Cost Optimization in Dc Solenoid Valve Used in Air Braking by Replacing Copper Winding Wire To Aluminum

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***Abstract* — Solenoid valves are used in air braking system in heavy vehicles. This is essentially used to prevent skidding in vehicles. Traditionally the coil uses copper wounded coils for producing the working flux for plunger attraction. Recent Cu price increases motivate careful examination of approaches to minimize Cu use. Approaches that can reduce Cu use without increasing losses include careful winding design, trading winding volume for core volume; replacing Cu with Al. Al wire is particularly attractive. The cost of Al is lower than it might appear from the cost per unit mass when the much lower density of Al is also considered, and the disadvantage of higher resistivity becomes less important. This paper shows the design details of a solenoid valve with aluminum wiring along with the advantages and disadvantages of copper and aluminum. It also includes the testing and performance results of aluminum air solenoid.**

***Index Terms*— solenoid valve, air braking system, Standard wire gauge, actuation, Retraction, on leak test, off leak test, endurance test.**

I. INTRODUCTION

The term solenoid usually refers to a coil used to create magnetic fields when wrapped around a magnetic object or core. A solenoid valve is an electromechanical device that is used in air braking system in heavy vehicles. Electromechanical solenoid valves consist of an electromagnetically inductive coil, wound around a movable steel or iron slug (termed the armature). The coil is shaped such that the armature can be moved in and out of the center, altering the coil's inductance and thereby becoming an electromagnet. The armature is used to provide a mechanical force to some mechanism (such as controlling a pneumatic valve).Air brakes or more formally a compressed air brake system is a type of friction brake for vehicles in which compressed air pressing on a piston is used to apply the pressure to the brake pad needed to stop the vehicle. Air brakes are used in large heavy vehicles, particularly those having multiple trailers which must be linked into the brake system, such as trucks, buses, trailers.

II. ADVANTAGES OF AIR BRAKING SYSTEM

Air brakes are used as an alternative to hydraulic brakes which are used on lighter vehicles such as Automobiles. Hydraulic brakes use a fluid (hydraulic fluid) to transfer pressure from the brake pedal to the brake shoe to stop the vehicle[2].

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Air brakes have several advantages for large multitrailer vehicles .The supply of air is unlimited, so the brake system can never run out of its operating fluid, as hydraulic brakes can. Minor leaks do not result in brake failures. Airline couplings are easier to attach and detach than hydraulic lines; there is no danger of letting air into the hydraulic fluid[2]. So air brake circuits of trailers can be attached and removed easily by operators with no training. Air not only serves as a fluid for transmission of force, but also stores potential energy. So it can serve to control the force applied. Air brake systems include an air tank that stores sufficient energy to stop the vehicle if the compressor fails[2]. Air brakes are effective even with considerable leakage, so an air brake system can be designed with sufficient "fail-safe" capacity to stop the vehicle safely even when leaking.

III. THE DC SOLENOID CONTAINS THE FOLLOWING PARTS

Coil: The coil is comprised of many tightly wound copper or aluminum wire. When DC current flows through this wire it created a strong magnetic flux path which flows around the coil and through its center.

Bobbin: A coil assembly for a solenoid valve includes a bobbin formed from an electrically insulate material and conductive wire wound on it.

Core tube: Core tube is a stainless steel tube that is used to concentrate the flux to a confined space and acts a path for the plunger movement.

Plunger: The moving component of a linear solenoid that opens and closes the valve body.

***Plunger spring*:** A part of the plunger that is used to return the plunger to its original position after demagnetization.

Magnet wire is a copper or aluminum wire coated with a very thin layer of insulation. Magnet wire is classified by diameter (AWG number or SWG) or area (square millimeters), temperature class, and insulation class.

IV. THE PROPERTIES OF ALUMINUM

1. Conductivity: Aluminum is a good thermal and electrical conductor, having 59% the conductivity of copper.

2. Light weight: Ease of handling, low installation costs, longer spans, and more distance between pull-ins.

3. Strength: A range of strengths from dead soft to that of mild steel, depending on alloy. The highest strength alloys are employed in structural, rather than electrical conductor, applications.

4. Workability: Permitting a wide range of processing from wire drawing to extrusion or rolling. Excellent bend quality.

5. Corrosion resilience: A tough, protective oxide coating quickly forms on freshly exposed aluminum and it does not thicken significantly from

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continued exposure to air. Most industrial, marine, and chemical atmospheres do not cause corrosion, providing the proper alloy is selected.

6. Creep: Like all metals under sustained stress, there is a gradual deformation over a term of years. With aluminum, design factors take it into account.

7. Compatibility with insulation: Does not adhere to or combine with usual insulating materials. No tin-coating required; clean stripping, Other qualities of aluminum, such as thermal conductivity and fatigue resistance, have a bearing on conductor section [1].

Table 1

Properties	Unit	Copper	Aluminum
Density	kg/dm^3	8.9	2.7
Tensile Strength (hard... annealed)	N/mm^2	450-240	180-80
Elongation at break (hard... annealed)	%	Jan-35	Feb-35
Modulus of elasticity	kN/mm^2	120	70
Melting point	^0C	1083	658
Coef. of thermal expansion	$10^{-6} / {}^0C$	16.6	23.8
Temperature coef.of resistance $+20^0C$	$1/ {}^0C$	0.0039	0.004
Conductivity at +20 ^0C IACS	%	97-100	61-62
Resistivity at +20 ^0C W	mm^2/m	0.01786	0.02857

A. Comparison of the properties of Copper and Aluminum [7]

B. Process of choosing the right aluminum wire:

The area of cross section must be 1.6 times higher than copper and it must be two SWG sizes bigger. The technically correct way to make these conversions is to select an equivalent or higher capacity rating while maintaining the same conductor temperature rating[2]. Now select an aluminum conductor from the 60°C column that has an capacity of 55 amperes[2]. The replacement lies with equipment ratings. A conductor must terminate at the equipment it serves and this equipment is tested and listed with definite conductor types. Always make conversions from aluminum to copper or copper to aluminum by selecting equivalent or large capacity while maintaining the same conductor temperature rating.

C. Procedure for calculating the equivalent Aluminum:

Constant input given to both the coils (existing and proposed) 24V, 0.31A, 74/80 ohms. Here a copper wounded solenoid of SWG size 37 is chosen and the aluminum of size SWG 35 was chosen.

Step1: The bare conductor diameter is measured. (As per SWG table)

Step 2: The increased conductor size with enamel coating is measured. (As per SWG table)

Step 3: The resistance per meter at 20 deg c is taken.. (As per SWG table)

Step 4: The total resistance required is calculated from the rated voltage and current of the solenoid.

Step 5: The outer diameter of the bobbin and the length of the bobbin on which the wire is to be wound are measured.

Step 6: The weight of the conductor is calculated as in kg/km using the formula mentioned below.

Step 7: The length required to meet the specified resistance is calculated using the formula mentioned below.

Step 8: The weight of the conductor in grams as per the norms is calculated.

Step 9: The turns per layer is calculated.

Step 10: The number of layers required to meet the given resistance at the given length is calculated.

Step 11: The number of turns is estimated.

Step 12: The force is calculated.

Note: The force must be enough to raise the plunger along with the spring load and across the air gap.

Step 13: The flux density is also calculated.

D. Formulas used for calculation:

1. Weight of the conductor=density*volume (kg/km)
   - density of copper=8.90
   - density of aluminum=2.70
2. Weight of copper= 6.9865*d^2
3. Weight of aluminum=2.1195*d^2
4. Total length of the wire} = $\frac{\text{Total resistance required}}{\text{Resistance per meter @ 20degC}}$
5. Weight of the conductor for the given resistance = Length of the wire *weight of conductor
6. Turns per layer= $\frac{\text{Bobbin winding length}}{\text{Overall wire diameter}}$
7. Number of turns = turns per layer*no of layers
8. Solenoid force calculation:

$$F = (N*I)^2 \mu_0 A / (2\ g^2)$$

Where n – no of turns
i – Rated current
μ_0 – permeability of air
a - average area of core and plunger
g - Length of air gap

9. Flux density b= $\mu_0 \mu_r ni / l$ (tesla)

Where μ_0 – permeability of air
μ_r - permeability of medium (wire)
n – No of turns
i – Rated current
l – Length of the wire

Note: the permeability of material such as copper brass, aluminum is the same as free air. So it's equal to 1.

Table 2: parameters calculated using above formula

Specifications	UNITS	Cu37	Al35
Wire dia(bare conductor)	d(mm)	0.173	0.21
Wire overall dia	d overall(mm)	0.21	0.24
Resistance per meter@20deg C	R(ohm/m)	0.727	0.78
Bobbin winding OD	D bobbin(mm)	10.4	10.4
bobbin winding length	L bobbin(mm)	26	26
Weight of conductor	kg/km (2.1195*d^2)	0.209	0.09
Length of the wire	L(m)	107.6	99.7
Weight of conductor	W(gm.)	22.35	9.58
Turns per layer	n	123.8	107
number of turns	N	2391	2148
Flux density	Tesla	8.65E-06	8.39E-06
Force	Newton	66.84	58.3

V. TESTS INVOLVED

A. Wire testing

Before the coil was wound the wire was heated to about 220 deg C for about30 minutes to check the strength of the enamel used and also it was dipped into acetone for 1 hour ensure the continuity of the enamel on the wire. Once the appropriate wire was chosen it was wound and molded and assembled into the solenoid valve structure. It was given into a series of testing procedures.

B. Solenoid Testing

1) Test procedure: The air cylinder assembly is independently tested as per TISC 51 before fitting the magnetic valve. Adjust the pressure regulator to deliver 8bar air pressure. Connect the test unit as shown in the circuit. Apply 8 bar air pressure by opening the 3 way valve. Inlet gauge G1 reacts 8 bars. Apply the rated voltage 24 V dc to the magnetic valve of the test unit. Valve delivers air pressure and the air cylinder is actuated. The piston rod moves out. Remove the applied voltage and the air pressure is exhausted. The piston rod moves out. The piston rod of the air cylinder retracts. Repeat the cycle for 3 days. Actuation and retraction of air cylinder should be without perceptible delay.

2) Operating voltage and power consumption check:

Apply 6 bar pressure to the inlet and 11.5 V to the test unit. The valve should not deliver air pressure to the air cylinder and the air cylinder should not get actuated. Apply 6 bar pressure to the inlet and 20 V to the test unit. The valve should deliver air pressure to the air cylinder and the air cylinder should not get actuated. Apply 24V DC to the test unit and check the current in the circuit. The current in the circuit should not exceed 0.35 A.

C. Leak tests

1) On leak test: This is the leak at the exhaust valve seat observed at the exhaust, leak at the joint of body and coil assembly leak at the joint of body and connector and leak at the joint of connector and air cylinder port. Without removing voltage from the test unit, bring the 3way valve to the neutral position and ensure air pressure of 8 bars in the gauge G1. Check for pressure drop in the pressure gauge G1 for a period of 15sec minimum. No drop pressure drop is permissible.

2) Off leak test: This is the leak at the inlet valve seat, observed at the exhaust. Remove the applied voltage from the test unit. With the 3way valve in neutral position, ensure air pressure of 8 bars in the gauge G1. Check for pressure drop in the gauge G1 for a period of 15sec minimum. No pressure drop is permissible.

Table 3: result of on leak and off leak test for Copper and Aluminum

Applied Voltage : 24 volt **Applied Pressure : 8 bar** **Stabilizing Time : 5 sec**		**On leak time : 15sec** **Off leak time : 15sec**	
Valve	Pressure Drop	On leak test	Off leak test
Copper	0.003	Passed	Passed
Aluminum	0.002	Passed	Passed

D. Endurance testing: (continuous on test):

To ensure that the coil can withstand severe working conditions it has to undergo a series of heating tests. The coil has to be heated for about 6 hours and the resistance will be measured. The resistance should not exceed 175Ω. Once this is done the coil is continued to heat for about 24 hours at 32 V and 80deg C. Then coil return to its ambient temperature. And a series of performance tests are performed. After the test the following condition should be satisfied by the coil to pass the endurance test.

$$\frac{234.5\ ^\circ C + \text{Temp.ambient}}{\text{Resistance ambient}} = \frac{234.5\ ^\circ C + \text{Temp.after } 48 \text{ hours}}{\text{Resistance after 48 hrs}}$$

The variation of resistance can also be calculated using the formula:

$$R_t = R_0\ (1 + \acute{a}t)$$

Where R_T= conductor resistance at temperature "t"

R_0 =conductor resistance at 20 deg C

t = conductor temperature in deg C.

á = temperature co efficient of the conductor

For copper co-efficient of resistance á=0.00393

For aluminum co-efficient of resistance á=0.00410

E. Duty cycle test

After the continuous on test the lift axle system needs 100% duty cycle. This is done and the following results were obtained.

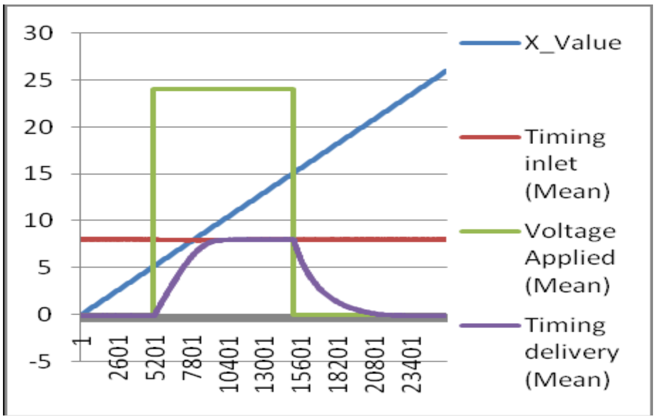

Fig 1. Copper coil characteristics among timing inlet,voltage applied,timing delivery after the test

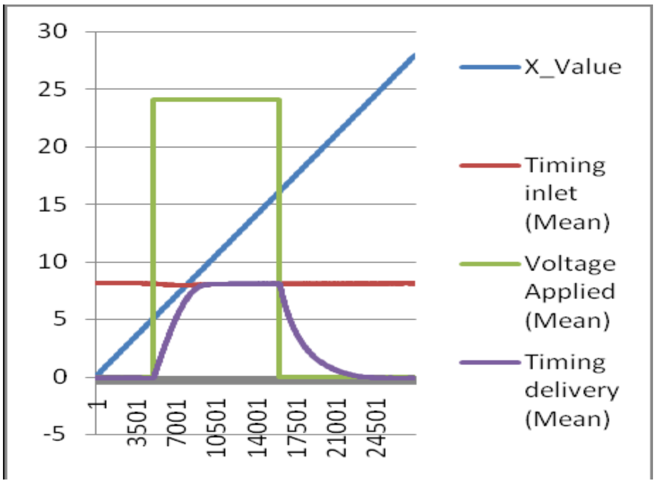

fig 2.aluminum coil characteristics among timing inlet, voltage applied, timing delivery after the test.

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VI. COST OPTIMIZATION

For 24V air magnetic coil the weight of the Copper (SWG37) per part is 0.02248 kgs and for equivalent Aluminum (SWG35) is 0.00958 kgs. Based on the weight cost reduction per coil and overall cost optimization is calculated. The whole process of changing the winding material from copper to aluminum involves a reduction in the production cost with the same performance as copper. The cost of the winding wire used for a single coil is Rs.14.612 but the cost of aluminum for a single coil is only Rs.2.874 per product. A total of Rs.11.738 can be saved in terms of winding wire per product.

VII. CONCLUSION

This paper has presented the working of a DC solenoid along with the various applications and cost optimization by changing the winding material. The selection between copper and aluminum is not an easy task since many factors have to be taken into consideration. In this paper a parametric analysis of solenoid valve design as a function of cost of copper against aluminum has been presented. Thus by replacing copper winding material with aluminum the cost of the product is reduced drastically providing the same performance as copper. With the availability of aluminum in India this could revolutionize the use of aluminum.

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