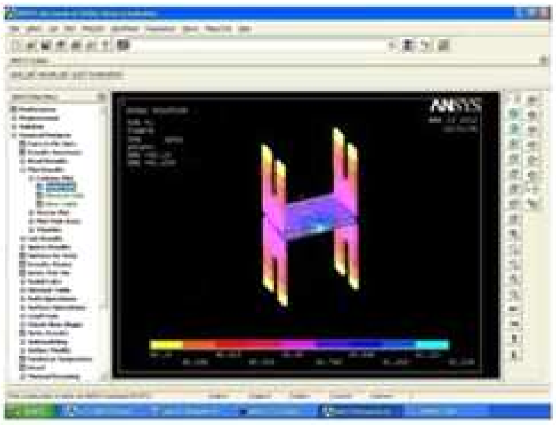
Contact surfaces of contact samples are meshed with a total of 411 surface to surface contact elements for the model with one contact point and 2027 surface to surface contact elements for the model with five contact points. The surface-to-surface contact model is used when contact zones are not known accurately and a significant amount of sliding is expected. In this model, one of the surfaces is called the contact surface and the other, the target surface. These two surfaces are considered deformable. Contact elements with triangular geometry located on the surfaces of 3D tetrahedral solid elements (Conta174-6 nodes) are used to mesh the spherical contact surface; target elements with triangular geometry located on the surfaces of 3D tetrahedral solid elements (Targe170-6 nodes) are used to mesh the plane contact surface.

9.2 Thermal and Electrical Contact Conditions

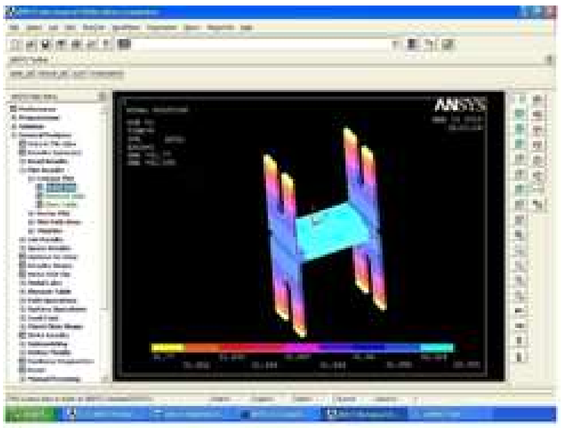
In case of contact between solids, it is assumed that there is no temperature jump at the interface, i.e., the temperatures of the contacting surfaces is equal and there is a continuity of temperature and conservation of energy at the interface.

The heat flux Q between two contacting surfaces can be decomposed into two parts:

$Q = QT + QE$

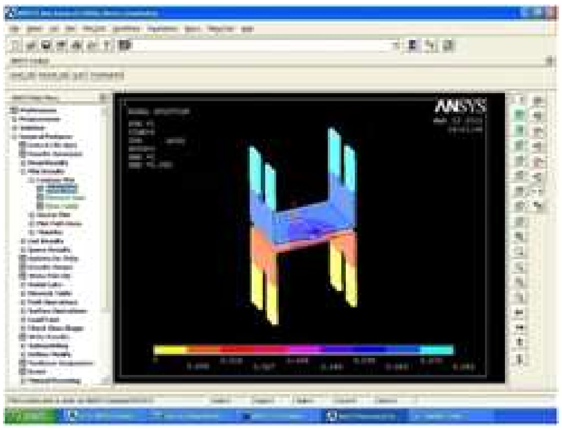


(a)

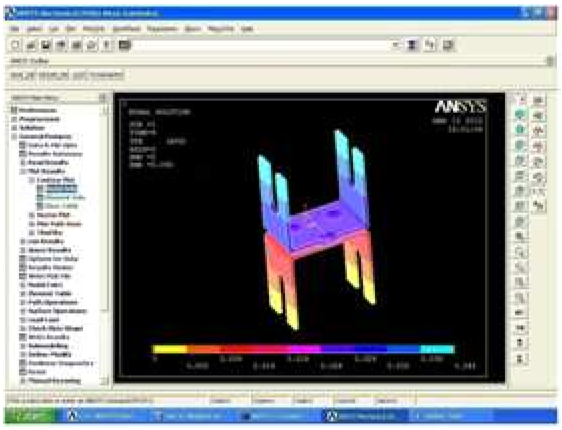


(b)

Fig. 7. Comparison of Contact Temperature Results between the Model with One Contact Point and the Model with Five Contact Points



(a)



(b)

Fig. 8. Comparison of Contact Resistance Results between the Model with One Contact Point and the Model with Five Contact Points

Due to symmetry, only a half of the contact samples are meshed in order to reduce modelling. The numerical curves of contact temperature and electrical contact resistance variations during 1500 milliseconds for the two models (with one contact point and five contact points) are shown in Figure 7, Figure 8, Figure 9 and Figure 10.

The temperature varies exponentially and increases over time until the equilibrium state when the time reaches approximately 1500 milliseconds with an equilibrium contact temperature of 41.23 °C for the model with one contact point and is higher than that of the five contact points which is equal to 32.05 °C. The electrical contact resistance increases exponentially with time because the resistivity increases with the increase of contact temperature. Also, we remark that the electrical contact resistance for one contact point is higher than the one obtained for five contact points.

Finally, the finite element model with five contact points presents several improvements i.e., contact resistance decrease, contact temperature decrease when compared with model with one contact point. Device for controlling an automobile vehicle starter solenoid contact has been designed to make sure that solenoid contact making proper contact in order to avoid uneven wear in the solenoid contacts that caused when driver go for further attempt to start the engine when battery voltage is low[5]. And new solenoid contact geometry with one spherical contact point model and five spherical contact point model at the contact surface has been designed and simulated. This new contact geometry gives reduced contact resistance than one with which we have higher contact resistance.

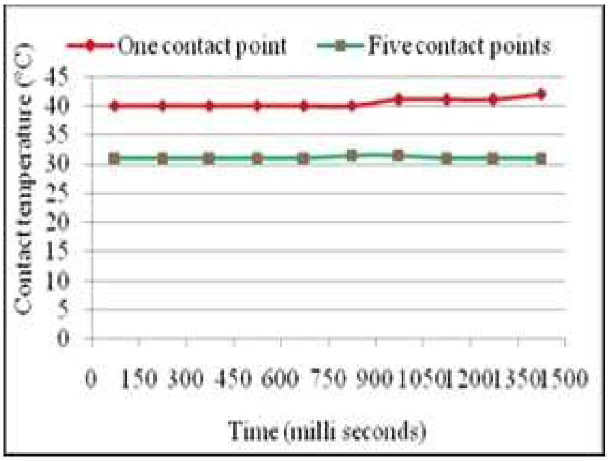


Fig. 9. Comparison of Contact Temperature of One Contact Point Model with Five Contact Points Model

In the present scenario the starter motor solenoid switch contact points are of flat type. Due to high current flow through these contacts during cranking, results with pitting effect. This leads to reduction in contact area. Hence contact resistance is increased. The contact resistance for sphere/plane contact is much lower than that of plane/plane contact which is existing in current starter motor solenoids contacts [3]. Therefore, in the proposed model the contact area is increased by single sphere/plane and five sphere/plane contact points which reduce contact area but increase in current carrying capability thereby increase in life. The new solenoid contact geometry with one sphere/plane contact point model and five sphere/plane contact point model has less contact resistance than existing solenoid contact points. From the finite element analysis it is observed that high contact of the starter motor terminal leads to high current density (current drawing from the battery) which increases the starting torque of the automobile starter motor.

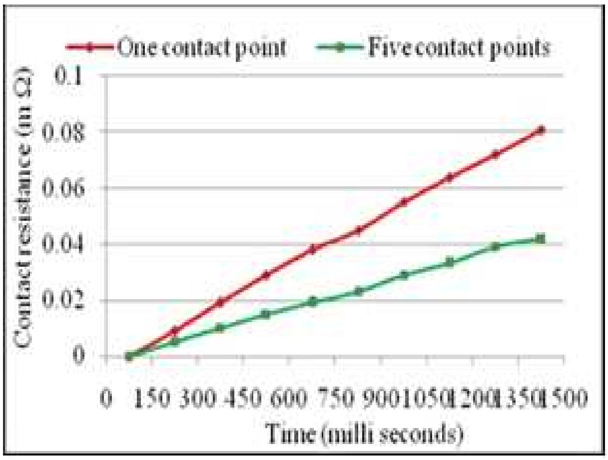


Fig. 10. Comparison of Contact Resistance of One Contact Point Model with Five Contact Points Model

Table 5. Comparison of contact resistance for existing solenoid contact points, one contact point model and five contact point model

Solenoid contact resistance with existing system ($m\Omega$)	Contact resistance with one contact point model ($m\Omega$)	Contact resistance with five contact points model ($m\Omega$)
10 - 15	0.036 - 0.045	0.019 - 0.024

10 CONCLUSION

This research work investigated the contact resistance offered by the new solenoid contact geometry. This new contact geometry is found useful in giving reduced contact resistance when compared with existing system. From the finite element analysis it is observed that high contact of the starter motor terminal leads to high current density (current drawing from the battery) which increases the starting torque of the automobile starter motor. Device for controlling an automobile vehicle starter solenoid contact can be designed to make sure that solenoid switch is making proper contact in order to avoid uneven wear in the solenoid contacts that caused when driver attempts to start the engine continuously. Hence the current drawn from the battery will be ensured in first attempt and avoids prolonged cranking and further attempts of cranking thereby overloading of battery is reduced and service life of battery and service life of solenoid contact is also improved thereby improved starter reliability.

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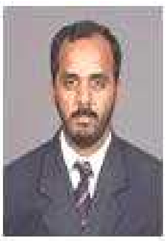

V. M. Murugesan born in the year 1970, is currently working as Assistant Professor (Selection Grade) in the Department of Automobile Engineering at PSG College of Technology, India. He has about 23 years of teaching experience. He obtained his B.E. Degree in Automobile Engineering (1991) from Institute of Road and Transport Technology, Bharathiar University, India, M.E. Degree in Computer Integrated Manufacturing (2006) from PSG College of Technology, Anna University, India. He has authored 7 journal papers and 10 conference papers. He has successfully completed many sponsored research projects. He has been actively involved in many consultancy works in the areas of automotive chassis design, automotive engines and automotive electrical systems. His fields of interest include automotive suspension system, automotive engines and automotive electrical and electronic system.

G. Chandramohan born in the year 1958, is currently working as Director-Academics at Sri Krishna College of Technology, India. He has 27 years of teaching experience and 2 years of Industrial experience. He obtained his B.E. Degree in Mechanical Engineering (1981) from PSG College of Technology, India, M Tech Degree in Industrial Metallurgy (1983) from Indian Institute of Technology, Madras, India and Ph.D. in Metal Forming (1998) from Indian Institute of Science, Bangalore, India. He has authored 47 journals. He was awarded Outstanding Corporate Fellow Member Award-2007 by Institution of Engineers (India), Coimbatore Local Chapter, India. He has successfully completed many sponsored research projects. His fields of interest include metal forming, fluid power control, pneumatic control & low cost automation and composite materials.

M. Senthil Kumar born in the year 1973, is currently working as Associate Professor in the Department of Production Engineering at PSG College of Technology, India. He has about 17 years of teaching experience and 1 year of industrial experience. He obtained his B.E. Degree in Mechanical Engineering (1994), M.E. Degree in Engineering Design (1996) and Ph.D. in Active Suspension System (2008). He was awarded “ISTE-Anna University National Award for Outstanding Academic in 2013. He received ISTE National Award for “Best Research in the field of Machine design and Vibration by Young Teacher” in 2006. He has also received AICTE Career Award for his research on Particle Damping in 2009. He was awarded with Dr.Sundaramoorthy Award for Outstanding Academic contribution in 2011 from PSG College of Technology. He has authored about 75 journal papers and about 50 conference papers. He has successfully completed many sponsored research projects. He has been actively involved in many consultancy works in the areas of design and vibration control. His fields of interest include vibration control, composites, smart structures, etc.

R. Rudramoorthy is currently working as Principal, PSG College of Technology and PSG Polytechnic College, Coimbatore; India. He obtained his B.E in Mechanical Engineering (1981) from Coimbatore Institute of Technology, Madras University, India. He obtained his ME degree in Heat Power Engineering (1984) from Coimbatore Institute of Technology, Bharathiar University Coimbatore India and obtained his PhD (1995) from Bharathiar University, India. He joined in the stream of Faculty of Mechanical Engineering at PSG college of Technology in the year 1984 and has more than 30 years of teaching experience. Under his guidance, 9 Ph.D and more than 100 UG and PG projects have been completed. He has authored 60 journal papers. His fields of research are Heat Transfer, Computational Fluid Dynamics and Refrigeration and Air Conditioning and Finite element analysis. He has completed many research projects for BARC, DST, AICTE, MNES and Swedish International Development Agency at a cost of about 1 crore.

L. Ashok Kumar is currently working as Associate Professor in the Department of Electrical and Electronics Engineering at PSG College of Technology, India. He has about 16 years of teaching experience and industrial experience. He obtained his B.E. Degree in Electrical and Electronics Engineering from university of Madras, M.E. Degree in Electrical Machines, PSG College of Technology, Anna University, India and Ph.D. in Wearable Electronics. He is a recipient of Young Engineer Award from IE, India, Prof. K Arumugam National Award from ISTE & Best Faculty Award from NGI, India. He has authored about 59 journal papers and about 76 conference papers. His areas of interest are Wearable Electronics and Renewable Energy Systems.

Rambabu Palla born in the year 1985, is currently working in IBM India Pvt. Ltd.Bangalore. He has about 2 years of industrial experience. He obtained his B.E. Degree in Electrical Engineering (2007) at GMR Institute of Technology, Rajam, India and M.E Degree in Automotive Engineering (2012) at PSG College of Technology India. His fields of interest include automobile electrical and electronics system.

AUTHORS’ ADDRESSES

V. M. Murugesan, M.E.
Rambabu Palla, M.E.
G. Chandramohan, Ph.D.
M. Senthil Kumar, Ph.D.
R. Rudramoorthy, Ph.D.
L. Ashok Kumar, Ph.D.
PSG College of Technology,
Coimbatore 641 004, Tamil Nadu, India,
email:covaimurugesanvm@yahoo.com,
murugesanvmpsg@gmail.com

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