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Proving that Eddy Current is the Main Heat Generator for a Current Carrying Cable Suspended in a Steel Pipe

Dr. Prashobh Karunakaran[1], Prashanth Karunakaran[2], Shanthi Karunakaran[3], Arjun Karunakaran[4], Dr. Man Djun Lee[5], Dr. M. Shahril Osman[6], Muhd Dina Fadhilah[7], Karuppanna V[8], Sung Chee Cheng[9]

[,1,5,6,7,8,9]University College of Technology Sarawak (UCTS), Sibu, Malaysia [2,3,4]Swinburne University of Technology Sarawak Campus, Kuching

[1]prashobh.karunakaran@gmail.com [2]prashanth.prashobh@gmail.com [3]shanthieoan@gmail.com [4]eratom12@gmail.com
[5]man.djun@ucts.edu.my [6]shahril@ucts.edu.my [7]adelfitherie95@gmail.com [8]Vayaloorank@gmail.com [9]davidsung@klt.edu.my

***Abstract*— The aim of this research is to prove that when a current carrying cable is sized sufficiently to carry a large current and is placed in a steel pipe, the main energy loss is eddy current and not joule heating or I2R loss. To prove this, two methods were used to negate the eddy current which are by placing live and neutral cables in the same pipe and the other was to place the same cable in HDPE pipes where eddy current cannot be induced. It was conclusively proved that eddy current was the main generator of heat. Heat was also observed all over the circuit and it was discovered that joints had the most heat. Finally, the steel pipe itself was made part of another circuit to attempt to drain off the induced eddy current but this did not prove effective.**

Keywords*— *Eddy Current, Joule Heating, Carbon-Steel, HDPE, PVC, Infrared, Heat

1. Introduction

There is a general lack of understanding of which effects cause eddy current and which causes joule heating. This is the experience of this author who got reviewed on this project in two different universities and comments by IEEE paper reviewers who claim that when a current carrying cable is placed in an iron pipe, the heat generated on the iron pipe is from primarily due to joule heating. It seems baffling that PhDs cannot see this but the root of the problem is that to a large extent most electrical engineering people have moved their focus away from electrical power to electronics and microcontrollers, probably because of the capabilities of those fields to effect changes in the world at a relatively cheap price. But a clear understanding of high power must be also taught because without the understanding of exactly how it flows, big mistakes can be made. And in electrical power, most parts are expensive. Therefore, mistakes can be terribly expensive [1].

The basic formular for current flow was taught to most students in the world in the eight or night year of schooling as below:

$$R = \frac{\rho L}{A} \text{ --------(1)}$$

This means that the resistance of a cable, R is equal to the resistivity, ρ multiplied with the length, L of the cable divided by the surface area, A of the conductor of the cable [1]. Therefore, if the surface area, A is sufficiently large for a given type of conductor with a specific ρ, the resistance can be almost negligible. Therefore, as long as the current carried is below the point where it starts to heat up, it will not have significant joule heating. These measurements have already been done long ago by respected organizations like IEE (of the U.K. which is now changed to IET) or IEEE [2]. Fig. 1 depicts a bird perching on a132kV lines which is carrying the main power for a relatively large city named Sibu in Malaysia. All that current is not enough to cause sufficient joule heating to make the bird uncomfortable.

Fig. 1

Fig. 1 is a picture of a bird perching on an uninsulated Al Conductor transmitting 132kV. Below left is a 11kV pole and line.

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Table 1 is the current carrying capacities of cables of copper conductor cross section areas on the left [3]. In this work a maximum of 54A was sent to four L wires and for N wires of size 2.5mm^2. This means the L and N wires are capable of carrying 21 X 4 = 84A. The load used was 132 incandescent bulbs of 100W each connected in parallel and every 12 bulbs are switchable with a switch. There are 11 switches, therefore there were 11 X 12 = 132 bulbs.

Table 1: Current carrying capacities of LV (low voltage) cables used in internal wiring.

Cable conductor cross section size in mm^2	Current carrying capacities in amperes
1.5	15.5
2.5	21
4	28
6	36
10	50
16	68

Various experiments were performed to prove that the heat generated on iron pipes surrounding a current carrying cable is caused by eddy current and not joule heating. In the electric power industry, three phases are run together if the cable is to be placed in a metal pipe for protection. Such cases arise in situations where underground cables need to cross a road, be strung along the sides of a bridge or when the cable needs to cross an open drain. When three phases are run together, the electric waves at 120^o apart superimpose each other, thereby nullifying the eddy current induction on the steel pipe. But today increasingly the iron or steel pipes are replaced with thick HDPE pipes which are insulators so there is no eddy current induction.

The initial aim of this research was to find a way to transmit electricity from Kuching to Pengerang Malaysia which are separated by 630km of the South China Sea [4]. It is one of the shallowest seas in the world with depth ranging between 50-70m. The whole Sundar straits where most of SouthEast Asia is located is shallow and historically it was all terrestrial till the ocean levels rose to submerge it. It was proposed that electricity can be transmitted by suspending HV cables of 1000kV at the center of 8” HDPE pipes. Three insulators will suspend the HV cable at the center. Such pipes to carry oil and gas (O&G) have already been laid by the oil and gas industry. But only recently have the O&G industry used HDPE pipes. Each O&G pipe is 11.3m and three insulators can be molded at one end of each pipe with the same HDPE to hold the transmission line at the centre. Standard transmission line binding wire can be used to fasten the transmission line to the three insulators. When this research was started, we were not aware that the O&G industry was actually using HDPE pipes running O&G at 200atm within them. Therefore, the eddy current heat loss was measured at varying current run through the conductor held at the centre of the carbon steel pipe. The measurements were extrapolation to discover that even an 8” Ø steel pipe is sufficient to have negligible eddy current loss as the cable at the centre of it carries the required power using a 500mm^2 (Ø=12.6mm) cable. It must be noted that there are suppliers whose 500mm^2 cables can carry 533A AC. And since DC can carry double the current compared to AC due to absence of skin effect, this 500mm^2 cable can carry 1000A. 1000A X 1000kV = 1000MW can be carried in a single HVDC cable. In Pengerang a GT (gas turbine) power station was built producing 1200MW of power. But GT power station has to continuously burn expensive and polluting gas while the power which can be supplied from Kuching is hydro since the Sarawak state of Malaysia has the perfect conditions for hydroelectricity production. Sarawak has one of the highest rainfalls in the world (at 157”) since it is located on the equator and has lots of mountains on the border with Indonesia. 157” is almost six times the rainfall of the USA, Europe, China and Japan. In addition, it is sparsely populated beyond the major cities. The water flow (rainfall rate) and head (mountains) are the primary criterion in decision making to build a hydroelectric dam. The other regions of the equator have a lack of mountains, Congo, Gabon and Brazil has a lack of mountains though having similar rainfall rate as Sarawak. Then, Tanzania, Kenya and Uganda which are also located on the equator must have been affected by whatever caused the Sahara Desert because the rainfall in these countries is less than the average 28” received by USA, Europe, China and Japan. Then Colombia is located on the equator but is too mountainous to easily carry out a hydroelectric dam construction project [4].

It should therefore be no problem using the same system of piping used by the O&G industry to carry a transmission line with only a few atm of N_2 blowing within them. The N_2 is to displace the O_2 and thus prevent corrosion of the transmission cable. But since the pipes are expensive, it was proposed that a pump be placed to compress the N_2 to double the pressure such that a 4” Ø pipe can be used to bring the N_2 back to Kuching to be cooled before sending it back in the 8” Ø pipe to Pengerang [5].

The postulate is that if this is successful, it could be a new form of international electric power transmission. Currently the natural gas is mined off Bintulu and compressed at the MLNG (Malaysian Liquified Natural Gas) plant. The gas is then compressed at -161^{o}C prior to being sent in refrigerated tankers all the way to Japan to be used to generate electricity. By the time it reaches Japan 5% of the LNG leaks from the tankers. Therefore, refrigeration plus leaks causes much loss before electricity can be generated. But if the electricity is generated in Bintulu, Malaysia and sent via this cable-in-pipe system, the loss should be very much less. It should be noted that there is a HVDC line in Brazil carrying 11.2 GW of power on overhead lines over a distance of 2543 km. Comparatively the longest XLPE encapsulated submarine cable can only carry 700MW over a distance of 580 km between Norway and Netherlands. This situation can be compared to humans wearing lots of jackets, they will get hot and shake in pain. Similarly, the more electrons shake and therefore move laterally instead of longitudinally, obviously the resistance will be higher. Sending electric power to Japan could be the beginning, the next step would be to send power from Australia to Indonesia, or even from the USA to Europe [4].

2. Literature Review

In 1840, James Prescott Joule published in the Royal Society Proceedings the fact that heat can be generated by a current carrying conductor. A current was sent through a current carrying conductor immersed in fixed mass of water. The heat of the water was measured in a 30 minutes interval. With the results he obtained, he came up with the equation (2) [6].

$$P_{loss} = I^2R \text{ ------(2)}$$

The English word eddy current was originally used to describe concentric ripples as a few stones were thrown into a still lake [7].

In electrical motors or transformers all interaction of electron flow and induction are supposed to happen between copper conductors. But normally steel is used as the structure for these machines because of its strength as well iron having the highest permeability among materials which enhances greatly the movement of magnetic field lines from one coil of copper to another. But because iron is also a conductor of electron flow, there is induction of current flow in the iron also. This induced current flow is generated according to Fleming’s right hand rule [8,3].

Fleming’s right hand rule dictates that as the right hand is shaped like a gun, the thumb is F of the direction the magnet moves, the pointing finger is B which represents the direction of the magnet’s or solenoid’s N to S and the middle finger points to the direction the generated current flows. But if F is force as is taught in schools the transformer cannot be explained. Therefore, it is best to let F represent the varying **F**ield density; that way it is still F. When a magnet is passing a wire at right angle, a current is generated in the wire. What does the wire “see”? Assume the magnet has 10 magnetic field lines. Initially it sees zero field lines, then it sees an increasing number of field lines and then a decreasing number of fields. It therefore sees a varying **F**ield density [3,8].

Similarly, in the primary coil of a transformer, AC current is sent and the field lines is initially zero then increases to a maximum as the current is at the peak and then the number of field lines decreases gradually back to zero as the current curve slopes to the X-axis. Therefore, the primary coil has a varying **F**ield density. It also has B, in being a solenoid therefore there is current induced in the secondary coil in inverse proportion to the turns ratio [3,9]. The reason a transformer is needed is say, in a hydro power generator; the water falling down the dam is power. The formula for power is P=VI. A transformer enables stepping up the V and obviously the I need to go down to keep the same P of the water. The reason this is done is because the power loss in transmission lines (or the factor that makes the transmission lines red hot) has the formula $P_{loss} = I^2R$. With I very low, the P_{loss} is very low. In the 275kV grid lines of Sarawak, the current ranges from 10A to 59A per line. This is low because 70A comes out of a typical car battery as a car is started. But the car battery is only used for starting, thenceforth the alternator drives the electric devices of the car. But if DC is sent to the primary coil, even if it is a very high DC, causing lots of magnetic field density outside the primary coil, there is no varying **F**ield density experienced by the secondary coil so there is no F of the F,B,I therefore, there is no current generation in the secondary coil. Therefore, DC cannot be stepped up with a transformer [10,11].

In between the primary and secondary, there is an iron core. But just as current is generated in the secondary using the F,B,I principle, current can also be generated in the iron core which is also a conductor of electrons. But in the iron core, there is no polarity like positive and negative or Live and Neutral so the electron flow does not have a direction, therefore, as it accumulates, it becomes like winds creating many hurricanes of electron flows. This is eddy current. Any flow of electrons generates heat, so the iron core will become hot. Also, rampant eddy current flows in the core can interrupt the generation of current flow in the secondary coil which means there will be noise in the current generated in the secondary coil; the output will be a sinusoid with lots of noise. To solve this problem, the core is made of laminates of iron with varnish in between. Electrons cannot cross the varnish but just as a magnet above a piece of paper can move another magnet below a paper, magnetism can pass through the varnish. This way, eddy current can only flow within one laminate and cannot grow into a big hurricane within the iron core [12,11].

In an induction motor, as the far away generator rotor passes L1, L1 in the motor becomes a magnet. And when the rotor in the generator passes L2 coil, L2 in the induction motor becomes a magnet and so forth. Thereby, there is a rotating magnet field (RMF) around the stator coils of the far away induction motor which follows the rotation of the rotor within the generator. As the RMF passes the initially stationary squirrel cage (shaped like a cage for a squirrel) rotor of the induction motor, current is induced within these bars of the squirrel care. This induced current flows to the end rings and then to the bar right below it to the other end ring and back in the initial bar. Thereby there is a circuit of current flow. These current forms a magnetic field since electrons are magnets. But the magnetic strength of the bars is not high enough. Therefore, the center of the squirrel cage is filled with laminated sheets of steel, separated with varnish. This is done because iron is the best conductor of magnetic field lines. For electron flow, conductivity is ranked from top down as silver, copper, gold, aluminum. But for magnetic field lines propagation, the best conductor (permeability is the scientific term) is iron. Most other metals as well as non-metals have a permeability of 1 while iron has a permeability of 1000. Since iron is cheap, it is always found in the highest percentage in even the strongest magnets with the few other rare and therefore expensive magnetic elements mixed-in only in very small proportions [13,11]. Hitachi is currently the world leader in pursuing ever stronger magnets [11]. This permeability results in the magnetism generated by the movement of the induced current in the stator bars to be very much higher. But if the rotor's center is of solid iron, there will be eddy current induced in the iron which will be wasted as heat. But even more importantly, the eddy current in the iron of the rotor will be big enough to disturb the electromagnetic interaction between the stator coil and the rotor coil. Similarly, the stator of the induction motor is also made of laminated steel sheets for the same reason of increasing magnetization and reducing eddy current [14,11]. This increases the magnetic strength of the squirrel cage rotor bars vastly increased but eddy current is limited to flow only within one laminate. This lamination is placed in the rotor as well as the stator of all induction motors which utilize 68% of industrial usage of all electricity generated in the world. Induction motors run every fan and air-conditioner of homes to largest machines in factories [11].

But the induction motor's frame is made of unlaminated solid steel. The eddy current generated within it can be quite significant. An experiment was done with a 25HP induction motor. The grounding wire which is joined to the frame is disconnected and it turned with a “tak, tak tak” noise. When the grounding wire was connected back, the motor run smoothly making the smooth sound, “theeeeeew”. What is happening is that the eddy current in the frame grew large enough to disturbing the electrical interaction between the stator and rotor. It may be possible for scientist to one day develop good enough plastic frames of motors to totally eliminate eddy current. But this plastic material must be able to eliminate eddy current as well as be a heat conductor to remove heat from the induction motor [11].

The third thing that taking F to be varying **F**ield density can help to explain is the skin effect of AC current flowing in a wire. Assume the wire has only one electron which is a magnet of 10 field lines. Assume the left arm is a wire and the right hand shaped as F, B, I is moving longitudinally along it back and forth as happens in AC. The right hand which represents that single electron magnet is moving in the direction of the thumb. This change in direction of I in AC is explained as the generator rotor magnet is passing the L1 clockwise coil, current is generated to go out away from the generator [15,11]. The rotor then crosses the anticlockwise located at the other end which causes the electron to move towards the generator. At both ends of the arm, the speed of the electron is zero because it is changing direction similar to a stone thrown up having zero speed at the top of its motion. But at the center of the arm, the speed of the electron is at maximum. Specifically, it increases in speed exactly till the ½ way point then decreases speed again. Assume the electron is slow. At t=1, there are 10 field lines, at t=2, there are10 field lines but at the center, the 10 field lines are very close to each other because the speed is maximum at this point. Therefore, the magnetic field density is also maximum at this point. So, there are 10 field lines at the ends and maximum field lines at the center. This is the F of the F,B,I. Electrons are magnets so there is B. The N, S orientation of the various electrons are widely varying but looking at your right hand, the net result is a generation of current, I away from the center to the outside of the wire. This generated current is termed eddy current and causes the skin effect of AC current flowing in a wire. At 50 or 60 Hz AC frequency where the steam turbines cause the generator's magnetic rotors to turn at 50Hz, the skin effect causes electrons to flow only on the conductor's surface area 1cm from the skin surface. In airplanes, the standard frequency of the generator is 400Hz. This is to enable the generator to produce more electricity with smaller size. At 400Hz with the same analogy as above, the single electron will still have 10 field lines at the two ends of its movement but at the center of its movement there will be much more field lines. Therefore, it has a higher F value or a higher varying **F**ield density value. This will cause a higher I or eddy current to be generated. Thereby the eddy current generated is greater which makes the skin effect even greater. This means the cross-sectional area through which the current can flow is much less [11,15]. This is why within an airplane, if 10 A needs to be sent with two or three wires of 1.5mm^2 while in a standard home, one 1.5mm^2 cable will be sufficient [16,3].

In DC, there may be billions of electrons moving in a wire which causes multibillion magnetic field lines outside the wire but it is not varying, therefore there is no F of the F,B,I so no eddy current is generated. This is just like placing a huge magnet over a wire; no current is generated in the wire. Only if the huge magnet is moved, causing varying **F**ield density, can current be generated in a wire below it. Therefore, with DC flowing in a wire, the whole cross-sectional surface area of the wire is used for current flow. This is why, when DC is used, the wire can carry 100% more current than when AC is used. But all generated current from generators are AC and DC cannot be stepped up with a transformer. And as the voltage increases, the cost of electronics to change from AC to DC (rectify) becomes very expensive. This is why DC is used only when a very large amount of power needs to be sent as has been done from Malaysia and Thailand. With very large power transmission, the cost of the rectifying electronics becomes worth it, because the higher efficiency of the transmission overcomes the cost of the electronics. The other reason DC is used is because DC does not go back and forth and therefore has no frequency. To join Malaysia's grid with Thailand is a very big task because the two grids must be slowly synchronized, but with DC, there is no synchronization needed. Therefore, DC is used all over the world as a link between AC grids [17,11].

In most cases, electrical engineers find ways to get rid of eddy current but it is utilized for the benefit of humanity in induction cookers. Here eddy current caused by high frequency AC is generated in steel cooking containers which is vibrating thereby producing heat enough to cook the food [18,11].

Another use of eddy current is for the detection of cracks in the surfaces of iron or steel. Eddy current testing (ECT) is one of the most effective NDT for steel structures. It basically used the current in a coil of many coils to detect the cracks. When the coil moves over a crack, the current load in the coil is decreased. The technology is old and has therefore developed such that even miniscule defects can be detected. Even the depth of the defects can be measured with ECT. It is also used to measure paint or other coating thickness over steel surfaces [19].

Another method of using eddy current in NDT of steel structures is that the generated eddy current will heat up the iron but a crack in the iron will result in a lower heat. A high sensitivity thermometer can measure this difference in heat and thereby highlight a crack within the iron or a defect in a welded joint [20].

3. Methodology and Results

Experiments were done with four 2.5mm^2 cross section cable wire carrying 54A of AC with the cable running through carbon steel pipes and HDPE pipes and measuring the heat generated on the pipe. In some cases, the cable has PVC insulation and, in some cases, bare 2.5mm^2 X 4 was run through the pipe. The heat emitted on the pipe was measured with a FLIR C2 infrared camera as well as a Fluke model 62 MAX infrared camera. Fig. 2 is the electrical schematic used for the experiment and Fig. 3 depicts the load used.

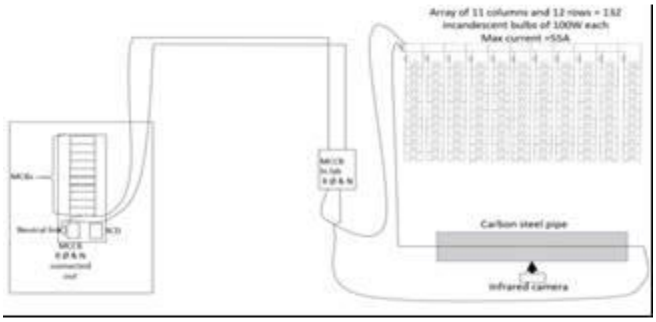


Fig. 2

Fig. 3

Fig, 2 is the electric schematic used and Fig. 3 is the load used 132 100W incandescent bulbs where every 12 bulbs are switchable.

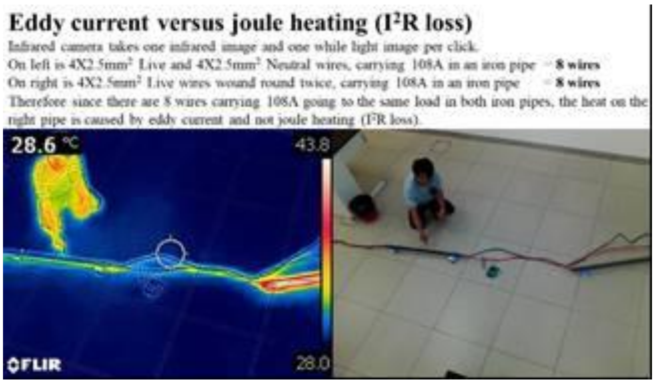
The FLIR C2 takes one infrared and one visible light image upon one click. In Fig. 4 this researcher purposely asked a student to point at the left setup because it was already hypothesized that the heat emitted from the left setup is only from joule heating and the image could be lost because the temperature will be almost at ambient levels. The hypothesis was proven correct. In the left setup, four 2.5mm^2 L and four 2.5mm^2 N cables were carrying 54A. Meaning 54A going to the 132 100W in the L cables and 54A returning via four 2.5mm^2 N cables. For the right setup four 2.5mm^2 L cables were wound round the carbon steel pipe; meaning there are eight 2.5mm^2 L cables within the carbon steel pipes. It should be noted that in both carbon steel pipes there are eight 2.5mm^2 cables carrying a total of 54 X 2 = 108A. But the only process of generating heat on the left setup is joule heating and in the right setup the processes to generate heat are joule heating plus eddy current. It can be clearly seen that the left setup is having just a little above ambient heat and the right setup is mostly white which is 43.8^{o}C.

Fig. 5 depicts why eddy current is negated in the left setup. For eddy current to form, F,B,I must be available. The F is, variable **F**ield density, B is available since electrons are magnets and therefore current is induced. The right setup can be explained as stated in the literature review where the right hand shaped as F,B,I is placed over the left arm and moved longitudinally representing the movement of a single electron with 10 field lines. It can be determined from Fleming’s rule that eddy current will be generated and it can be seen that the eddy current will be moving from the center of the copper conductor to the outside. And since magnetic field travels through the air in the pipe, it continues till the pipe where eddy current is generated. Using Fleming’s right hand rule, and assuming an electron moves a one cm back and forth because it is AC. Since at the ½ cm point it has the maximum field density and therefore maximum F, the current generated at the ½ way point will be maximum and decreases at both ends of that 1cm Fig. 6 depicts the shape of the eddy current. Fig. 5 depicts why the right setup is almost at ambient temperature. This is because of the superimposition of the current in the L and N cables resulting in zero induced eddy current.

Using Fleming’s right hand rule Fig. 6 depicts the shape of the eddy current induced in the steel pipe surrounding it, if a single electron is assumed to move back and forth 1cm in the cable below it. The eddy current formed is shaped like an isosceles triangle with curved slopes that continuously builds up to the peak (when the electron is at ½ cm) then decreases to zero. Therefore, assume there are 20 such electrons over 20cm of the pipe, there will be 20 build-ups of eddy current and falling eddy current. At 50 Hz there will be much more build-ups and reduction of eddy current. It is this eddy current that generates the heat on the pipe in the right setup of Fig. 2.

Fig. 7 is another experimental setup of L cable ($4X2.5mm^2$) wound round a steel pipe on the left and a HDPE pipe on the right, such that each pipe has eight L cables ($8X2.5mm^2$). This way there is 108A of L cables within each pipe. It must be noted that theoretically there is no process to form eddy current in a HDPE pipe while there is in steel pipes. And the result in Fig. 4 depicts the white-hot pipe when 108A is flowing in the steel pipe and slightly above ambient temperature when 108A is flowing in the HDPE pipe. The pipe on the right is heated up only with joule heating while the pipe on the left is heated with eddy current plus joule heating. It can be noted, comparing Fig. 4 and Fig. 7. In both Fig 4, left setup and Fig. 7 right setup there is no eddy current. But in Fig. 4, left setup (steel pipe) looks cooler by visualization of the colors than Fig. 7 right setup (HDPE pipe) because steel can conduct heat and dissipate it while HDPE will retain the joule heating within.

Fig. 8 shows three experiments namely: (1) measuring heat on a 1” Ø steel pipe with $2.5mm^2X4$ Cu cables suspended at the center (top left), (2) measuring heat on 1” Ø HDPE with $2.5mm^2X4$ cable suspended at the center (top right), (3) measuring heat on bare $2.5mm^2X4$ cables. The bottom right is the highest temperature point in this experiment which is the join at the cable clip.



Eddy current versus joule heating (I^2R loss)

Infrared camera takes one infrared image and one while light image per click.

On left is $4X2.5mm^2$ Live and $4X2.5mm^2$ Neutral wires, carrying 108A in an iron pipe = **8 wires**

On right is $4X2.5mm^2$ Live wires wound round twice, carrying 108A in an iron pipe = **8 wires**

Therefore since there are 8 wires carrying 108A going to the same load in both iron pipes, the heat on the right pipe is caused by eddy current and not joule heating (I^2R loss).

Fig. 4

The left and right of Fig. 4 are the infrared and visible light image of a student pointing at the carbon steel pipe because it appears that the heat on the carbon steel pipes carrying 8 wires is the same as the uncovered portion.

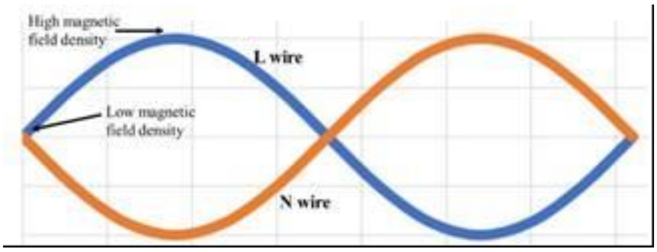


Fig. 5

Fig. 5 is the reason the left setup is almost at ambient temperature.

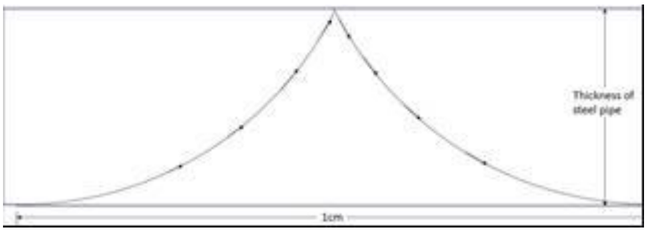


Fig. 6

Fig. 6 is the reason why the right setup gets hot. Eddy current building up then decreasing continuously along the pipe.

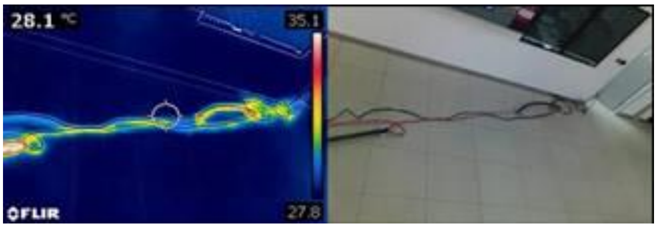


Fig. 7

Fig. 7 is the heat when 108A flows in a steel pipe in the left setup and 108A (eddy current plus joule heating) flowing in a HDPE pipe in the right setup (only joule heating).

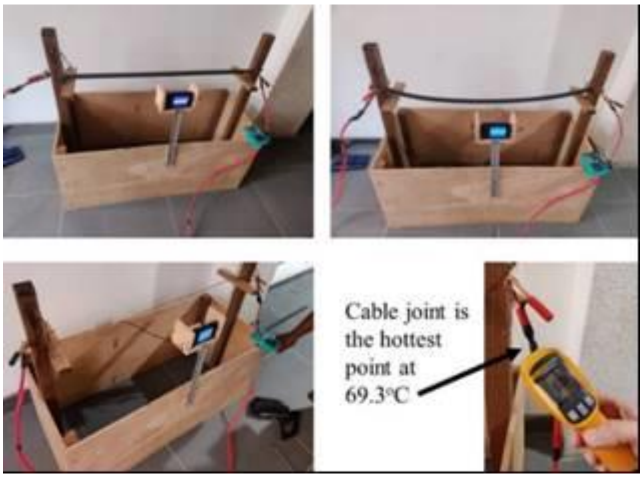


Fig. 8

Fig. 8 depicts the setup of running 54A in $2.5mm^2X4$ cable suspended in a steel pipe (top left), suspended in a HDPE pipe (top right), bare wire 2,5mm2X4 (bottom left). Bottom right is the hottest point in the whole experiment which is the joint at the cable clip.

Fig. 9

Fig. 9 left is the current meter = 54.1A. Middle is the infrared image of 54A flowing in a bare $2.5mm^2X4$ bare Cu cable. Hard to decipher because cable at near ambient temperature. Right is the infrared image of the $2.4mm^2X4$ cable run in a steel pipe

The results are listed in Table 1. The purpose of the first two columns is to depict that PVC or other insulation over the cable drastically increases the heat on the cable. This is depicted in the chart of Fig 10. This means that underground cables which are encapsulated with very much more plastic than the cables in this experiment will run very hot. This explains why a typical lifespan of underground cable is officially specified as only ½ that of bare overhead lines. But underground cables can cost up to eight times more than overhead lines. Plus, the statistical downtime for an underground cable fault is one week compared to only three hours for overhead lines [21].

The third and fourth columns show that when the $2.5mm^2X4$ cables are run in a steel pipe the heat generated is far greater than in HDPE pipe of almost the same diameter. This can be more easily seen in the chart of Fig. 11. This is because with a steel pipe surrounding the Cu cable heat is generated with eddy current as well as joule heating but when the Cu is covered with a HDPE pipe the only process of generating heat is joule heating.

The fourth and fifth columns are data similar to the third and fourth columns but with 60psi of air being blown in the steel and HDPE pipes. The difference can be more easily seen in Fig. 11. It is obvious that despite the greater heat when the Cu is covered with the steel pipe, the 60psi of air blowing will dissipate the heat. This was done because the final pipe in which the 500mm^2 Al conductor will be suspended over the 630km of the south China Sea will have about that pressure of N_2 continuously blowing within it. In this simulation, 78% of N_2 since the percentage of N_2 in air is 78%.

Table1: Heat measurements made.

<table>
<tr><td colspan="8">Heat measurement with FLIRC2 and verified with FLUX62</td></tr>
<tr><td colspan="8">Ambient temperature = 29° C</td></tr>
<tr><td colspan="8">In all cases 2.5mm²X4 Cu cable was used to carry the current</td></tr>
<tr><td>#</td><td>Time (mins)</td><td>Bare Cu cable</td><td>PVC insulated Cu cable</td><td>Cu cable within Ø=2.18 steel pipe</td><td>Cu cable within Ø=2.14 HDPE pipe</td><td>Cu cable within Ø=2.18 steel pipe with compressor @ 60psi</td><td>Cu cable within Ø=2.14 HDPE pipe with compressor @ 60psi</td></tr>
<tr><td>1</td><td>0.0</td><td>30.0</td><td>30.0</td><td>30.0</td><td>30.0</td><td>30.0</td><td>30.0</td></tr>
<tr><td>2</td><td>5.0</td><td>30.2</td><td>35.5</td><td>41.0</td><td>33.2</td><td>36.2</td><td>32.8</td></tr>
<tr><td>3</td><td>10.0</td><td>28.5</td><td>38.3</td><td>45.0</td><td>34.4</td><td>38.0</td><td>33.3</td></tr>
<tr><td>4</td><td>15.0</td><td>29.4</td><td>40.0</td><td>47.3</td><td>34.5</td><td>38.7</td><td>34.3</td></tr>
<tr><td>5</td><td>20.0</td><td>29.7</td><td>39.9</td><td>49.3</td><td>34.0</td><td>38.8</td><td>32.9</td></tr>
<tr><td>6</td><td>25.0</td><td>29.6</td><td>41.0</td><td>49.1</td><td>34.0</td><td>39.0</td><td>32.6</td></tr>
<tr><td>7</td><td>30.0</td><td>29.6</td><td>42.0</td><td>48.6</td><td>34.0</td><td>39.2</td><td>32.2</td></tr>
<tr><td>8</td><td>35.0</td><td>29.7</td><td>41.3</td><td>47.5</td><td>34.0</td><td>39.0</td><td>32.7</td></tr>
<tr><td>9</td><td>40.0</td><td>28.0</td><td>40.3</td><td>47.6</td><td>32.3</td><td>39.2</td><td>32.6</td></tr>
<tr><td>10</td><td>45.0</td><td>28.5</td><td>40.3</td><td>48.8</td><td>33.4</td><td>38.3</td><td>32.5</td></tr>
<tr><td>11</td><td>50.0</td><td>28.7</td><td>40.8</td><td>49.6</td><td>34.5</td><td>38.3</td><td>32.6</td></tr>
<tr><td>12</td><td>55.0</td><td>28.5</td><td>40.0</td><td>49.0</td><td>34.4</td><td>38.6</td><td>32.8</td></tr>
<tr><td>13</td><td>60.0</td><td>28.9</td><td>42.4</td><td>48.6</td><td>34.5</td><td>39.2</td><td>32.9</td></tr>
</table>

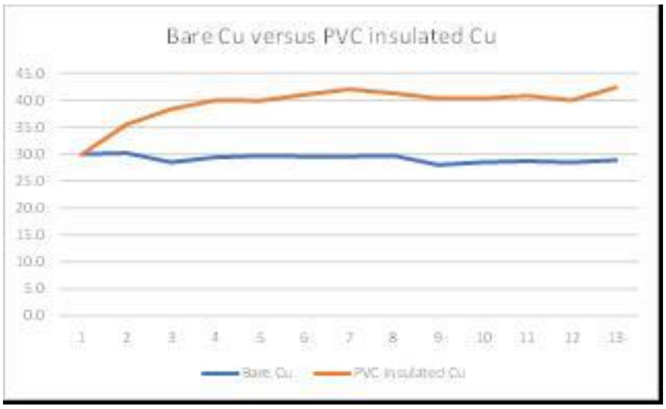


Fig. 10

Fig. 10 depicts the heat on bare Cu cable versus PVC insulated cables

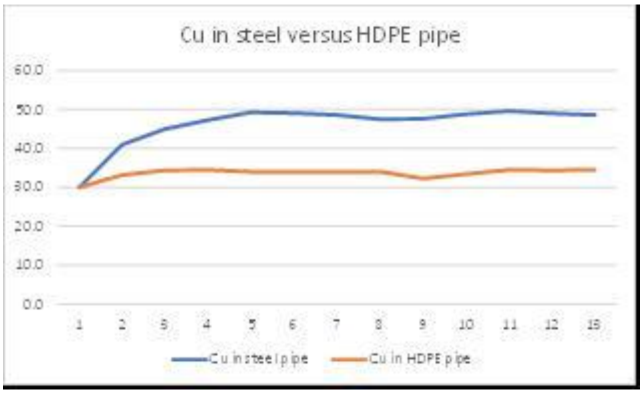


Fig. 11

Fig. 11 depicts the heat on steel versus HDPE pipes surrounding Cu cable

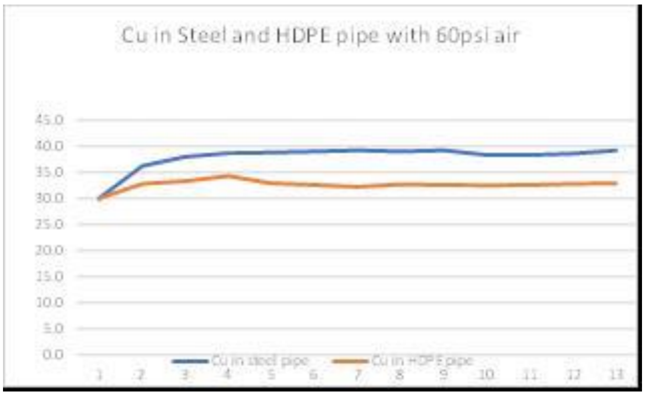


Fig. 12

Fig. 12 depicts the heat on steel versus HDPE pipe surrounding Cu with 60psi air blowing within it

The results of all these experiments conclusively prove that if a conductor’s current carrying capacity is higher than the current it is carrying is surrounded by a steel pipe, the heat generated on the steel pipe is primarily caused by eddy current and not joule heating.

Fig. 9 middle image shows the infrared camera when measuring heat on the bare cable carrying 54A. The cable can barely be seen because the temperature is almost at ambient temperature. But when a steel pipe is placed surrounding the Cu conductor, the image on the right turns red indicating a clear difference between it and ambient temperature.

The left image of Fig. 9 indicates that the temperature at joints are the hottest in the whole circuit. The importance of this data is to show electrical contractors who do not follow the original IEE (now IET) specifications that all electrical wire joints must be soldered. Fig. 13 shows the higher heat as wires are joint with a weak twist, a tight twist and a tight twist which was also soldered. The properly soldered joint has the least heat emission. Most contractors just twist joints and tape with an insulation tape. The image of Fig. 14 can be shown to contractors who wrongly feel it is alright. In fact, it will get worse later as corrosion sets into the Cu. Comparatively a soldered joint is protected from corrosion. The reason most contractors give for not soldering is that there is no electricity on construction sites, but a standard butane flamer can be used. Only the ends of the joint must be flamed and the solder dropped on the un-flamed portion because even a slight flaming turns the Cu to CuO on which the soldering lead will not stick. If the wire is of large diameter, an oxygen-acetylene torch can be utilized as shown in Fig. 15 where a Cu earthing strip (1”X⅛”) is welded to the earth rod. A brass welding rod is used. This is much easier than using the cadweld method. Cadweld is fraught with problems because it is difficult to hold the cadweld equipment in place without falling and being an explosive, it is much harder to keep in a store or in a vehicle. And if the explosiveness is too high, it can be a safety hazard for the electrical technician. Though there is a handle on the cadweld equipment, most humans do not dare to hold it. Comparatively, with oxygen-acetylene welding, the human hand can control precisely the portions being welded with their hands.

Fig. 13

Fig. 13 depicts the measurement of heat in the steel pipe with 60psi air blowing within the pipe. Fig. 16 is the experiment to try to drain off some of the eddy current generated in the steel pipe. The steel pipe was made part of the L circuit to light up an incandescent bulb. The result in Fig.17 shows that there is no significant difference. Therefore, eddy current cannot be drained out in this way. That was a 24V bulb, later a 240V, 100W bulb was used and the result also shows no significant difference in the heat measured.

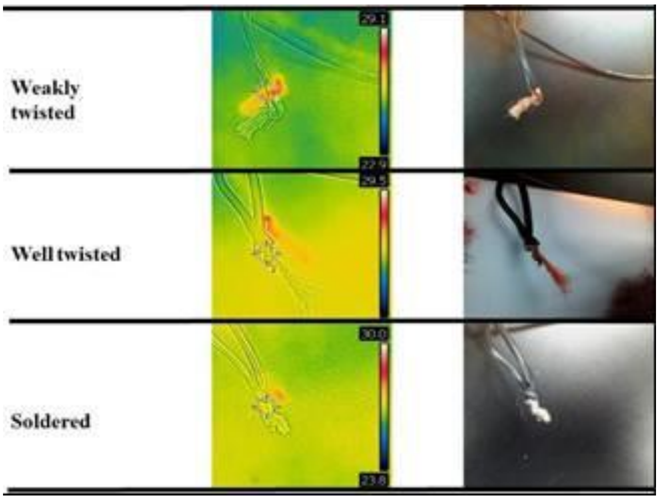


Fig. 14

Fig. 14 depicts the heat signature in weakly twisted joint, a well twisted joint and a soldered joint.

Fig. 15

Fig. 15 depicts the oxygen-acetylene joining of earth rod to Cu earthing strip using brass welding rods.

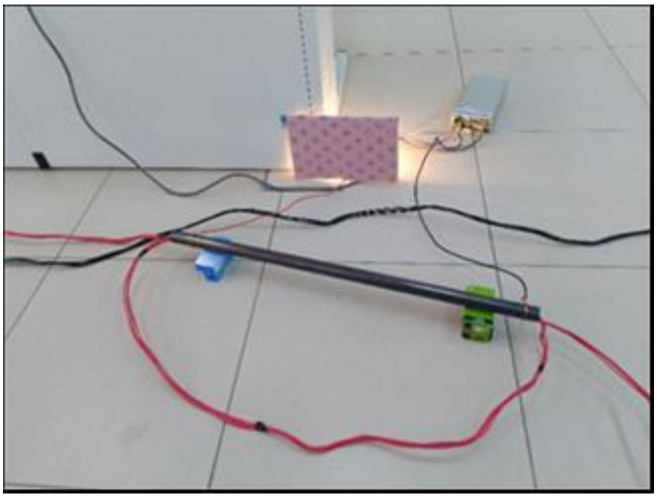


Fig. 16

Fig. 16 depicts an incandescent bulb load was connected across the steel pipe to drain off the eddy current

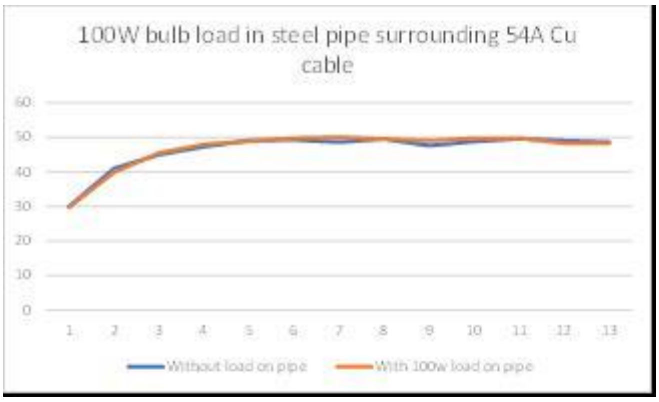


Fig. 17

Fig. 17 depicts the comparison of heat on steel pipe with a 100W bulb load and without on the steep pipe.

4. Conclusion

The many experiments done in this research conclusively proves that when a current carrying conductor whose current carrying capacity is higher than the current it is carrying, is suspended in a steel pipe, the main heat generated on the steel pipe is from eddy current and not joule heating. In fact, the joule heating is almost negligible as shown in Fig. 4 left setup. The student was purposely asked to point to it or else the infrared image could be lost due it having the same temperature as ambient. In this pipe there are four L and four N 2.5mm^2 wires carrying a total of 108A. The superimposition of the electric waves in L and N nullifies the generation of eddy current. This is compared to very hot temperatures in the right setup of Fig. 4 where eight L wires are within the steel pipe carrying 108A. If joule heating was the cause of the heat why are the two pipes not having the same heat? Both have eight 2.5mm^2 wires and both are carrying 108A of current.

The other method used to negate eddy current was to place the current carrying cable in a HDPE pipe in which eddy current cannot be induced. Fig. 11 shows that the HDPE pipe had just slightly above ambient temperature with 54A running in the cable suspended in the center.

Heat was also observed all over the circuit and it was discovered that joints which were not soldered had the maximum heat. The final test was to proof a hypothesis that if the steel pipe surrounding a copper cable carrying 54A was made part of another circuit, the eddy current could be drained off from the steel pipe, but the results proved that this was not the case as shown by the Fig. 17.

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