DESIGN OPTIMISATION OF BARE CONDUCTORS FOR OVERHEAD LINE APPLICATIONS

by

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PREFACE

The work described in this dissertation was carried out through the School of Electrical, Electronic and Computer Engineering, University of KwaZulu-Natal (UKZN) Durban, from January 2008 to December 2009, under the supervision of Professor N.M Ijumba (UKZN-Durban) and co-supervisor Professor Dzevad Muftic (Trans African Projects-Eskom-Johannesburg).

These studies represent original work by the author and have not otherwise been submitted in any form for any degree or diploma to any university. Where use has been made of the work of others, it is duly acknowledged in the text.

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Prof. N.M Ijumba (Supervisor)

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To my Lord and Saviour Jesus Christ, thank you for providing me with the opportunity and giving me the ability to study, as without you none of what I have accomplished would have been possible.

ABSTRACT

The South African economy is an emerging market and as such there is a continued and growing need for the efficient supply of cost effective electricity. The capital investment involved in the design, construction, installation and commissioning of overhead transmission line networks are high and so too are the subsequent maintenance and operation costs, incurred over their life cycle periods. The need to improve the electrical operating efficiency of existing and future electrical transmission networks, through the reduction of electrical losses, focused and motivated the research in this particular area.

The results and findings produced by this research study show that the magnetic induction produced by the steel core in ACSR (Aluminium conductor, steel reinforced) conductors cause in increase in the ac power losses, associated ac-dc resistance ratio and the effective ac resistance of the conductor, whilst the conductor is energised during normal operation. More specifically, the key parameters that cause this increase in the effective ac resistance of the conductor, as a result of the magnetic induction produced by the steel core, are those of hysterisis and eddy current power losses in the steel core and an added power loss caused by the non-uniform redistribution of current in the layers of aluminum wires, due to the ‘transformer effect’. Therefore the addition of the conductor dc resistance value to the component resistances produced by the current redistribution and magnetic hysterisis & eddy current power losses, form the total effective ac conductor resistance. This is contrary to standard practice where assumption is made that the conductor ac and dc resistance values are equal.

The factors which influence the magnetic induction, include amongst others; the ferro-magnetic properties of the steel core, the physical construction of the conductor, the conductor operating/core temperature and the load current. In order to calculate the effective ac-resistance of multi-layer ACSR conductors a computer simulation program was developed, which was largely based on determining the impact of varying these key factors, by evaluating its effect on the ac resistance of the conductor. It was found through manipulation of these factors that the total effective ac resistance of the conductor could be reduced and significantly so with higher load currents. The conductor sample used in this research study is commonly known as TERN ACSR conductor in the South African market and it was shown that with practical changes in lay ratios or lay lengths, one is able to reduce the total effective ac resistance of the conductor and associated power losses.

Several software simulation exercises were performed using the developed software simulation program, to ultimately produce a set of optimised lay-lengths (lay-ratios) for the TERN ACSR conductor, with the intention that these simulated parameters would be employed in the production of actual conductor samples. The intention going forward after the planned production trial runs would be to test these conductor samples to verify compliance, in meeting both electrical and mechanical performance requirements.

It should be noted that the planned production trials and relevant conductor-testing processes did not form part of the scope of this research report but are processes that have been planned for in the near future. Although testing to IEC 61089 are post processes that are planned for outside of this research scope, the specification requirements of IEC61089 were incorporated into the various computer simulation exercises.

CONTENTS

1. INTRODUCTION

1.1 Background

The use of aluminium conductors, steel reinforced (i.e. ACSR) for transmission and distribution networks, were first introduced by Alcoa in 1909. The use of copper for overhead transmission line constructions are slowly diminishing because the use of aluminium for such applications offers many more advantages over copper [1]. The determination of accurate values of effective ac resistance of ACSR conductors is primarily important for two key reasons i.e.

1. To determine the current carrying capacity of ACSR conductors and
2. To determine the electrical losses that ACSR conductors will produce whilst in normal operation at varying load currents and conductor operating temperatures.

The key differentiator between All Aluminium Conductors (AAC), All Aluminium Alloy Conductors (AAAC) and ACSR conductors, which are also used quite extensively for overhead transmission and distribution line applications, is the presence of a steel core in ACSR conductors. The steel core provides the added advantage of mechanical strength to the conductor but this also has consequential effects on its electrical characteristics.

The magnetic induction produced by the steel core in ACSR (Aluminium conductor steel reinforced) conductors is the cause of ac power losses, the associated ac-dc resistance ratio and the effective ac resistance of the conductor, whilst the conductor is energised during normal operation. More specifically, the key parameters that cause this increase in the effective ac resistance of the conductor, as a result of the magnetic induction produced by the steel core, are those of hysterisis and eddy current power losses in the steel core and an added power loss caused by the non-uniform redistribution of current in the layers of aluminum wires, due to the ‘transformer effect’ [2]. Therefore the addition of the conductor dc resistance value to the component resistances produced by the current redistribution and magnetic hysterisis & eddy current power losses, form the total effective ac conductor resistance. This is contrary to standard practice where assumption is made that the conductor ac and dc resistance values are equal [3].

The factors which influence the magnetic induction, include amongst others; the ferro-magnetic properties of the steel core, the physical construction of the conductor, the conductor operating/core temperature and the load current [3].

1.2 Motivation for the research

The global demand for electric power continues to grow daily and the demand for electricity far exceeds supply [4], thus making it essential to supply electricity effectively and efficiently.

Within the African continent it is evident that the South African economy is the fastest growing emerging market [5] and as such there is a continued and growing need for the efficient supply of cost-effective electricity. The capital investment involved in the design, construction, installation and commissioning of overhead transmission and/or distribution line networks are high and so too are the subsequent maintenance and service operation costs incurred over their life cycle periods. Therefore the motivation behind the selection of this research area was to investigate a means that would improve the electrical operating efficiency of existing and future Electrical Transmission networks through the reduction of electrical losses and financial savings as a result thereof. Cost savings realised through the reduction of electrical losses will assist in supplying more cost-effective electricity, which is essential in assisting an economy to grow and strengthen.

1.3 Primary Research Objectives

The primary objective of this research study was aimed at investigating a technique of optimising ACSR conductor lay-lengths to reduce electrical losses experienced by ACSR conductors, in order to optimise the electrical performance characteristics of bare ACSR conductors, in overhead line applications.

The hypothesis in carrying out this study was: The variation of stranding lay-lengths (i.e. pitch) will result in optimised service operation of multi-layered ACSR overhead-line conductors (Aluminium Conductor Steel Reinforced), through reduced power losses, in comparison to that, which would otherwise be experienced with the use of current conventional ACSR conductor lay-length constructions/designs.

The specific outcomes of this research study were to determine whether the effective ac resistance, ac-dc resistance ratio and ac power losses of overhead ACSR conductors could be reduced by varying the lay ratios or lay lengths, of the non-ferrous/metallic layers of aluminium wires that make up the ACSR conductor.

1.4 Research Methodology

In order to determine and test the specific outcomes of this research study (i.e. evaluation of effective ac resistance, ac-dc resistance ratio and ac power losses of overhead ACSR conductors), a suitable research and analysis tool needed to be identified/developed. Having identified that there are several variables (i.e. the ferro-magnetic properties of the steel-core, the physical construction of the conductor, the conductor operating/core temperature, the load current and the electrical system frequency) that interact simultaneously with lay-length variations to alter the effective ac resistance of the conductor, it was decided that the most effective research tool would be to develop a computer simulation program to perform and compute the outputs of these complex interactions.

Through in-depth literature review it was identified that the most suitable theoretical model on which to base and develop the computer simulation model, bearing in mind the primary research objectives, was the **Electromagnetic Model** as presented by Morgan and Price [6] and Barrett, Nigol, Fehervari & Findlay [7].

The selected theoretical model [7] was then used as a basis to develop the computer software simulation program, using MATCAD 13 ® as the programming software. Several software simulation exercises were performed for a set of varied scenarios (described fully in Chapter 4). Using the developed software simulation program, a proposed set of optimised lay-lengths (lay-ratios) for the identified ACSR conductor research sample, was developed. The scenarios for which each of the computer simulations were performed, simulated what one could expect primarily in terms of electrical losses as a result of effective ac resistance variations, by changing or varying the lay ratios or lay lengths, of the non-ferrous/metallic layers of aluminium wires that make up the ACSR conductor. At the same time the behaviour of other critical parameters (i.e. magnetic induction, magnetic field strength and current re-distribution factors [i.e. ac-dc resistance ratio]) were noted and assessed for both cases of current lay-lengths versus optimised lay-lengths, for the identified ACSR conductor research sample.

1.5 Research Scope

In order to determine the specific outcomes of this research study as described in 1.3 above, a single ACSR conductor type needed to be identified on which the relevant research could be conducted. The conductor type which this research study was based on, is commercially known as ***TERN ACSR*** Conductor within the South African market and is manufactured to the IEC 61089 [8] conductor specification (i.e. International Electrical Committee - “Round wire concentric lay overhead electrical stranded conductors”).

This research study was conducted jointly between the conductor manufacturer **(Aberdare Cables Pty. Ltd.)** and the industrial end-user **(Eskom Pty. Ltd.)** who both shared mutual interest in this research area. With the research being focused on yielding benefits in the short term, the approach to selecting the identified research sample (i.e. TERN ACSR Conductor) was based on identifying which conductor type has been and will most be used by Eskom Pty. Ltd. in their existing and future infrastructure development. All presented analysis and recommendations are based on the assessment of this specific conductor type within this research report.

This research study was aimed at investigating the technique of optimising ACSR conductor lay-lengths to reduce electrical losses experienced by ACSR conductors to improve its electrical performance characteristics. Several software simulation exercises were performed using the developed software simulation program (Refer 1.4), to determine a set of optimised lay-lengths (lay-ratios) for the TERN research conductor sample. To this end, the research conducted lead to a proposal of optimised lay-lengths for the research conductor sample and a summary of potential savings in electrical losses that could be obtained should the conventional lay-lengths be changed to the optimized lay-lengths as generated by the computer simulation program.

The intention when going forward will be to use these optimised lay-lengths in the production of actual conductor samples. Thereafter to test these conductor samples to verify compliance, in meeting both electrical and mechanical performance requirements.

It should be noted that the planned production trials and relevant conductor testing processes did not form part of the scope of this research report but are processes that have been planned for in the near future. Although testing to IEC 61089 are post processes that are planned for outside of this research scope, the specification requirements of IEC61089 were incorporated into the various computer simulation exercises.

1.6 Post Research Objectives

Using the developed software simulation program (i.e. the research tool) that defines and computes the interactions between lay-length (lay-ratio) variations and its impact on ac resistance for multi-layered ACSR conductors, one is able to quite accurately predict the expected electrical power losses based on the total effective ac resistance of the conductor.

Having developed a proposal that specifies optimal lay-lengths, for the TERN ACSR conductor sample, the post research objective will be the manufacturing of a TERN ACSR type conductor using these optimised production lay-lengths. To this end and based on the research findings contained in this research report, Aberdare Cables Pty Ltd. has initiated a development project aimed at trial production/manufacturing runs and testing of the TERN ACSR conductor samples **(Refer to Appendix C - PACE Project number: 00412).** The aim of this process will be to validate the projected/simulated savings in terms of electrical losses and the calculated reduction in ac resistance.

On successful validation, the intention is to optimise the lay-lengths of all other ACSR conductors manufactured by Aberdare Cables Pty. Ltd. with the use of the developed software simulation program. The factory trial and testing processes, as will be applied to the TERN conductor research sample, would then be employed for each ACSR conductor identified for lay-length optimisation.

1.7 Definition of Key Terms

1.7.1 **ACSR Cable/Conductors – "Aluminium Conductor Steel Reinforced** (or **ACSR**) cable is a specific type of high-capacity, high-strength stranded cable used in overhead power lines. The outer strands are aluminum, chosen for its excellent conductivity, low weight, and low cost. The centre strand is of steel, providing extra strength" [9].

1.7.2 **Lay-length – "**The axial length of one complete turn of the helix formed by an individual wire in a stranded conductor" [8].

1.7.3 **Lay-ratio – "**Means the ratio of the lay-length to the external diameter of the corresponding layer of wires in the stranded conductor" [8].

1.7.4 **ac-dc ratio –** Means the ratio of the ac resistance of the conductor to its dc resistance value.

1.7.5 **Concentric lay stranded conductor –** “A conductor composed of a central core surrounded by one or more adjacent layers of wires being laid helically in opposite direction” [8].

1.7.6 **Magnetic field strength –** “that part of the magnetic induction that is determined at any point in space by the current density and displacement current at that point independently of the magnetic or other physical properties of the surrounding medium. Symbol: H ” [10].

1.7.7 **Magnetic flux-density/induction** – “Represented by the Greek letter Φ (phi), is a measure of quantity of magnetism, taking into account the strength and the extent of a magnetic field. The SI unit of magnetic flux is the weber (in derived units: volt-seconds), and the unit of magnetic field is the weber per square meter, or tesla.” [11].

1.7.8 **Electrical resistance** – “a material's opposition to the flow of electric current; measured in ohms.” [12].

1.7.9 **Transformer Effect –** “The transformer effect, or mutual induction, is one of the processes by which an electromotive force (e.m.f.) is induced. In a transformer, a changing electric current in a primary coil creates a changing magnetic field that induces a current in a secondary coil” [2].

2. LITERATURE REVIEW: SUMMARY

The primary objective of this research study was to investigate the use of lay-length variations to reduce electrical power losses yielded by ACSR conductors, by reducing its effective ac resistance and associated ac-dc resistance ratio. The approach taken in realising this objective was firstly to perform an intensive study of existing literature based on or related to the optimisation of electrical performance characteristics of ACSR overhead conductors. The intention behind the literature study was to evaluate a suitable method/model/technique that effectively dealt with reducing electrical losses experienced by ACSR conductors through lay-length variations and to gain an in-depth knowledge in the subject area.

The skin effect [13], [14], [15], [16] and proximity effect [17], [15] are the 2 key phenomena that influence the current density redistribution in non-metallic conductors and are dependant on system operating frequency. Typical increases in the ac-dc resistance ratio are in the range of less than 5 percent, when the spacing between conductors is ten times greater than its diameter and operated at system frequency [17].

The vast majority of conductors used for overhead transmission and distribution lines are of the ACSR type (Aluminium conductor, steel reinforced), where the stranded steel core provides the mechanical strength of the conductor and the non-ferrous/metallic layers of aluminium wires provide the path of electrical conductance. Longitudinal flux is produced in the steel core due to the spiraling effect of the currents in the different layers of aluminium. The magnetic field strength and permeability of the stranded steel core are factors that determine the magnitude of the steel core longitudinal flux. This in translation implies that the longitudinal flux depends on the magnitude of the aluminium layer currents and the geometric construction of the conductor (i.e. its lay-length). In an effort to reduce this longitudinal flux, the conductor is manufactured with the different layers of aluminium being laid in opposite directions to the layer below it [18].

However, during the manufacturing of the conductor, the lay-lengths of the aluminium layers of wires are not optimal and this results in a ‘residual flux’ in the steel core, which generates power losses, due to hysterisis and eddy currents which circulate in the steel core [19], [20].

Although it has been measured and practically shown that the effective ac resistance of ACSR conductors increase with increasing load currents [21], [22], many authors could not provide the exact reasoning for it although many attempts were made to do so. Initial analyses attempted to evaluate consider the impact of hysteresis and eddy currents in the steel core as well skin-effect [23], [24], [22] while later studies used equivalent circuits to simulate the effects of the steel core [25], [26], but such simulations/studies were not very effective as they did not establish a relationship between the core losses and the steel core itself.

Morgan, V. T. & Price, C. F. [6] established the first model that developed and interpreted the relationships between longitudinal & circular fluxes and how they interacted with the different layer inductances and resistivity, by way of expressing the layer currents in complex notation. The short coming of this model, however, was that the magnetic loss angles and permeability of the steel core were not expressed in the same format as that of the complex value layer currents [6]. Barrett et al [7] later corrected this model developed by Morgan and Price, by introducing and showing that through the ‘transformer effect’ mutual and self inductances are produced in the aluminium layers and that these inductances bring about a redistribution of the current through the various layers of aluminium wires making up the ACSR conductor, as they are increased .

The paper by Barrett et al [7] also showed that “the measured ac resistance of ACSR conductors sometimes exceeds values calculated by traditional methods” and that “three layer conductors were specifically identified as having ac-dc ratios up to three percent higher than the calculated values”. Therefore the addition of the conductor dc resistance value to the component resistances produced by the current redistribution and magnetic hysterisis & eddy current power losses, form the total effective ac conductor resistance. With transmission lines having a life expectancy of +/-50 years, this increase in ac resistance becomes very significant when one takes into consideration the cumulative losses that are incurred as a result of this increase in ac resistance [7].

The later paper by Morgan and Price [6], which was based on the ‘corrected’ model developed by Barrett et al [7], aimed to examine the effect of core temperature and total load current on the ac-dc resistance ratio, the magnetic power loss in the core and the power losses caused by the redistribution of the aluminium layer currents, for a 3 layer ACSR conductor.

It was experimentally shown by Morgan and Price [6], “that the modulus, real and imaginary parts of the permeability, for a three-layer Grackle ACSR, all increase with increasing magnetic field strength at constant tensile stress and constant temperature, up to maximum values of about 2000 A/m, and then decrease as the saturation of the steel sets in. It was also found that, with constant temperature and tensile stress, the core loss increases with 1.83 x the power of the magnetic induction”.

Morgan and Price [6] also show experimentally that “the distribution of the current density in the middle layer is about 30% greater than those in the inner and outer layers for a Grackle ACSR conductor at 1608 A, 20°C and 300 MPa core stress”, which also shows agreement to the work performed by Barrett et al [7] where the “average current density was 2.65 A/mm^2 with the steel core conducting only about 2% of the total current”. This is indicative of the impact that the “transformer-effect” and “skin-effect” have on the individual wires within the different layers aluminium of wires.

It was also experimentally shown that the density of the current in the middle layer of aluminium wires increased, while that of the density of the current in the outer and inner layers of aluminium wires decreased, as the temperature was gradually increased between 25 to 120 degrees celcius, with 300MPa steel core stress at a load current of 1608 amps [6].

The experimental work performed by Morgan and Price, to evaluate the effect of load current on the total effective ac resistance of a three layered ACSR conductor (Grackle ACSR), showed that at a load current of 1800A and with the conductor steel core at 290MPa stress and 25°C, that the increase of the ac-dc resistance ratio of by 9.1 percent resulted, with the core loss component contributing to 2.3 percent, while 6.8 percent was attributed to the transformer effect. This invariably showed that the increase in the ac-dc resistance ratio was proportional to an increase in load current.

Therefore the key relationships depicted by Morgan’s experimental work [6], to examine the effect of core temperature and total load current on the ac-dc resistance ratio, the magnetic power loss in the core and the power losses caused by the redistribution of the aluminium layer currents, for a 3 layer ACSR conductor can be summarized as:

1. The ac-dc resistance ratio and the associated ac power loss both increased with increasing load current and 2. Increasing the core temperature causes a redistribution of the current density between the 3 layers of aluminium wires which results in a further power loss.

3. THE COMPUTER SIMULATION MODEL

3.1 Introduction

In order to determine and test the specific outcomes of this research study (i.e. evaluation of effective ac resistance, ac-dc resistance ratio and ac power losses of overhead ACSR conductors) a suitable research and analysis tool needed to be developed. Having identified that there are several variables (i.e. the ferro-magnetic properties of the steel core, the physical construction of the conductor, the conductor operating/core temperature, the load current and the electrical system frequency) that interact simultaneously with lay-length variations, to alter the effective ac resistance of the conductor, it was decided that the most effective research tool would be to develop a computer simulation program to perform and compute the outputs of these complex interactions.

Through in-depth literature review it was identified that the most suitable theoretical model on which to base and develop the computer simulation model, bearing in mind the primary research objectives, was the 'Electromagnetic Model' as presented by Morgan and Price [6] and Barrett et al [7], where it is shown in the model to include "the ferromagnetic power loss in the steel core and the redistribution of current due to the transformer effect. Input variables are the geometry of the conductor, the electrical and magnetic properties of the ferrous and nonferrous materials, the total current and the temperature and the output variables are the complex layer currents, the power loss and the ac resistance".

It is on this model that the computer software simulation program was developed, using MATCAD 13 ® as the programming software. Several software simulation exercises were performed for a set of varied scenarios (described fully in Chapter 4). Using the developed software simulation program, a proposed set of optimised lay lengths (lay-ratios) for the identified TERN ACSR conductor (i.e. the research sample) was produced. The scenarios for which each of the computer simulations were performed, simulated what one could expect primarily in terms of electrical losses as a result of effective ac resistance variations, by changing the aluminium wire lay-lengths of the different layers of aluminium wires making up the conductor. Concurrently the behaviour of other critical parameters (i.e. magnetic induction, magnetic field strength and current re-distribution factors [i.e. ac-dc resistance ratio]) were noted and assessed for both cases of current lay-lengths versus optimised lay-lengths, for the identified TERN ACSR conductor research sample.

3.2 Background

The conventional method employed in calculating the effective ac resistance of ACSR conductors is to experimentally determine and apply the magnetic losses (i.e. eddy-current and hysteresis losses) together with the skin-effect as a correction factor to the actual dc resistance of the conductor [7]. The very first models employed the use of equivalent transformer circuits to evaluate the impact of core losses but were inadequate in a sense that they did not specifically account for these losses. The 'equivalent resistance method' did not associate the core losses with the specific layers of aluminum and 'the correction method' did not cater for the effect that the core losses have on the current redistribution through the various layers of aluminum [7].

In the model presented by Barrette et al, the core losses of the steel core are represented by means of complex permeability values which ensured that the core losses have an impact on the current redistribution in the layers of aluminium and while at the same time are correctly related to the steel core. The key differentiation between the models presented/developed by Barrett et al [7] to that of Morgan and Price [6], comes from the use of complex permeability values for the core losses and the determination of layer inductances through an alternative method of calculation. The density of the current in the different layers of aluminium wires is calculated from the center of the layer whilst the surface current density is assumed as constant in determining the steel core current.

The model presented by Barrett et al [7], calculates the magnetic field strength in the steel core, by assuming that assuming that the entire load current flows through helical pathways of the aluminium wires.

3.3 Data Inputs and Outputs

The computer simulation program was developed and written using MATCAD 13 ® and based on the electromagnetic model as presented by Barrett et al [5]. The computer simulation model proved to be a useful design tool in terms of processing these input and output parameters.

Displayed below in 3.3.1 are typical input data and simulated output data for an *example* simulation scenario. The simulated data outputs are produced through mathematical processing of the input values through a series of matrices and formulae.

EXAMPLE SCENARIO – TERN ACSR Conductor with original lay-lengths @ 600A Load Current

3.3.1 General Input Data

$\mathbf{tc} = 75$ - Core Temperature (Degrees Celcius)

$\mathbf{Itot} = 600$ - Total load Current (A)

$\mathbf{f} := 50$ - frequency

$\mu_0 := 4 \cdot \pi \cdot 10^{-(7)}$ - magnetic permeability of the air

$\rho\,\mathbf{st} := 0.1775 \quad \dfrac{\mathbf{\Omega \cdot mm^2}}{\mathbf{m}}$ - specific resistance of steel, Code 1

$\alpha\,\mathbf{st} := 0.00393 \quad \dfrac{1}{\mathbf{deg_C}}$ - temperature coefficient of steel

$\rho\,\mathbf{aal} := 0.0327 \quad \dfrac{\mathbf{\Omega \cdot mm^2}}{\mathbf{m}}$ - specific resistance of alloy, Code 2

$\alpha\,\mathbf{aal} := 0.00360 \quad \dfrac{1}{\mathbf{deg_C}}$ - temperature coefficient of alloy

$\rho\,\mathbf{al} := 0.028126 \quad \dfrac{\mathbf{\Omega \cdot mm^2}}{\mathbf{m}}$ - specific resistance of aluminium, Code 3

$\alpha\,\mathbf{al} := 0.00404 \quad \dfrac{1}{\mathbf{deg_C}}$ - temperature coefficient of aluminium

$\mathbf{Nls} := 2$ - number of steel layers

$\mathbf{Nlaa} := 0$ - number of alloy layers

$\mathbf{Nla} := 3$ - number of aluminium layers

$\mathbf{Nl} := \mathbf{Nls} + \mathbf{Nlaa} + \mathbf{Nla} \qquad \mathbf{Nl} = 5$ - total number of layers

$\mathbf{Mc}_0 := 1$	- material code of 1st layer (first wire in centre assumed as 1st layer)
$\mathbf{nw}_0 := 1 \quad \mathbf{dw}_0 := 2.25$	- number and diameter (mm) of wires in 1st layer
$\mathbf{Layratio}_0 := 0$	- lay ratio of 1st layer
$\mathbf{Mc}_1 := 1$	- material code of 2nd layer
$\mathbf{nw}_1 := 6 \quad \mathbf{dw}_1 := 2.25$	- number and diameter (mm) of wires in 2nd layer
$\mathbf{Layratio}_1 := 16.44$	- lay ratio of 2nd layer
$\mathbf{Mc}_2 := 3$	- material code of 3rd layer
$\mathbf{nw}_2 := 9 \quad \mathbf{dw}_2 := 3.38$	- number and diameter (mm) of wires in 3rd layer
$\mathbf{Layratio}_2 := 13.54$	- lay ratio of 3rd layer
$\mathbf{Mc}_3 := 3$	- material code of 4th layer
$\mathbf{nw}_3 := 15 \quad \mathbf{dw}_3 := 3.38$	- number and diameter (mm) of wires in 4th layer
$\mathbf{Layratio}_3 := 11.85$	- lay ratio of 4th layer
$\mathbf{Mc}_4 := 3$	- material code of 5th layer
$\mathbf{nw}_4 := 21 \quad \mathbf{dw}_4 := 3.38$	- number and diameter (mm) of wires in 5th layer
$\mathbf{Layratio}_4 := 10.74$	- lay ratio of 5th layer

$\mathbf{Layratio}_0 := 0$	- lay ratio of 1st layer (First straight wire in the centre is assumed as the 1st layer)
$\mathbf{Layratio}_1 := 16.44$	- lay ratio of 2nd layer
$\mathbf{Layratio}_2 := 13.54$	- lay ratio of 3rd layer
$\mathbf{Layratio}_3 := 11.85$	- lay ratio of 4th layer
$\mathbf{Layratio}_4 := 10.74$	- lay ratio of 5th layer

3.3.2 General Output Data

$$\mathbf{i} = \begin{pmatrix} 0.242 \\ 0.255 \\ 1.451 \\ 1.525 \\ 1.44 \end{pmatrix}$$

- ac current density (A/mm^2) per layer

$$\boldsymbol{\lambda} = \begin{pmatrix} 0 \\ 110.97 \\ 182.925 \\ 240.2 \\ 290.302 \end{pmatrix}$$

- lay length (mm) per layer:

$\mathbf{Bm} = 0.108$ - Magnetic flux density / magnetic induction (T/m)

$\mathbf{H} = 727.724$ - Magnetic field strength (A/m)

$\mathbf{kred} = 1.008$ - ac-dc ratio (Current redistribution factor)

$\mathbf{\Delta R} = 2.575\times 10^{-7}$ - Magnetic Resistance (Ω/m)

$\mathbf{Rcon} = 8.639\times 10^{-5}$ - Total dc resistance of conductor (Ω/m)

$\mathbf{Rac} = 8.704\times 10^{-5}$ - Total ac resistance (Ω/m)

$\mathbf{Pmagnetic} = 0.093$ - Magnetic Loss Component (W/m)- (Core losses as a result of Hysterisis & Eddy Currents)

$\mathbf{Itot}^2\,\mathbf{Rac} = 31.334$ - ac Resistance loss Component (W/m)

$\mathbf{Itot}^2\,\mathbf{Rcon} = 31.099$ - dc Resistance loss Component (W/m)

The detailed results of key computer simulated scenarios and analysis thereof, as presented in Chapter 4, are based on the determination of these key output variables for each scenario. Determination of the set of optimised lay-lengths was based on firstly adhering to the lay-ratio constraints as detailed in IEC 61089 [8] (i.e. International Electrical Committee – "Round wire concentric lay overhead electrical stranded conductors") and secondly, within these constraints, to determine the combination of lay-lengths that would yield the highest reduction in terms of the Magnetic field strength (H), Magnetic resistance (ΔR) & Magnetic Core losses (Pmagnetic).

4. RESULTS AND FINDINGS

4.1 Introduction

The factors which influence the magnetic induction, include amongst others; the ferro-magnetic properties of the steel core, the physical construction of the conductor, the conductor operating/core temperature, the load current and system frequency. In order to calculate the effective ac-resistance of multi-layer ACSR conductors a computer simulation program was developed, which was largely based on determining the impact of varying these key factors, by evaluating its effect on the ac resistance of the conductor. It should be noted that although this research dissertation was based on the study of a single type of ACSR conductor (i.e. TERN ACSR with 3 layers of aluminium), the computer simulation program that has been written, caters for the simulation of the identified data outputs (Refer 3.3.2), for a range of ACSR conductor types with 1 to 5 layers of aluminium.

The primary objective of this research study was aimed at investigating the technique of optimising ACSR conductor lay-lengths to reduce electrical losses experienced by ACSR conductors in order to optimise the electrical performance characteristics of bare ACSR conductors in overhead line applications.

The specific outcomes of this research study were to determine whether ac power losses, associated ac-dc resistance ratio and the effective ac resistance of the conductor could be reduced by varying the lay ratios or lay lengths, of the non-ferrous/metallic layers of aluminium wires that make up the ACSR conductor.

The magnetic induction produced by the steel core in ACSR (Aluminium conductor, steel reinforced) conductors cause in increase in the ac resistance, ac-dc resistance ratio and the associated ac power loss of the conductor, whilst the conductor is energised during normal operation. More specifically, the key parameters that cause this increase in the effective ac resistance of the conductor, as a result of the magnetic induction produced by the steel core, are those of hysterisis and eddy current power losses in the steel core and an added power loss caused by the non-uniform redistribution of current in the layers of aluminum wires, due to the ‘transformer effect’ [2]. Therefore the addition of the conductor dc resistance value to the component resistances produced by the current redistribution and magnetic hysterisis & eddy current power losses, form the total effective ac conductor resistance.

4.2 Analysis

This research study was aimed at investigating the technique of optimising ACSR conductor lay-lengths to reduce electrical losses experienced by ACSR conductors, with the primary aim of optimising the electrical performance characteristics of bare ACSR conductors, in overhead line applications

In order to determine and test the specific outcomes of this research study (i.e. evaluation of effective ac resistance, ac-dc resistance ratio and ac power losses of overhead ACSR conductors), a suitable research and analysis tool needed to be identified/developed. Having identified that there are several variables (i.e. the ferro-magnetic properties of the steel core, the physical construction of the conductor, the conductor operating/core temperature, the load current and the electrical system frequency) that interact simultaneously with lay-length variations to alter the effective ac resistance of the conductor, it was decided that the most effective research tool would be to develop a computer simulation program to perform and compute the outputs of these complex interactions.

Having developed a reliable computer simulation program to test the outcomes of lay-length variations, a suitable ACSR conductor type needed to be selected as the research study sample. The conductor type which this research study was based on is commercially known as ***TERN ACSR.*** Figure 4.1 below is a ***GRACKLE*** ACSR conductor and is similar to the ***TERN*** ACSR conductor construction, except that the GRACKLE conductor as a 19 wire steel core. However the behaviour of the longitudinal and circular fluxes is similar.

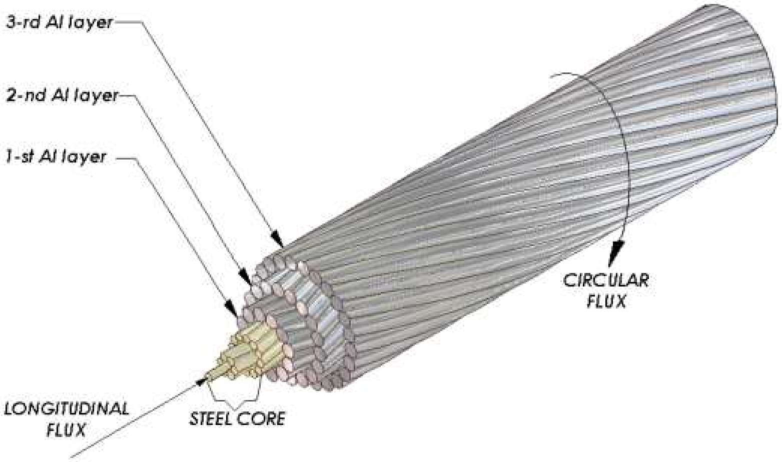


Figure 4.1 - GRACKLE ACSR– Showing Longitudinal and Circular Flux paths

All the presented analysis and recommendations are based on the assessment of the TERN ACSR conductor type within this research report – a diagrammatic representation of which is shown in Figure 4.2 below.

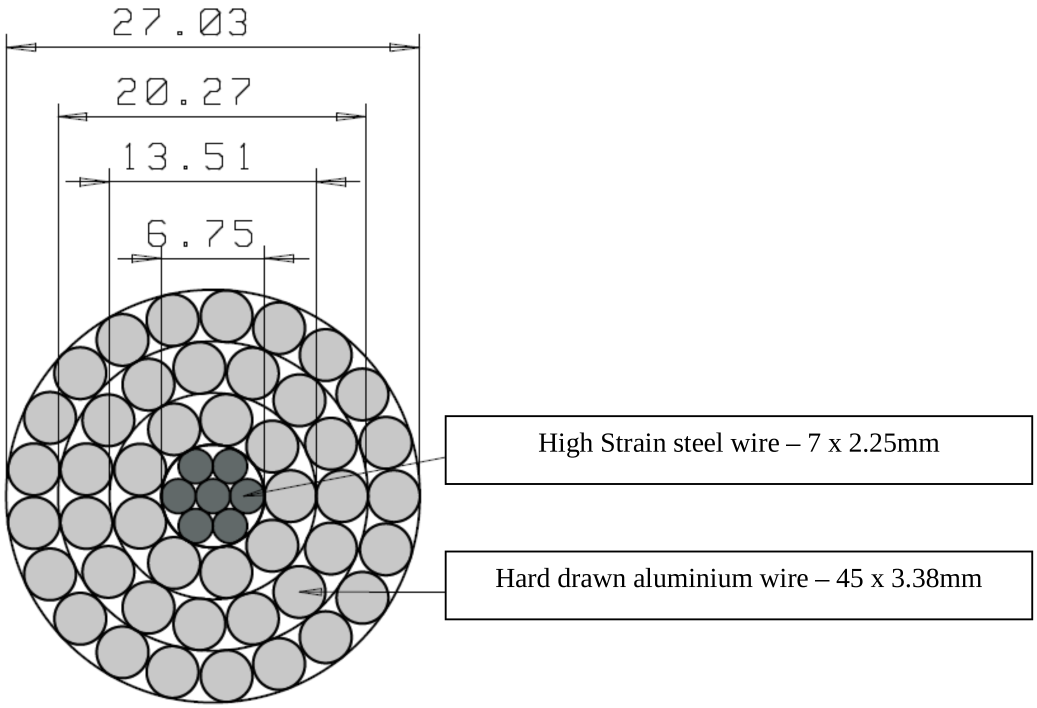


Figure 4.2 - TERN ACSR Conductor

Using the developed software simulation program, several software simulation exercises were performed for a set of varied scenarios to ultimately produce a proposed set of optimised lay-lengths/lay-ratios for the identified ACSR research conductor sample (i.e. TERN ACSR). The scenarios for which each of the computer simulations were performed, simulated what one could expect primarily in terms of electrical losses as a result of effective ac resistance variations, by changing the lay-lengths of the aluminium wires within each layer of aluminium wires making up the ACSR conductor. At the same time the behaviour of other critical parameters (i.e. magnetic induction, magnetic field strength and current re-distribution factors [i.e. ac-dc resistance ratio]) were noted and assessed for both cases of current lay-lengths versus optimised lay-lengths, for the identified ACSR conductor research sample.

The approach taken in performing this research study was to:

a) Identify the scenarios for which the computer simulations would be conducted and
b) To determine the output variables on which to base the required analysis on for each of the simulated scenarios.

In establishing the requirements of a) above, it was firstly required that a set of optimised lay-lengths be determined whilst adhering to the lay-ratio constraints as detailed in IEC 61089 [8] and secondly, within these constraints, to determine the combination of lay-lengths that would yield the highest reduction in terms of the Magnetic field strength (H), Magnetic resistance (ΔR) & Magnetic Core losses (Pmagnetic) at maximum rated load current of 875A and constant core temperature of 75 degrees Celcius. After the determination of what would be the optimised lay-lengths for the TERN ACSR conductor, comparison would be performed against the TERN ACSR with current lay-lengths, in a bid to establish the possible savings in terms of wattage losses as a result of the reduced ac resistance of the conductor.

In establishing the requirements of b) above, the research objectives were noted and invariably determined the key data outputs which are reflected in Table 4.1 below. All computer simulation exercises performed and reflected in this research study, are displayed in this format.

Output Data Fields	**Description of Output Data Fields**
Bm	Magnetic Flux density / Magnetic Induction (T/m)
H	Magnetic field strength (A/m)
Kred	AC-DC ratio (Current redistribution factor)
ΔR	Magnetic Resistance (Ω/m)
Rcon	Total DC resistance of the conductor (Ω/m)
Rac	Total AC resistance of the conductor (Ω/m)
Pmagnetic	Magnetic Loss Component (W/m)- CORE losses as a result of Hysteresis & Eddy Currents
$Itot^2$ Rac	AC Resistance loss Component (W/m)
$Itot^2$ Rcon	DC Resistance loss Component (W/m)

Table 4.1 – Key Output Data fields for Computer Simulation exercises

According to IEC 61089 [8], the following lay-ratio/lay-length parameters were noted and adhered to:

“5.4.4 a) The lay ratio for the 6-wire layer of the 7 and 19-wire steel cores shall be not less than 16 nor more than 26”
“5.4.5 a) The lay ratio for the outside layer of aluminium wires shall be not less than 10 nor more than 14”
“5.4.5 b) The lay ratios for the inner layers of aluminium wires shall be not less than 10 nor more than 16” and
“5.4.6 In a conductor having multiple layers of wires, the lay ratio of any layer shall be not greater than the lay ratio of the layer immediately beneath it”

Applying the above parameters as defined in IEC 61089 [8], to the particular TERN ACSR conductor sample, the maximum and minimum lay-lengths for each layer of steel and aluminium wires were calculated and reflected in Table 4.2. In order to calculate these maximum and minimum lay-lengths, the actual outer diameters for each layer of steel and aluminium were required. These layer diameters were sourced from the datasheet and design drawing of the Conductor manufacturer (Refer to Appendix A and Appendix B for Design drawing and Datasheet respectively).
The mathematical formula governing the interaction between Lay-ratio (LR), Lay-length (LL-mm) and Layer Outer Diameter (OD-mm) is given by Equation 1 below:

$$\boxed{LR=LL/OD} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{Equation 1}$$

It is important to note that the 7-wire high-strain steel inner, is a bought-in item to Aberdare Cables Pty. Ltd. and since it is not a manufactured component within the companies domain, its measured lay-length was maintained as a constant as this could not be changed through the companies manufacturing processes. It should be noted that this philosophy was maintained throughout all computer simulations performed and discussed with this research study. Therefore only changes to the lay-lengths of the aluminium wires of the different layers of aluminium making up the conductor were simulated.

Steel Reinforcement:	**7 x 2.25mm Strands (Laylength = 111mm - Bought in)**		
IEC Lay ratio (L1)	Minimum =	16	
	Maximum =	26	
Outer diameter of L1 (mm)		6.75	**(Tern Drawing / Datasheet)** **(Refer to Appendix A and B)**
Lay length (mm) (L1)	Minimum =	108	
	Maximum =	175.5	

Aluminium Conductor:	**45 x 3.38mm Strands (3 Layers - 9/15/21 wires)**		
IEC Lay ratio (L1)	Minimum =	10	
	Maximum =	16	
Outer diameter of L1 (mm)		13.51	**(Tern Drawing / Datasheet)** **(Refer to Appendix A and B)**
Lay length (mm) (L1)	Minimum =	135.1	
	Maximum =	216.16	
IEC Lay ratio (L2)	Minimum =	10	
	Maximum =	16	
Outer diameter of L2 (mm)		20.27	**(Tern Drawing / Datasheet)** **(Refer to Appendix A and B)**
Lay length (mm) (L2)	Minimum =	202.7	
	Maximum =	324.32	
IEC Lay ratio (L3)	Minimum =	10	
	Maximum =	14	
Outer diameter of L3 (mm)		27.03	**(Tern Drawing / Datasheet)** **(Refer to Appendix A and B)**
Lay length (mm) (L3)	Minimum =	270.3	
	Maximum =	378.42	

Table 4.2 – IEC 61089 maximum and minimum lay-ratios and lay-lengths as applied to and calculated for the TERN ACSR conductor sample

Since only changes to the lay-lengths of the aluminium layers were simulated, only 8 permutations existed (i.e. A – H): in terms of maximum and minimum lay-ratios, for the lay-length combinations of the 3 layers of aluminium wires making up the TERN ACSR conductor. These 8 permutations are reflected below and indicate the maximum and minimum allowable lay-ratios (as per IEC 61089 [8]), from the innermost aluminium layer to the outermost aluminium layer respectively:

A) Max lay-ratio (16), Max lay-ratio (16), Max lay-ratio (14)
B) Max lay-ratio (16), Max lay-ratio (16), Min lay-ratio (10)
C) Min lay-ratio (10), Min lay-ratio (10), Min lay-ratio (10)
D) Max lay-ratio (16), Min lay-ratio (10), Min lay-ratio (10)
E) Min lay-ratio (10), Max lay-ratio (16), Max lay-ratio (14)
F) Max lay-ratio (16), Min lay-ratio (10), Max lay-ratio (14)
G) Min lay-ratio (10), Max lay-ratio (16), Min lay-ratio (10)
H) Min lay-ratio (10), Min lay-ratio (10) Max lay-ratio (14)

When the lay-ratio parameters of IEC 61089 [8] were applied to the 8 possible permutations above, only 4 of the 8 permutations were allowable (i.e. A – D). The computer simulations that were performed to determine the optimised lay-lengths/lay-ratios were therefore simulated for these 4 scenarios and were primarily based on identifying which of these scenarios yielded the highest reduction in terms of the Magnetic field strength (H), Magnetic resistance (ΔR) & Magnetic Core losses (Pmagnetic) at maximum rated load current of 875A and at a constant core temperature of 75 Degrees Celcius. Based on these parameters, computer simulations were performed for the scenarios below (i.e. A – D), to determine the optimal lay-lengths/lay-ratios, for the TERN ACSR conductor sample:

- SCENARIO A- TERN Conductor: Max lay-ratio(16), Max lay-ratio(16), Max lay-ratio(14) at 875A Load Current
- SCENARIO B- TERN Conductor: Max lay-ratio(16), Max lay-ratio(16), Min lay-ratio(10) at 875A Load Current
- SCENARIO C- TERN Conductor: Min lay-ratio (10), Min lay-ratio(10), Min lay-ratio(10) at 875A Load Current
- SCENARIO D- TERN Conductor: Max lay-ratio(16), Min lay-ratio(10), Min lay-ratio(10) at 875A Load Current

The key output results for each of these computer simulations (i.e. for scenarios A – D described above) are shown in the proceeding Tables 4.3 – 4.6.

SUMMARY OF KEY DATA FOR
SCENARIO A - TERN Conductor: With MAX, MAX, MAX Lay-ratios at 875A Load Current

PROGRAMMATIC SIMULATION RESULTS : SCENARIO A		
Parameter	**Value**	**Description of measured Parameter**
tc	75	**Conductor Core / Operating Temperature (Degrees Celcius)**
Itot	875	**Total load Current (A)**
Bm	0.187	**Magnetic Flux density / Magnetic Induction (T/m)**
H	902.597	**Magnetic field strength (A/m)**
kred	1.009	**AC-DC ratio (Current redistribution factor)**
ΔR	3.299E-07	**Magnetic Resistance (Ω/m)**
Rcon	8.551E-05	**Total DC resistance of the conductor (Ω/m)**
Rac	8.628E-05	**Total AC resistance of the conductor (Ω/m)**
Pmagnetic	0.253	**Magnetic Loss Component (W/m)- CORE losses as a result of Hysteresis & Eddy Currents**
Itot^2 Rac	66.055	**AC Resistance loss Component (W/m)**
Itot^2 Rcon	65.467	**DC Resistance loss Component (W/m)**
Layratio 0	0	**Lay ratio of 1st layer (First straight wire in the center is assumed as the 1st layer) (Steel)**
Layratio 1	16.44	**Lay ratio of 2nd layer (Steel)**
Layratio 2	16	**Lay ratio of 3rd layer (First Aluminium Layer)**
Layratio 3	16	**Lay ratio of 4th layer (Second Aluminium Layer)**
Layratio 4	14	**Lay ratio of 5th layer (Third Aluminium Layer)**

Table 4.3 – Computer simulation results for SCENARIO A:
TERN Conductor: With MAX, MAX, MAX Lay-ratios @ 875A Load Current

SUMMARY OF KEY DATA FOR
SCENARIO B - TERN Conductor: With MAX, MAX, MIN Lay-ratios at 875A Load Current

PROGRAMMATIC SIMULATION RESULTS : SCENARIO B

Parameter	Value	Description of measured Parameter
tc	75	**Conductor Core / Operating Temperature (Degrees Celcius)**
Itot	875	**Total load Current (A)**
Bm	0.398	**Magnetic Flux density / Magnetic Induction (T/m)**
H	1313	**Magnetic field strength (A/m)**
kred	1.04	**AC-DC ratio (Current redistribution factor)**
ΔR	0.000001311	**Magnetic Resistance (Ω/m)**
Rcon	8.620E-05	**Total DC resistance of the conductor (Ω/m)**
Rac	8.961E-05	**Total AC resistance of the conductor (Ω/m)**
Pmagnetic	1.003	**Magnetic Loss Component (W/m)- CORE losses as a result of Hysteresis & Eddy Currents**
Itot^2 Rac	68.611	**AC Resistance loss Component (W/m)**
Itot^2 Rcon	65.994	**DC Resistance loss Component (W/m)**
Layratio 0	0	**Lay ratio of 1st layer (First straight wire in the center is assumed as the 1st layer) (Steel)**
Layratio 1	16.44	**Lay ratio of 2nd layer (Steel)**
Layratio 2	16	**Lay ratio of 3rd layer (First Aluminium Layer)**
Layratio 3	16	**Lay ratio of 4th layer (Second Aluminium Layer)**
Layratio 4	10	**Lay ratio of 5th layer (Third Aluminium Layer)**

Table 4.4 – Computer simulation results for SCENARIO B:
TERN Conductor: With MAX, MAX, MIN Lay-ratios @ 875A Load Current

SUMMARY OF KEY DATA:
SCENARIO C - TERN Conductor: With MIN, MIN, MIN Lay-ratios at 875A Load Current

PROGRAMMATIC SIMULATION RESULTS : SCENARIO C		
Parameter	**Value**	**Description of measured Parameter**
tc	75	**Conductor Core / Operating Temperature (Degrees Celcius)**
Itot	875	**Total load Current (A)**
Bm	0.377	**Magnetic Flux density / Magnetic Induction (T/m)**
H	1280	**Magnetic field strength (A/m)**
kred	1.044	**AC-DC ratio (Current redistribution factor)**
ΔR	0.000001186	**Magnetic Resistance (Ω/m)**
Rcon	8.705E-05	**Total DC resistance of the conductor (Ω/m)**
Rac	9.090E-05	**Total AC resistance of the conductor (Ω/m)**
Pmagnetic	0.908	**Magnetic Loss Component (W/m)- CORE losses as a result of Hysteresis & Eddy Currents**
$Itot^2$ Rac	69.599	**AC Resistance loss Component (W/m)**
$Itot^2$ Rcon	66.647	**DC Resistance loss Component (W/m)**
Layratio 0	0	**Lay ratio of 1st layer (First straight wire in the center is assumed as the 1st layer) (Steel)**
Layratio 1	16.44	**Lay ratio of 2nd layer (Steel)**
Layratio 2	10	**Lay ratio of 3rd layer (First Aluminium Layer)**
Layratio 3	10	**Lay ratio of 4th layer (Second Aluminium Layer)**
Layratio 4	10	**Lay ratio of 5th layer (Third Aluminium Layer)**

Table 4.5 – Computer simulation results for SCENARIO C:
TERN Conductor: With MIN, MIN, MIN Lay-ratios @ 875A Load Current

SUMMARY OF KEY DATA:
SCENARIO D - TERN Conductor: With MAX, MIN, MIN Lay-ratios at 875A Load Current

PROGRAMMATIC SIMULATION RESULTS : SCENARIO D		
Parameter	**Value**	**Description of measured Parameter**
tc	75	**Conductor Core / Operating Temperature (Degrees Celcius)**
Itot	875	**Total load Current (A)**
Bm	0.129	**Magnetic Flux density / Magnetic Induction (T/m)**
H	807.157	**Magnetic field strength (A/m)**
kred	1.005	**AC-DC ratio (Current redistribution factor)**
ΔR	1.685E-07	**Magnetic Resistance (Ω/m)**
Rcon	8.677E-05	**Total DC resistance of the conductor (Ω/m)**
Rac	8.724E-05	**Total AC resistance of the conductor (Ω/m)**
Pmagnetic	0.129	**Magnetic Loss Component (W/m)- CORE losses as a result of Hysteresis & Eddy Currents**
Itot^2 Rac	66.79	**AC Resistance loss Component (W/m)**
Itot^2 Rcon	66.43	**DC Resistance loss Component (W/m)**
Layratio 0	0	**Lay ratio of 1st layer (First straight wire in the center is assumed as the 1st layer) (Steel)**
Layratio 1	16.44	**Lay ratio of 2nd layer (Steel)**
Layratio 2	16	**Lay ratio of 3rd layer (First Aluminium Layer)**
Layratio 3	10	**Lay ratio of 4th layer (Second Aluminium Layer)**
Layratio 4	10	**Lay ratio of 5th layer (Third Aluminium Layer)**

Table 4.6 – Computer simulation results for SCENARIO D:
TERN Conductor: With MAX, MIN, MIN Lay-ratios @ 875A Load Current

It is therefore evident, from the preceding computer simulation results (i.e. simulation results A – D) that **‘Simulation Scenario D’**, would be the optimum lay-ratio combination, as it yielded the highest reduction in terms of the Magnetic field strength (H), Magnetic resistance (ΔR) & Magnetic Core losses (Pmagnetic) – refer to Tables 4.7 and 4.8 below.

This invariably meant that the lay-ratio combination of maximum (16) / minimum (10) / minimum (10) (as per IEC 61089 [8]), applied from the innermost aluminium layer to the outermost aluminium layer respectively, are optimum and when translated into lay-lengths, this lay-ratio combination, yielded the following for each layer of aluminium wires (Using Equation 1):

- Innermost Aluminium layer: 216.16 mm (Lay-length)
- Middle Aluminium layer: 202.70 mm (Lay-length)
- Outermost Aluminium layer: 270.30 mm (Lay-length)

H	A	902.597
	B	1313.000
	C	1280.000
	D	807.157

Table 4.7 – Magnetic field strength (H) in A/m for Scenarios A – D @ 875A Load Current

Pmagnetic	A	0.253	**ΔR**	A	3.3E-07
	B	1.003		B	1.31E-06
	C	0.908		C	1.19E-06
	D	0.129		D	1.69E-07

Table 4.8 – Magnetic Resistance (ΔR) in Ω/m and Core/Magnetic losses (Pmagnetic) in W/m, for Scenarios A – D @ 875A Load Current

Having established a set of theoretical optimised lay-lengths for reduced power losses, the next objective of this study was to determine and quantify the possible savings in terms of ac resistive losses, if the current lay-lengths of the TERN ACSR conductor were changed/manufactured to the ‘optimised’ set of lay-lengths, as identified by that of the computer simulation results for scenario D, previously described.

In order to achieve this objective, a set of 4 computer simulations were performed for the identified scenarios below (i.e. Scenarios 1 – 4), for the TERN ACSR conductor sample:

- SCENARIO 1: TERN Conductor: With Original Lay-lengths at 750A Load Current
- SCENARIO 2: TERN Conductor: With Original Lay-lengths at 875A Load Current
- SCENARIO 3: TERN Conductor: With Optimised Lay-lengths at 750A Load Current
- SCENARIO 4: TERN Conductor: With Optimised Lay-lengths at 875A Load Current

In performing the computer simulations for Scenarios 1-4, the core temperature was maintained at a constant temperature of 75 degrees Celcius while the load current was changed between 2 values in performing the computer simulations (i.e. 750 and 875 amps). The reason for performing the simulations at 2 different load currents was to establish a range of expected ac wattage losses that could practically be expected in the field, as transmission lines in actual operation don’t necessarily operate at maximum load current. This approach would then also produce a range of expected ac wattage savings based on the load current applied.

Computer simulations for scenarios 1 and 2 were performed on the TERN conductor sample with its current (Original) lay-lengths for 2 different load currents (i.e. 750 and 875 amps). These computer simulation results produced the base-line values of expected ac resistance and associated ac wattage losses, for comparison of expected savings/reductions against these parameters, when compared to the results produced by the simulations for scenarios 3 and 4 (i.e. TERN conductor with ‘optimised’ lay-lengths for load currents of 750 and 875 amps respectively).

The key output results for each of these computer simulations (i.e. for scenarios 1 – 4 described above) are shown in Tables 4.9 – 4.12.

SUMMARY OF KEY DATA FOR
SCENARIO 1 - TERN Conductor: With Original Lay-lengths at 750A Load Current

PROGRAMMATIC SIMULATION RESULTS : SCENARIO 1		
Parameter	**Value**	**Description of measured Parameter**
tc	75	**Conductor Core / Operating Temperature (Degrees Celcius)**
Itot	750	**Total load Current (A)**
Bm	0.169	**Magnetic Flux density / Magnetic Induction (T/m)**
H	909.654	**Magnetic field strength (A/m)**
kred	1.012	**AC-DC ratio (Current redistribution factor)**
ΔR	3.753E-07	**Magnetic Resistance (Ω/m)**
Rcon	8.639E-05	**Total DC resistance of the conductor (Ω/m)**
Rac	8.744E-05	**Total AC resistance of the conductor (Ω/m)**
Pmagnetic	0.211	**Magnetic Loss Component (W/m)- CORE losses as a result of Hysteresis & Eddy Currents**
$Itot^2$ Rac	49.185	**AC Resistance loss Component (W/m)**
$Itot^2$ Rcon	48.593	**DC Resistance loss Component (W/m)**
Layratio 0	0	**Lay ratio of 1st layer (First straight wire in the center is assumed as the 1st layer) (Steel)**
Layratio 1	16.44	**Lay ratio of 2nd layer (Steel)**
Layratio 2	13.54	**Lay ratio of 3rd layer (First Aluminium Layer)**
Layratio 3	11.85	**Lay ratio of 4th layer (Second Aluminium Layer)**
Layratio 4	10.74	**Lay ratio of 5th layer (Third Aluminium Layer)**

Table 4.9 – Computer simulation results for SCENARIO 1:
TERN Conductor: With Original Lay-lengths at 750A Load Current

SUMMARY OF KEY DATA FOR
SCENARIO 2 - TERN Conductor: With Original Lay-lengths at 875A Load Current

PROGRAMMATIC SIMULATION RESULTS : SCENARIO 2		
Parameter	**Value**	**Description of measured Parameter**
tc	75	**Conductor Core / Operating Temperature (Degrees Celcius)**
Itot	875	**Total load Current (A)**
Bm	0.232	**Magnetic Flux density / Magnetic Induction (T/m)**
H	1061	**Magnetic field strength (A/m)**
kred	1.017	**AC-DC ratio (Current redistribution factor)**
ΔR	4.911E-07	**Magnetic Resistance (Ω/m)**
Rcon	8.639E-05	**Total DC resistance of the conductor (Ω/m)**
Rac	8.782E-05	**Total AC resistance of the conductor (Ω/m)**
Pmagnetic	0.376	**Magnetic Loss Component (W/m)- CORE losses as a result of Hysteresis & Eddy Currents**
$Itot^2$ Rac	67.238	**AC Resistance loss Component (W/m)**
$Itot^2$ Rcon	66.14	**DC Resistance loss Component (W/m)**
Layratio 0	0	**Lay ratio of 1st layer (First straight wire in the center is assumed as the 1st layer) (Steel)**
Layratio 1	16.44	**Lay ratio of 2nd layer (Steel)**
Layratio 2	13.54	**Lay ratio of 3rd layer (First Aluminium Layer)**
Layratio 3	11.85	**Lay ratio of 4th layer (Second Aluminium Layer)**
Layratio 4	10.74	**Lay ratio of 5th layer (Third Aluminium Layer)**

Table 4.10 – Computer simulation results for SCENARIO 2: TERN Conductor: With Original Lay-lengths at 875A Load Current

SUMMARY OF KEY DATA:

SCENARIO 3 - TERN Conductor: With Optimised Lay-lengths at 750A Load Current

PROGRAMMATIC SIMULATION RESULTS : SCENARIO 3		
Parameter	**Value**	**Description of measured Parameter**
tc	75	**Conductor Core / Operating Temperature (Degrees Celcius)**
Itot	750	**Total load Current (A)**
Bm	0.096	**Magnetic Flux density / Magnetic Induction (T/m)**
H	691.849	**Magnetic field strength (A/m)**
kred	1.004	**AC-DC ratio (Current redistribution factor)**
ΔR	1.328E-07	**Magnetic Resistance (Ω/m)**
Rcon	8.677E-05	**Total DC resistance of the conductor (Ω/m)**
Rac	8.711E-05	**Total AC resistance of the conductor (Ω/m)**
Pmagnetic	0.075	**Magnetic Loss Component (W/m)- CORE losses as a result of Hysteresis & Eddy Currents**
$Itot^2$ Rac	49.001	**AC Resistance loss Component (W/m)**
$Itot^2$ Rcon	48.806	**DC Resistance loss Component (W/m)**
Layratio 0	0	**Lay ratio of 1st layer (First straight wire in the center is assumed as the 1st layer) (Steel)**
Layratio 1	16.44	**Lay ratio of 2nd layer (Steel)**
Layratio 2	16	**Lay ratio of 3rd layer (First Aluminium Layer)**
Layratio 3	10	**Lay ratio of 4th layer (Second Aluminium Layer)**
Layratio 4	10	**Lay ratio of 5th layer (Third Aluminium Layer)**

**Table 4.11 – Computer simulation results for SCENARIO 3:
TERN Conductor: With Optimised Lay-lengths at 750A Load Current**

SUMMARY OF KEY DATA:

SCENARIO 4 - TERN Conductor: With Optimised Lay-lengths at 875A Load Current

PROGRAMMATIC SIMULATION RESULTS : SCENARIO 4		
Parameter	**Value**	**Description of measured Parameter**
tc	75	**Conductor Core / Operating Temperature (Degrees Celcius)**
Itot	875	**Total load Current (A)**
Bm	0.129	**Magnetic Flux density / Magnetic Induction (T/m)**
H	807.157	**Magnetic field strength (A/m)**
kred	1.005	**AC-DC ratio (Current redistribution factor)**
ΔR	1.685E-07	**Magnetic Resistance (Ω/m)**
Rcon	8.677E-05	**Total DC resistance of the conductor (Ω/m)**
Rac	8.724E-05	**Total AC resistance of the conductor (Ω/m)**
Pmagnetic	0.129	**Magnetic Loss Component (W/m)- CORE losses as a result of Hysteresis & Eddy Currents**
$Itot^2$ Rac	66.79	**AC Resistance loss Component (W/m)**
$Itot^2$ Rcon	66.43	**DC Resistance loss Component (W/m)**
Layratio 0	0	**Lay ratio of 1st layer (First straight wire in the center is assumed as the 1st layer) (Steel)**
Layratio 1	16.44	**Lay ratio of 2nd layer (Steel)**
Layratio 2	16	**Lay ratio of 3rd layer (First Aluminium Layer)**
Layratio 3	10	**Lay ratio of 4th layer (Second Aluminium Layer)**
Layratio 4	10	**Lay ratio of 5th layer (Third Aluminium Layer)**

**Table 4.12 – Computer simulation results for SCENARIO 4:
TERN Conductor: With Optimised Lay-lengths at 875A Load Current**

Having established what would be optimum lay-ratios for the 3 layers of aluminium wires for the TERN sample conductor (i.e. scenario D) and also having established the expected ac resistance and ac wattage losses for this lay-ratio combination (as per computer simulation results for Scenarios 3 and 4), the next objective of this research study was to determine if these 'optimum' lay-ratios/lay-lengths i.e.

- Innermost Aluminium layer : 216.16mm Lay-length (@ Lay-ratio 16)
- Middle Aluminium layer: 202.70mm Lay-length (@ Lay-ratio 10)
- Outermost Aluminium layer: 270.30mm Lay-length (@ Lay-ratio 10)

were obtainable through the actual manufacturing processes, before attempting to calculate any possible savings in ac wattage losses, if these optimised lay-lengths were employed.

After consultation with the relevant production personnel and taking into consideration the machine-gearing ratio capability chart (Refer to Appendix D – Gearing ratio sheet), it was found that these lay-lengths could not be achieved exactly as specified/simulated by Scenario D. An alternative set of lay-lengths (i.e. 'Optimised Production lay-lengths) was then developed, which was kept as close as possible to the initially proposed lay-lengths of 'Scenario D', which could be achieved in actual product manufacturing. These 'Optimised Production lay-lengths' are depicted below:

- Innermost Aluminium layer : 206mm Lay-length (@ Lay-ratio 15.25)
- Middle Aluminium layer: 206mm Lay-length (@ Lay-ratio 10.16)
- Outermost Aluminium layer: 271mm Lay-length (@ Lay-ratio 10.03)

Based on these 'Optimised Production lay-lengths', computer simulation exercises were performed for the scenarios 5 and 6 below, on the TERN conductor sample:

- SCENARIO 5: TERN Conductor: With Optimised Production Lay-lengths at 750A Load Current
- SCENARIO 6: TERN Conductor: With Optimised Production Lay-lengths at 875A Load Current

The key output results for each of these computer simulations (i.e. scenarios 5 & 6) (described above) are shown in Tables 4.13 and 4.14.

SUMMARY OF KEY DATA:

SCENARIO 5 - TERN Conductor: With Optimised Production lay-lengths at 750A Load Current

PROGRAMMATIC SIMULATION RESULTS : SCENARIO 5		
Parameter	**Value**	**Description of measured Parameter**
tc	75	**Conductor Core / Operating Temperature (Degrees Celcius)**
Itot	750	**Total load Current (A)**
Bm	0.109	**Magnetic Flux density / Magnetic Induction (T/m)**
H	739.728	**Magnetic field strength (A/m)**
kred	1.005	**AC-DC ratio (Current redistribution factor)**
ΔR	1.680E-07	**Magnetic Resistance (Ω/m)**
Rcon	8.675E-05	**Total DC resistance of the conductor (Ω/m)**
Rac	8.720E-05	**Total AC resistance of the conductor (Ω/m)**
Pmagnetic	0.094	**Magnetic Loss Component (W/m)- CORE losses as a result of Hysteresis & Eddy Currents**
$Itot^2$ Rac	49.051	**AC Resistance loss Component (W/m)**
$Itot^2$ Rcon	48.796	**DC Resistance loss Component (W/m)**
Layratio 0	0	**Lay ratio of 1st layer (First straight wire in the center is assumed as the 1st layer) (Steel)**
Layratio 1	16.44	**Lay ratio of 2nd layer (Steel)**
Layratio 2	15.25	**Lay ratio of 3rd layer (First Aluminium Layer)**
Layratio 3	10.16	**Lay ratio of 4th layer (Second Aluminium Layer)**
Layratio 4	10.03	**Lay ratio of 5th layer (Third Aluminium Layer)**

Table 4.13 – Computer simulation results for SCENARIO 5:
TERN Conductor: With Optimised Production Lay-lengths at 750A Load Current

SUMMARY OF KEY DATA:

SCENARIO 6 - TERN Conductor: With Optimised Production lay-lengths at 875A Load Current

PROGRAMMATIC SIMULATION RESULTS : SCENARIO 6		
Parameter	**Value**	**Description of measured Parameter**
tc	75	**Conductor Core / Operating Temperature (Degrees Celcius)**
Itot	875	**Total load Current (A)**
Bm	0.147	**Magnetic Flux density / Magnetic Induction (T/m)**
H	863.017	**Magnetic field strength (A/m)**
kred	1.007	**AC-DC ratio (Current redistribution factor)**
ΔR	2.140E-07	**Magnetic Resistance (Ω/m)**
Rcon	8.675E-05	**Total DC resistance of the conductor (Ω/m)**
Rac	8.737E-05	**Total AC resistance of the conductor (Ω/m)**
Pmagnetic	0.164	**Magnetic Loss Component (W/m)- CORE losses as a result of Hysteresis & Eddy Currents**
Itot^2 Rac	66.89	**AC Resistance loss Component (W/m)**
Itot^2 Rcon	66.416	**DC Resistance loss Component (W/m)**
Layratio 0	0	**Lay ratio of 1st layer (First straight wire in the center is assumed as the 1st layer) (Steel)**
Layratio 1	16.44	**Lay ratio of 2nd layer (Steel)**
Layratio 2	15.25	**Lay ratio of 3rd layer (First Aluminium Layer)**
Layratio 3	10.16	**Lay ratio of 4th layer (Second Aluminium Layer)**
Layratio 4	10.03	**Lay ratio of 5th layer (Third Aluminium Layer)**

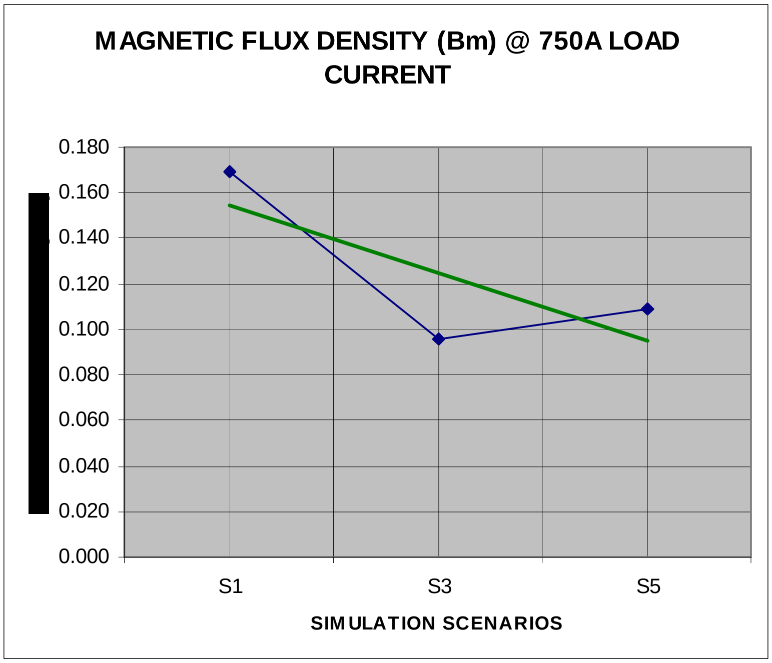
Table 4.14 – Computer simulation results for SCENARIO 6:
TERN Conductor: With Optimised Production Lay-lengths at 875A Load Current

The results obtained for Scenarios 1 – 6, were grouped and analysed for 2 load current values (i.e. 750A & 850A load currents). This analysis is shown graphically for grouped Scenarios 1, 3 and 5 (i.e. at 750A load current and Core temperature of 75 Degrees Celcius) and grouped Scenarios 2, 4 and 6 (i.e. at 875A load current and Core temperature of 75 Degrees Celcius). The graphical representations for this grouped scenario approach, are shown for each of the data output fields as previously reflected in Table 4.1 (shown again below):

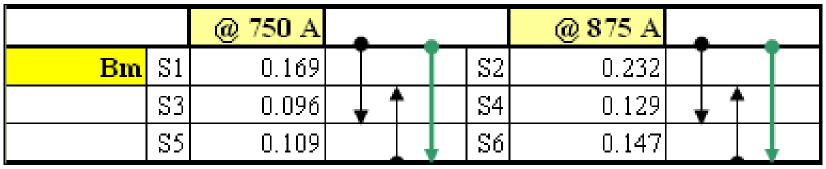
Output Data Fields	**Description of Output Data Fields**
Bm	Magnetic Flux density / Magnetic Induction (T/m)
H	Magnetic field strength (A/m)
Kred	AC-DC ratio (Current redistribution factor)
ΔR	Magnetic Resistance (Ω/m)
Rcon	Total DC resistance of the conductor (Ω/m)
Rac	Total AC resistance of the conductor (Ω/m)
Pmagnetic	Magnetic Loss Component (W/m)- CORE losses as a result of Hysteresis & Eddy Currents
$Itot^2$ Rac	AC Resistance loss Component (W/m)
$Itot^2$ Rcon	DC Resistance loss Component (W/m)

Table 4.1 – Key Output Data fields for Computer Simulation exercises

Each of these graphical representations (Graphs 4.1 – 4.18) are accompanied by tables (Tables 4.15 – 4.32) which reflect the actual results obtained from the computer simulations performed, for that specific parameter, at the particular load current, for the grouped scenarios. Each graph also depicts the behaviour trend of the particular parameter within these defined conditions and this is represented by either green (i.e. decreasing trend) or red (i.e. increasing trend) trend lines. As previously mentioned the core temperature for all computer simulations was maintained at a constant value of 75 Degrees Celcius.

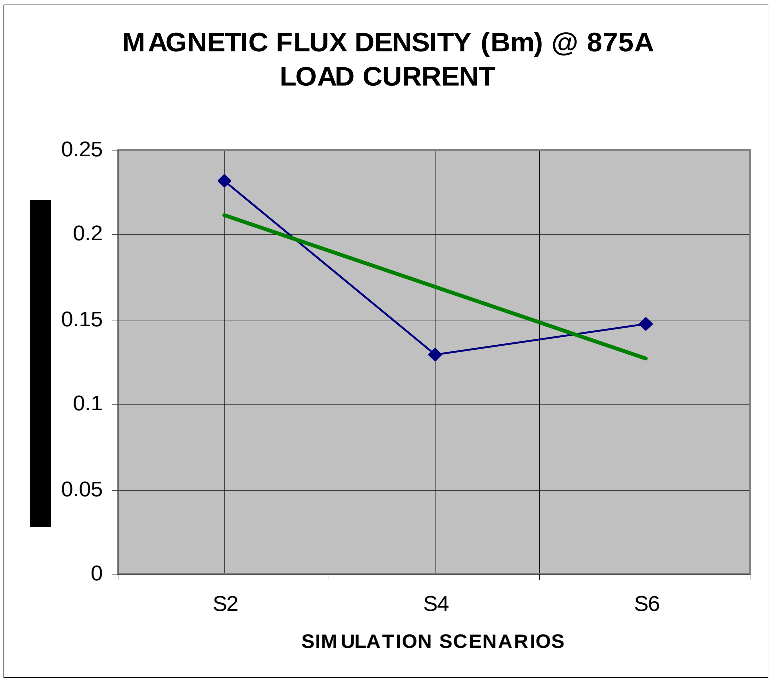


Graph 4.1 – Magnetic Flux Density (Bm)
for Computer Simulation scenarios 1, 3 and 5 at load current of 750A

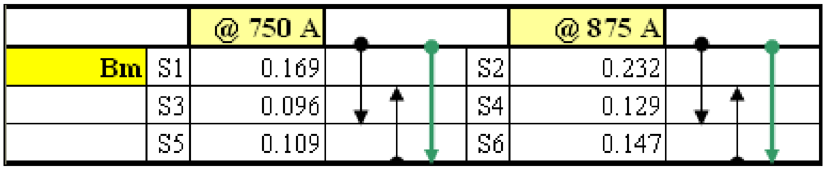


		@ 750 A			@ 875 A	
Bm	S1	0.169		S2	0.232	
	S3	0.096		S4	0.129	
	S5	0.109		S6	0.147	

Table 4.15 – Tabulated values of Magnetic Flux Density (Bm)
for Computer Simulation scenarios 1 – 6 at load currents of 750A and 875A

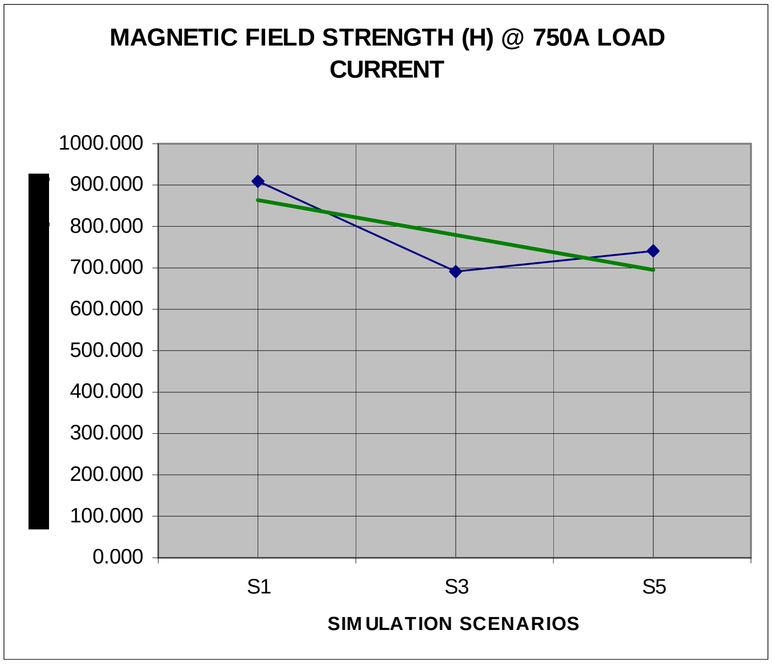


Graph 4.2 – Magnetic Flux Density (Bm)
for Computer Simulation scenarios 2, 4 and 6 at load current of 875A

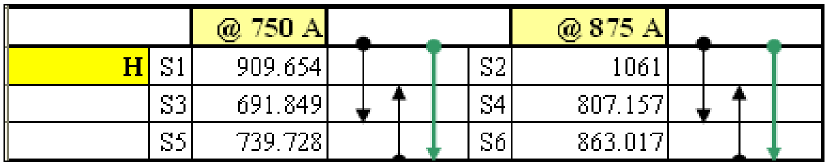


		@ 750 A			@ 875 A	
Bm	S1	0.169		S2	0.232	
	S3	0.096		S4	0.129	
	S5	0.109		S6	0.147	

Table 4.16 – Tabulated values of Magnetic Flux Density (Bm)
for Computer Simulation scenarios 1 – 6 at load currents of 750A and 875A

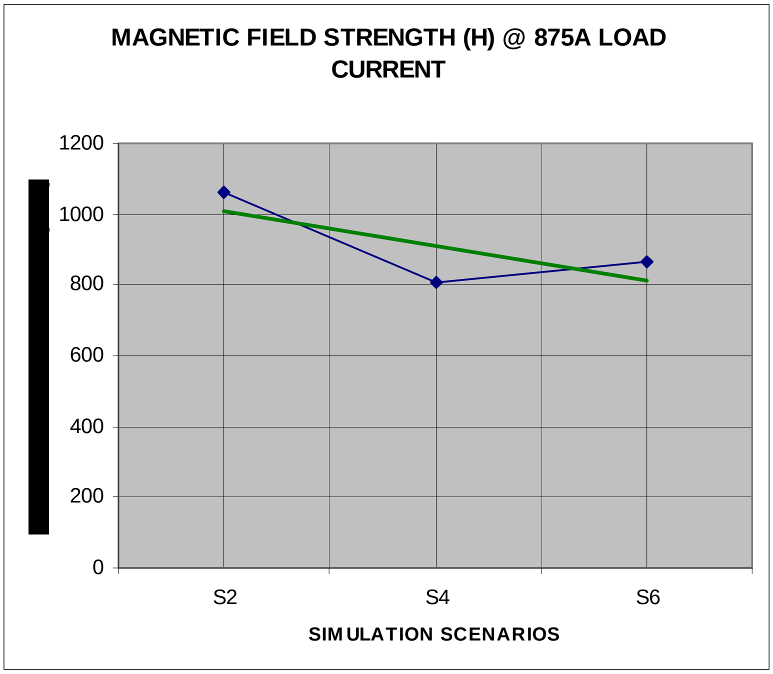


Graph 4.3 – Magnetic field strength (H)
for Computer Simulation scenarios 1, 3 and 5 at load current of 750A

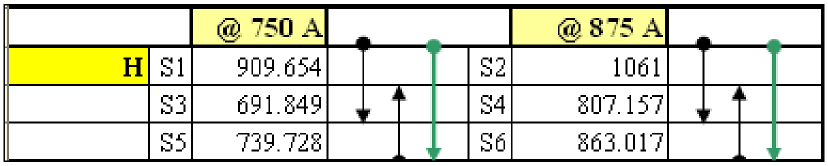


		@ 750 A			@ 875 A	
H	S1	909.654		S2	1061	
	S3	691.849		S4	807.157	
	S5	739.728		S6	863.017	

Table 4.17 – Tabulated values of Magnetic field strength (H)
for Computer Simulation scenarios 1 – 6 at load currents of 750A and 875A

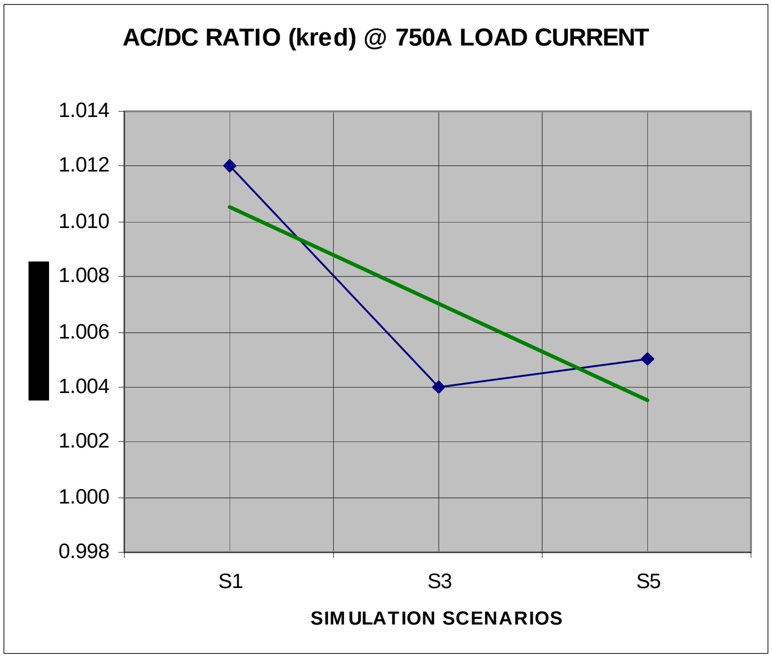


Graph 4.4 – Magnetic field strength (H)
for Computer Simulation scenarios 2, 4 and 6 at load current of 875A

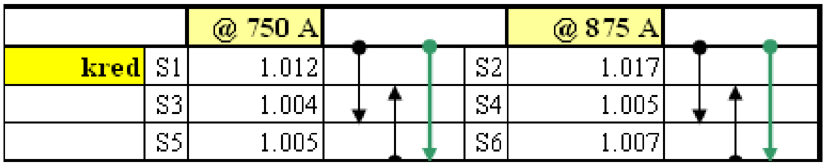


		@ 750 A			@ 875 A	
H	S1	909.654		S2	1061	
	S3	691.849		S4	807.157	
	S5	739.728		S6	863.017	

Table 4.18 – Tabulated values of Magnetic field strength (H)
for Computer Simulation scenarios 1 – 6 at load currents of 750A and 875A

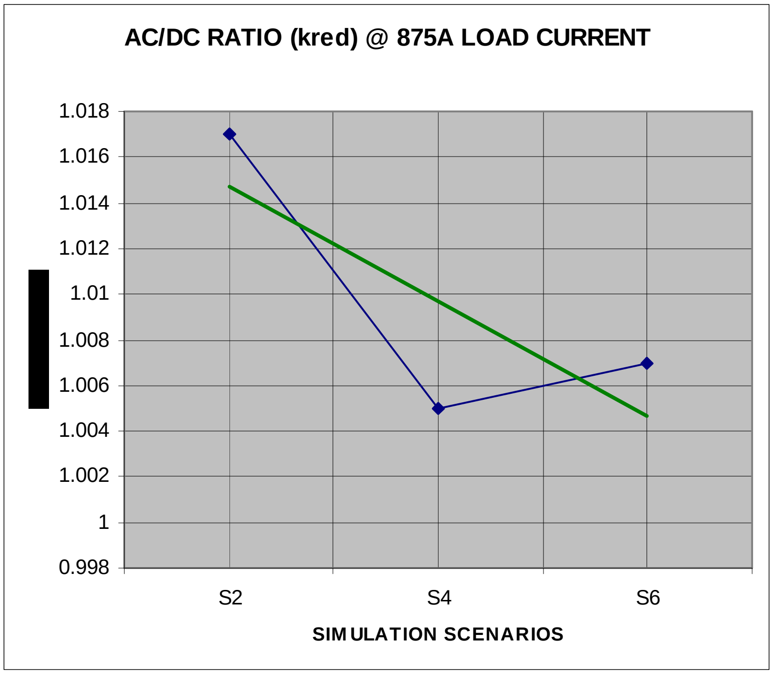


Graph 4.5 – AC-DC ratios (kred)
for Computer Simulation scenarios 1, 3 and 5 at load current of 750A

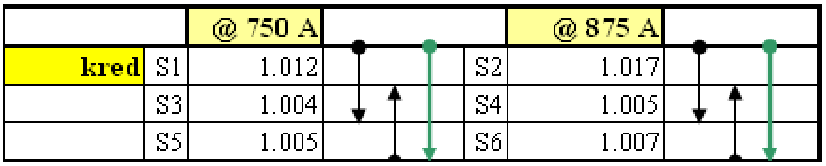


		@ 750 A			@ 875 A	
kred	S1	1.012		S2	1.017	
	S3	1.004		S4	1.005	
	S5	1.005		S6	1.007	

Table 4.19 – Tabulated values of AC-DC ratios (kred)
for Computer Simulation scenarios 1 – 6 at load currents of 750A and 875A

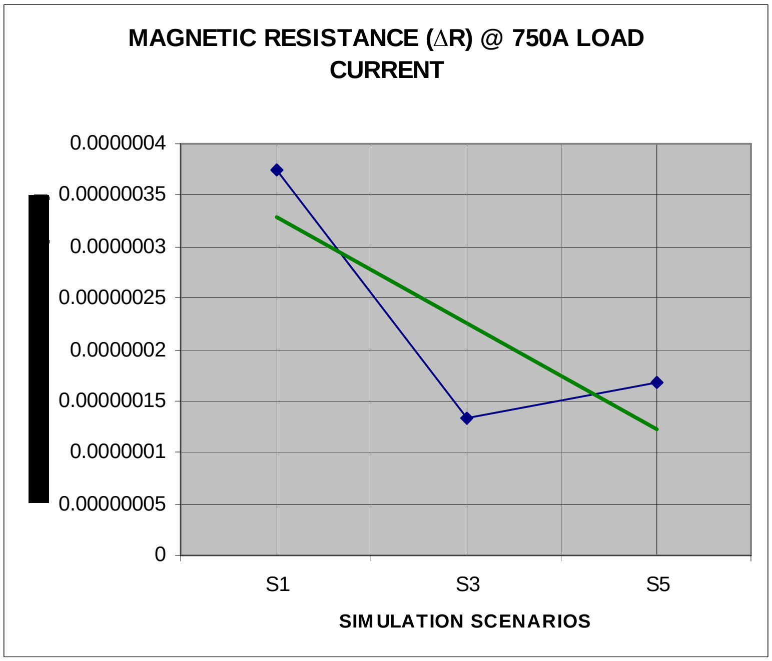


Graph 4.6 – AC-DC ratios (kred)
for Computer Simulation scenarios 2, 4 and 6 at load current of 875A

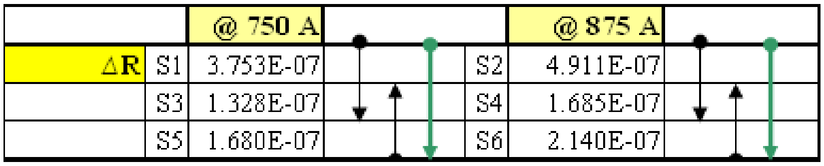


		@ 750 A			@ 875 A	
kred	S1	1.012		S2	1.017	
	S3	1.004		S4	1.005	
	S5	1.005		S6	1.007	

Table 4.20 – Tabulated values of AC-DC ratios (kred)
for Computer Simulation scenarios 1 – 6 at load currents of 750A and 875A

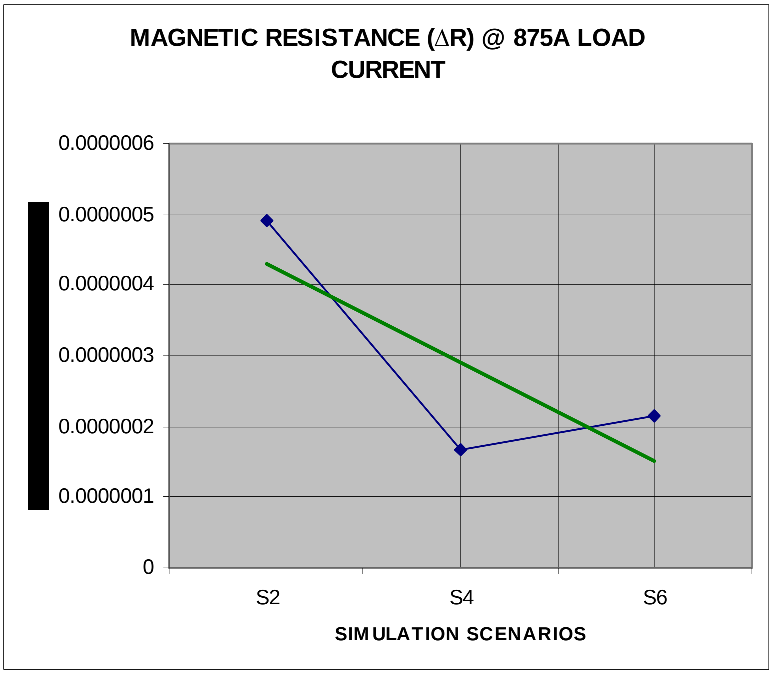


Graph 4.7 – Magnetic resistance (ΔR)
for Computer Simulation scenarios 1, 3 and 5 at load current of 750A

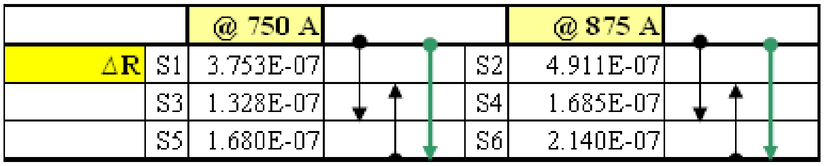


		@ 750 A			@ 875 A	
ΔR	S1	3.753E-07		S2	4.911E-07	
	S3	1.328E-07		S4	1.685E-07	
	S5	1.680E-07		S6	2.140E-07	

Table 4.21 – Tabulated values of Magnetic resistance (ΔR)
for Computer Simulation scenarios 1 – 6 at load currents of 750A and 875A

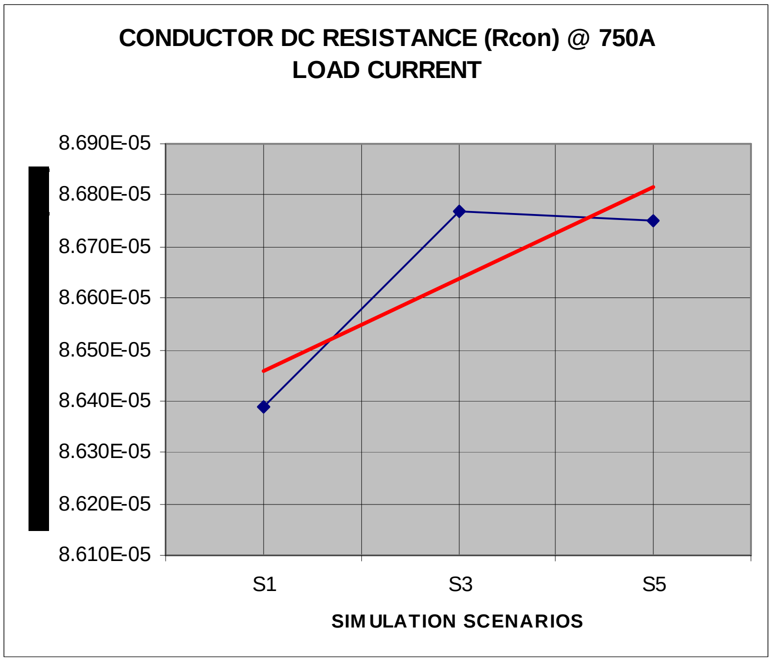


Graph 4.8 – Magnetic resistance (ΔR)
for Computer Simulation scenarios 2, 4 and 6 at load current of 875A



		@ 750 A			@ 875 A	
ΔR	S1	3.753E-07		S2	4.911E-07	
	S3	1.328E-07		S4	1.685E-07	
	S5	1.680E-07		S6	2.140E-07	

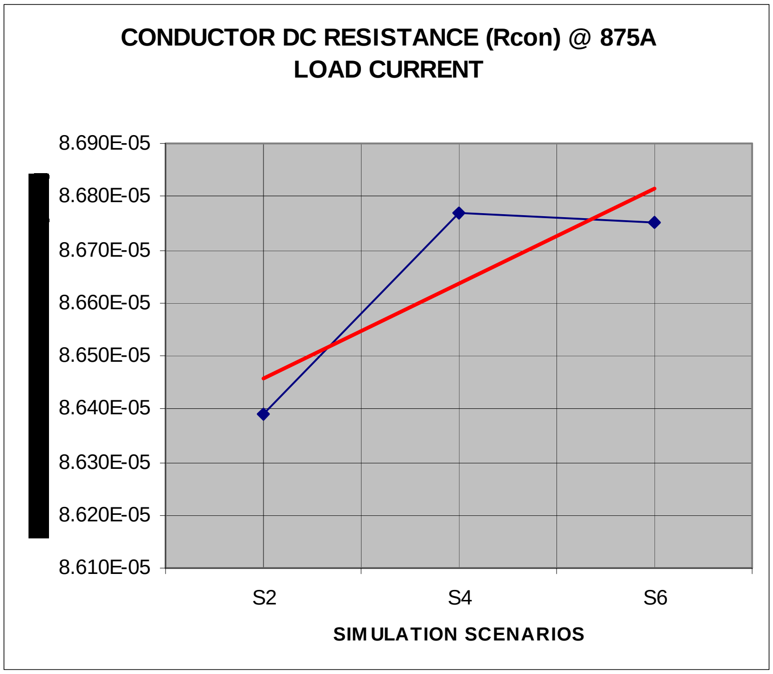
Table 4.22 – Tabulated values of Magnetic resistance (ΔR)
for Computer Simulation scenarios 1 – 6 at load currents of 750A and 875A



Graph 4.9 – Conductor dc resistance (Rcon)
for Computer Simulation scenarios 1, 3 and 5 at load current of 750A

		@ 750 A			@ 875 A	
Rcon	S1	8.639E-05		S2	8.639E-05	
	S3	8.677E-05		S4	8.677E-05	
	S5	8.675E-05		S6	8.675E-05	

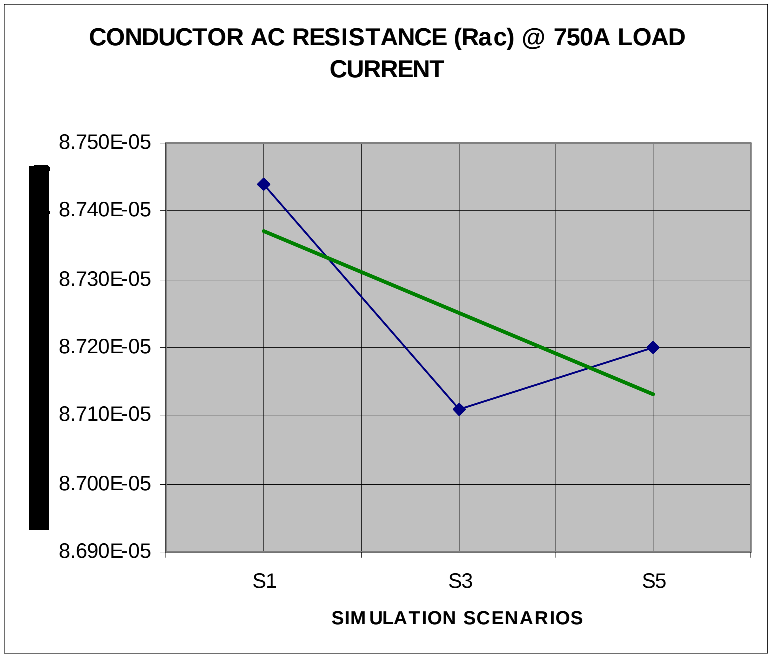
Table 4.23 – Tabulated values of Conductor dc resistance (Rcon)
for Computer Simulation scenarios 1 – 6 at load currents of 750A and 875A



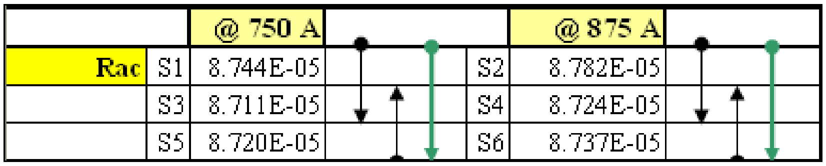
Graph 4.10 – Conductor dc resistance (Rcon)
for Computer Simulation scenarios 2, 4 and 6 at load current of 875A

		@ 750 A			@ 875 A	
Rcon	S1	8.639E-05		S2	8.639E-05	
	S3	8.677E-05		S4	8.677E-05	
	S5	8.675E-05		S6	8.675E-05	

Table 4.24 – Tabulated values of Conductor dc resistance (Rcon)
for Computer Simulation scenarios 1 – 6 at load currents of 750A and 875A

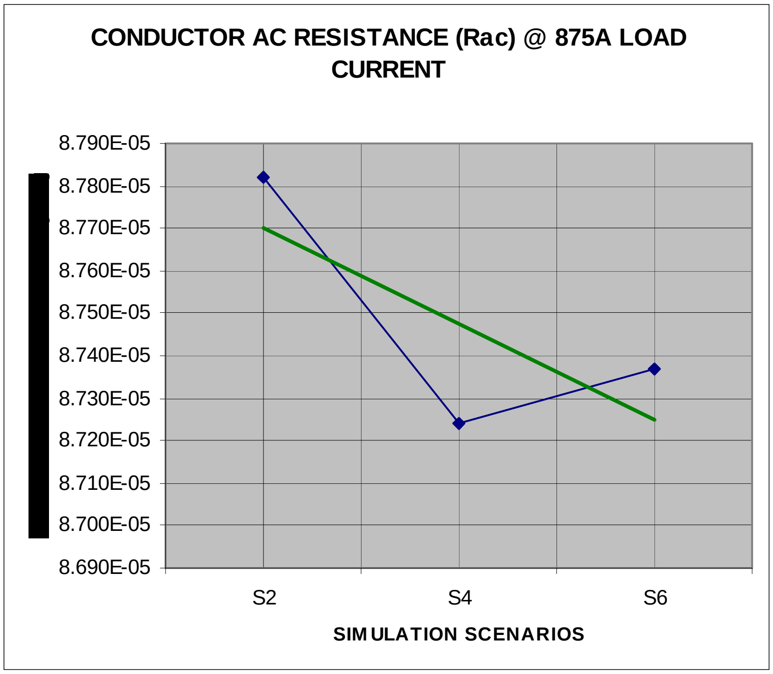


**Graph 4.11 – Conductor ac resistance (Rac)
for Computer Simulation scenarios 1, 3 and 5 at load current of 750A**



		@ 750 A			@ 875 A	
Rac	S1	8.744E-05		S2	8.782E-05	
	S3	8.711E-05		S4	8.724E-05	
	S5	8.720E-05		S6	8.737E-05	

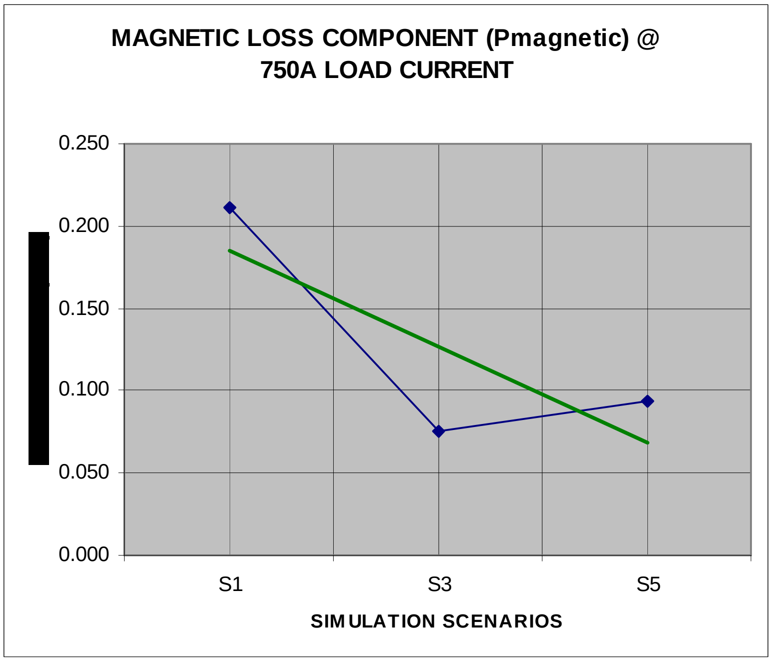
**Table 4.25 – Tabulated values of Conductor ac resistance (Rac)
for Computer Simulation scenarios 1 – 6 at load currents of 750A and 875A**



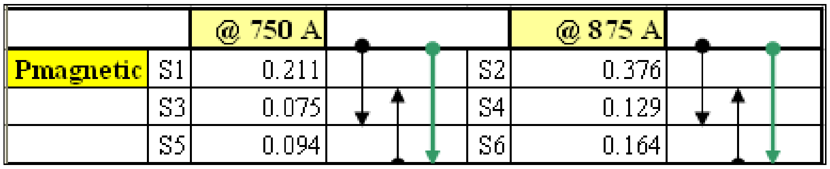
Graph 4.12 – Conductor ac resistance (Rac)
for Computer Simulation scenarios 2, 4 and 6 at load current of 875A

		@ 750 A			@ 875 A	
Rac	S1	8.744E-05		S2	8.782E-05	
	S3	8.711E-05		S4	8.724E-05	
	S5	8.720E-05		S6	8.737E-05	

Table 4.26 – Tabulated values of Conductor ac resistance (Rac)
for Computer Simulation scenarios 1 – 6 at load currents of 750A and 875A

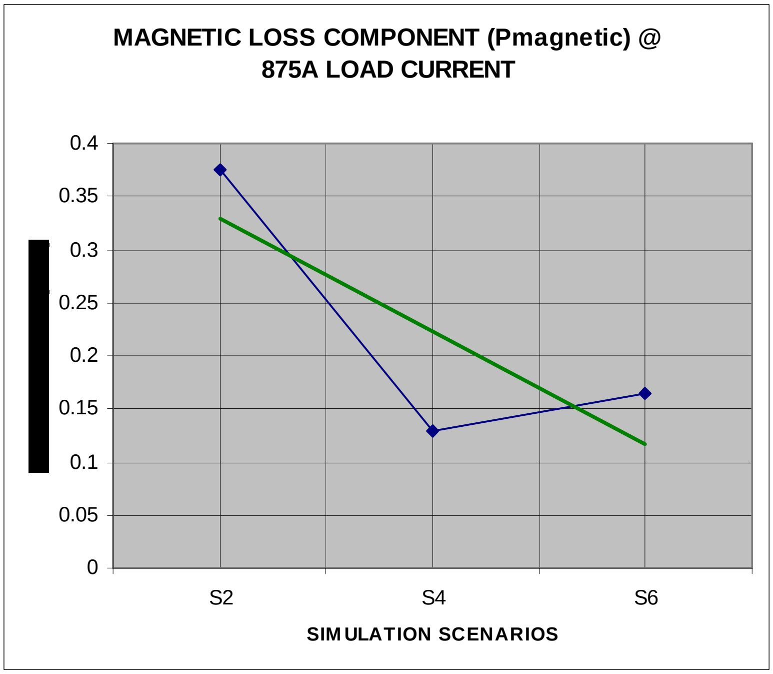


**Graph 4.13 – Magnetic Losses (Pmagnetic)
for Computer Simulation scenarios 1, 3 and 5 at load current of 750A**

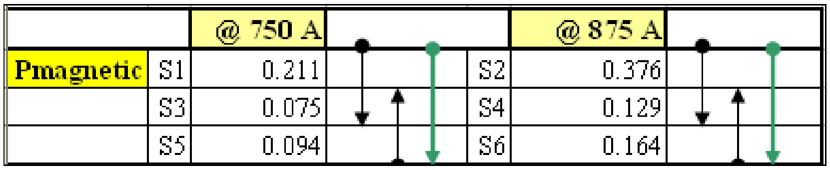


		@ 750 A		@ 875 A
Pmagnetic	S1	0.211	S2	0.376
	S3	0.075	S4	0.129
	S5	0.094	S6	0.164

**Table 4.27 – Tabulated values of Magnetic Losses (Pmagnetic)
for Computer Simulation scenarios 1 – 6 at load currents of 750A and 875A**

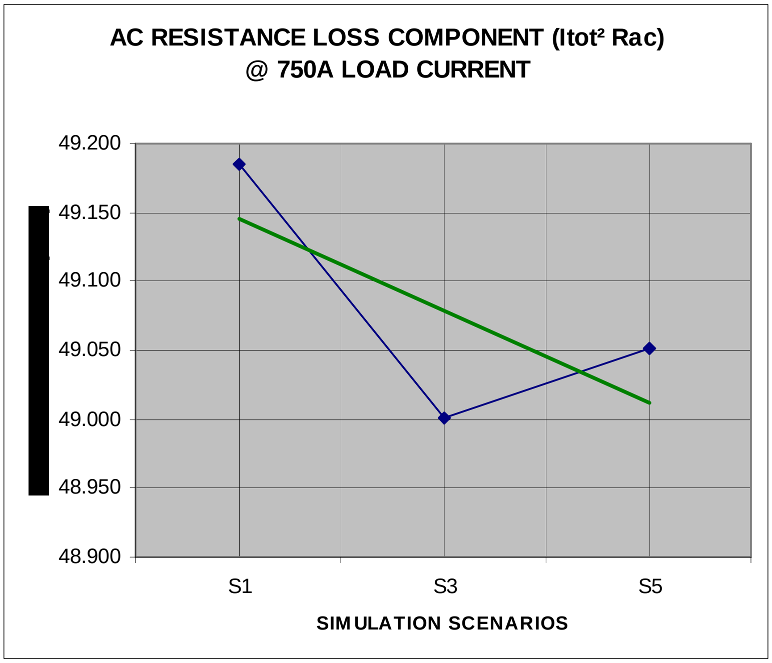


Graph 4.14 – Magnetic Losses (Pmagnetic)
for Computer Simulation scenarios 2, 4 and 6 at load current of 875A

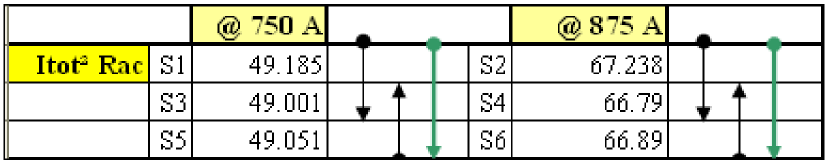


		@ 750 A			@ 875 A	
Pmagnetic	S1	0.211		S2	0.376	
	S3	0.075		S4	0.129	
	S5	0.094		S6	0.164	

Table 4.28 – Tabulated values of Magnetic Losses (Pmagnetic)
for Computer Simulation scenarios 1 – 6 at load currents of 750A and 875A

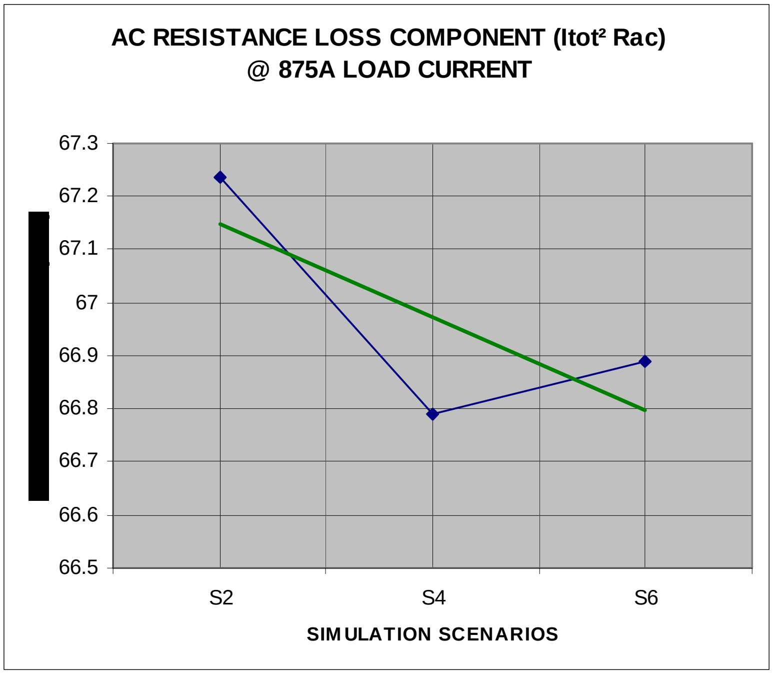


**Graph 4.15 – ac Resistance losses (I_{tot}^2 Rac)
for Computer Simulation scenarios 1, 3 and 5 at load current of 750A**

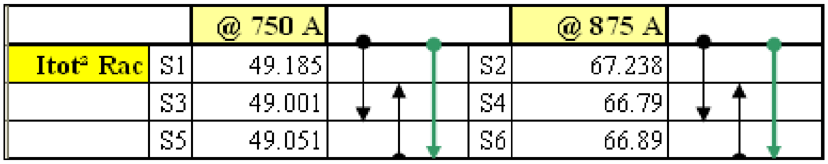


		@ 750 A			@ 875 A	
I_{tot}^2 Rac	S1	49.185		S2	67.238	
	S3	49.001		S4	66.79	
	S5	49.051		S6	66.89	

**Table 4.29 – Tabulated values of ac Resistance losses (I_{tot}^2 Rac)
for Computer Simulation scenarios 1 – 6 at load currents of 750A and 875A**

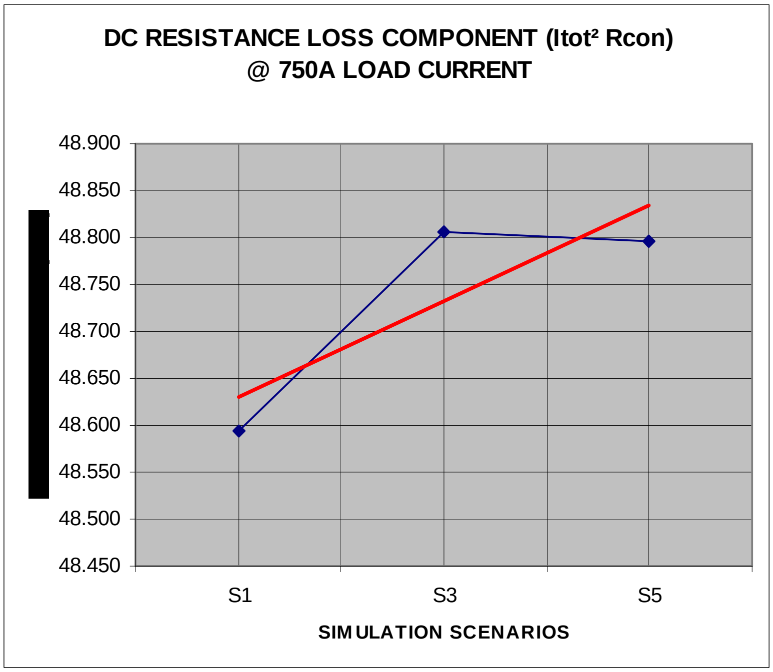


Graph 4.16 – ac Resistance losses (Itot² Rac) for Computer Simulation scenarios 2, 4 and 6 at load current of 875A

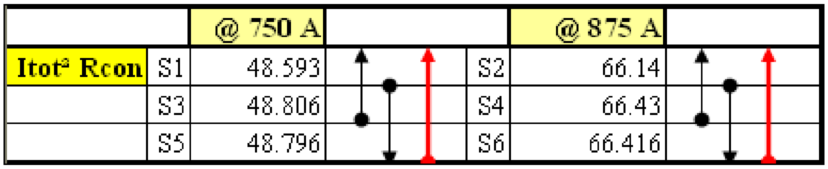


		@ 750 A			@ 875 A	
Itot² Rac	S1	49.185		S2	67.238	
	S3	49.001		S4	66.79	
	S5	49.051		S6	66.89	

Table 4.30 – Tabulated values of ac Resistance losses (Itot² Rac) for Computer Simulation scenarios 1 – 6 at load currents of 750A and 875A

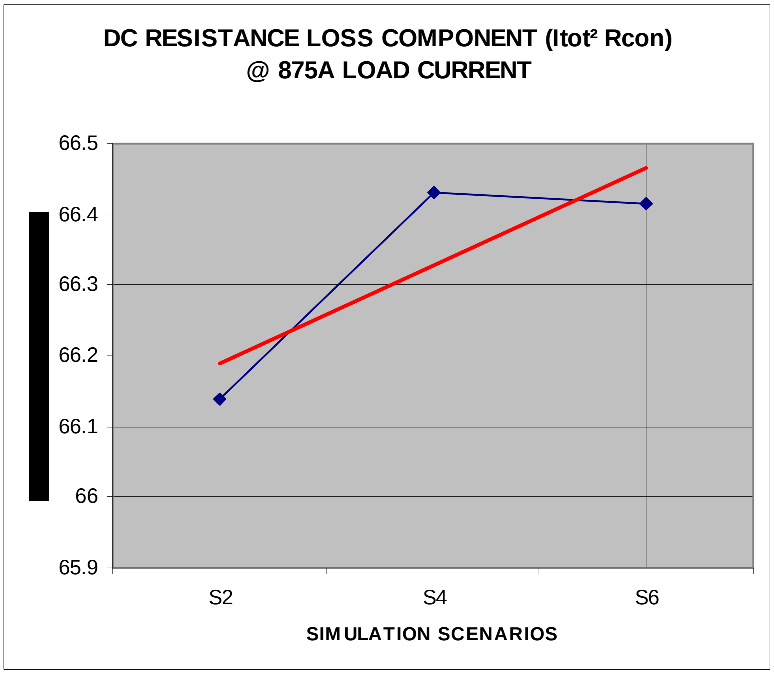


**Graph 4.17 – dc resistance losses (Itot^2 Rcon)
for Computer Simulation scenarios 1, 3 and 5 at load current of 750A**

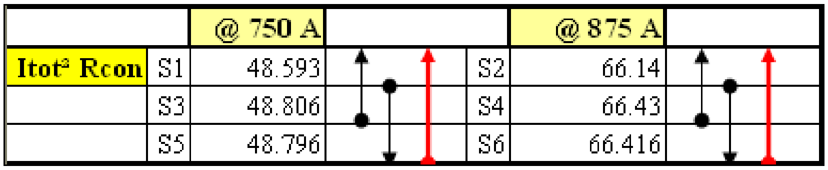


		@ 750 A			@ 875 A	
Itot^2 Rcon	S1	48.593		S2	66.14	
	S3	48.806		S4	66.43	
	S5	48.796		S6	66.416	

**Table 4.31 – Tabulated values of dc resistance losses (Itot^2 Rcon)
for Computer Simulation scenarios 1 – 6 at load currents of 750A and 875A**



**Graph 4.18 – dc resistance losses (Itot^2 Rcon)
for Computer Simulation scenarios 2, 4 and 6 at load current of 875A**



		@ 750 A			@ 875 A	
Itot^2 Rcon	S1	48.593		S2	66.14	
	S3	48.806		S4	66.43	
	S5	48.796		S6	66.416	

**Table 4.32 – Tabulated values of dc resistance losses (Itot^2 Rcon)
for Computer Simulation scenarios 1 – 6 at load currents of 750A and 875A**

Having established a set of optimised lay-lengths for reduced power losses (i.e. scenario D), the next objective of this study was to determine and quantify the possible savings in terms of ac resistive losses, if the current/original lay-lengths of the TERN ACSR conductor were changed/manufactured to the 'optimised' set of lay-lengths.

In order to compute the possible savings in ac wattage losses a series of computer simulations were performed (i.e. Scenarios 1 – 4) at 2 different load currents.

The intention behind performing computer simulations for **scenarios 1 and 2** (i.e. TERN Conductor with **original lay-lengths** at load currents of 750 and 875A respectively), was to produce expected base-line values for the key data output parameters and more importantly the expected ac resistance and associated ac wattage loss. for comparison of expected savings/reductions against these parameters, when compared to the results produced by the simulations for scenarios 3 and 4 (i.e. TERN conductor with 'optimised' lay-lengths for load currents of 750 and 875 amps respectively).

The computer simulations performed for **scenarios 3 & 4** (i.e. TERN conductor with optimised lay-lengths/lay-ratios at 750 and 875A respectively), was based on the optimised lay-ratio combination (16/10/10) as was initially reflected/identified for scenario D. The key difference between scenarios 3 and 4 to that of scenario D was the extrapolation of the computer simulation at different load current levels in order to calculate the range of savings in terms ac wattage losses.

Earlier discussions noted that after consultation with the relevant production personnel and taking into consideration the actual machine constraints, it was found that these lay-lengths/lay-ratios of scenarios 3 and 4, could not be achieved in production. An alternative set of lay-lengths (i.e. 'Optimised Production lay-lengths) was then developed, which was kept as close as possible to the initially proposed lay-lengths of scenarios 3 and 4. These 'Optimised production lay-lengths' were then employed in computer simulation exercises for scenarios 5 and 6 (TERN conductor with Optimised Production lay-lengths) and the associated ac wattage losses were noted together with other key parameters.

Tables 4.33 and 4.34 show the expected ac wattage loss savings for comparisons of both scenarios 3 & 4 and 5 & 6 to scenarios 1 & 2.

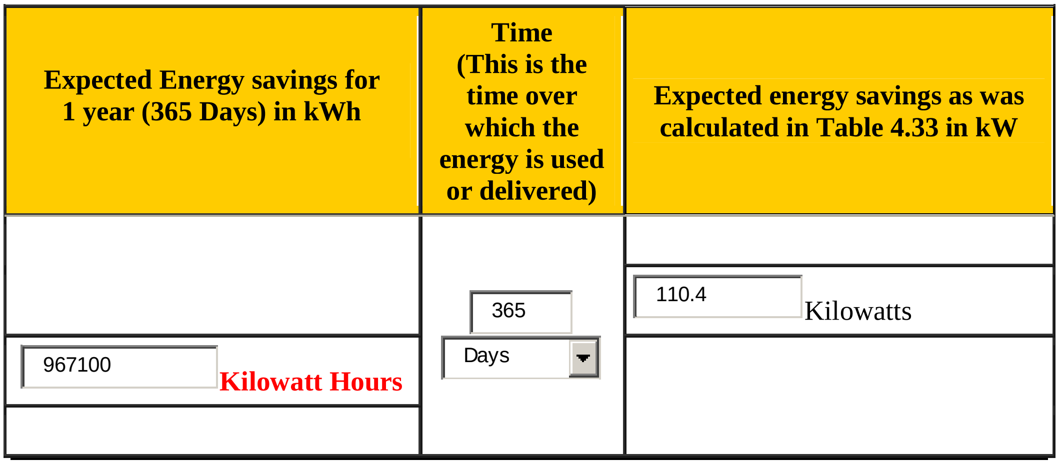
It should be noted that the total savings in ac wattage losses are based on the following assumption: The transmission system is a 100km, 3-phase, double-circuit system, with 1 conductor being used per phase. The expected kWh savings for all cases is then calculated and shown in Tables 4.35 – 4.38.

Load/Line Current (A)	**750**	**875**
Percentage load current to rated current (Approx.)	**85%**	**100%**
TERN Conductor with current Laylengths	***Scenario 1***	***Scenario 2***
AC Wattage Loss Component (W/m)	49.185	67.238
TERN Conductor with Optimised Laylengths (Simulated)	***Scenario 3***	***Scenario 4***
AC Wattage Loss Component (W/m)	49.001	66.79
Summary between Scenarios 1&2 and 3&4		
Theoretical AC Wattage Saving (W)	0.184	0.448
% AC Wattage Saving	0.37	0.67
Assumption: ie. A Single Conductor is used per Phase - 3 Phase system - Double circuit network - 100km Length		
Total Theoretical AC Wattage Saving (W)	110400	268800
Total Theoretical AC Wattage Saving (kW)	**110.4**	**268.8**

Table 4.33 – Expected ac wattage savings with Optimised lay-ratios/lay-lengths at load currents of 750A and 875A

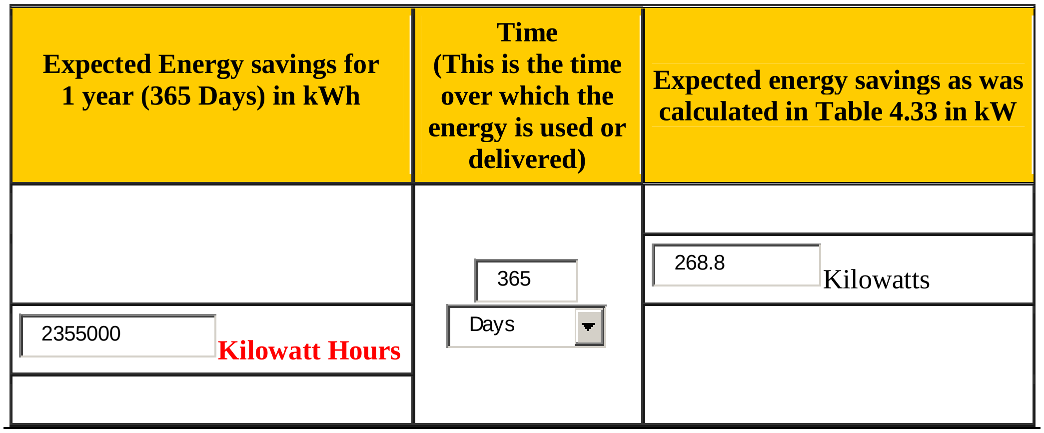
Load/Line Current (A)	**750**	**875**
Percentage load current to rated current (Approx.)	**85%**	**100%**
TERN Conductor with current Lay-lengths	***Scenario 1***	***Scenario 2***
AC Wattage Loss Component (W/m)	49.185	67.238
TERN Conductor with Optimised Lay-lengths (Production)	***Scenario 5***	***Scenario 6***
AC Wattage Loss Component (W/m)	49.051	66.89
Summary between Scenarios 1&2 and 5&6		
Theoretical AC Wattage Saving (W)	0.134	0.348
% AC Wattage Saving	0.27	0.52
Assumption: ie. A Single Conductor is used per Phase - 3 Phase system - Double circuit network - 100km Length		
Total Theoretical AC Wattage Saving (W)	80400	208800
Total Theoretical AC Wattage Saving (kW)	**80.4**	**208.8**

Table 4.34 – Expected ac wattage savings with Optimised Production lay-ratios/lay-lengths at load currents of 750A and 875A



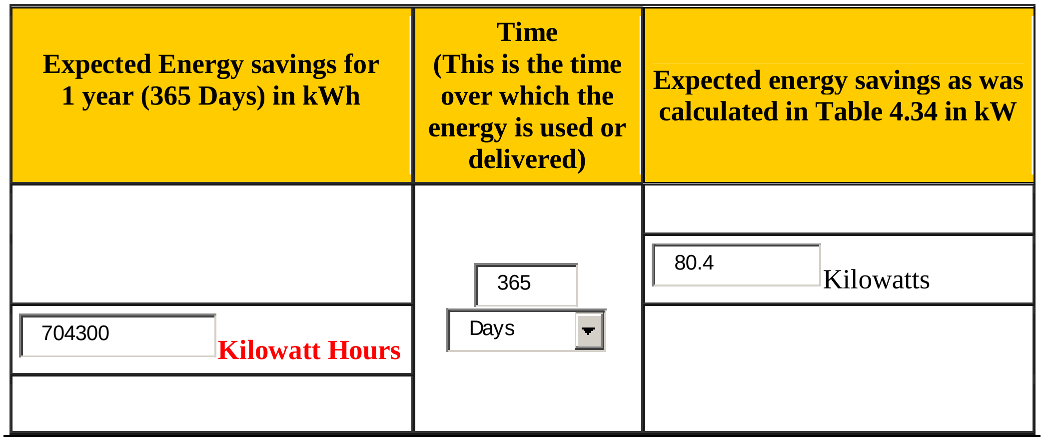
Expected Energy savings for 1 year (365 Days) in kWh	Time (This is the time over which the energy is used or delivered)	Expected energy savings as was calculated in Table 4.33 in kW
967100 Kilowatt Hours	365 Days ▾	110.4 Kilowatts

Table 4.35 – Expected ac wattage savings with Optimised lay-ratios/lay-lengths at a load current of 750A (For 1 year)



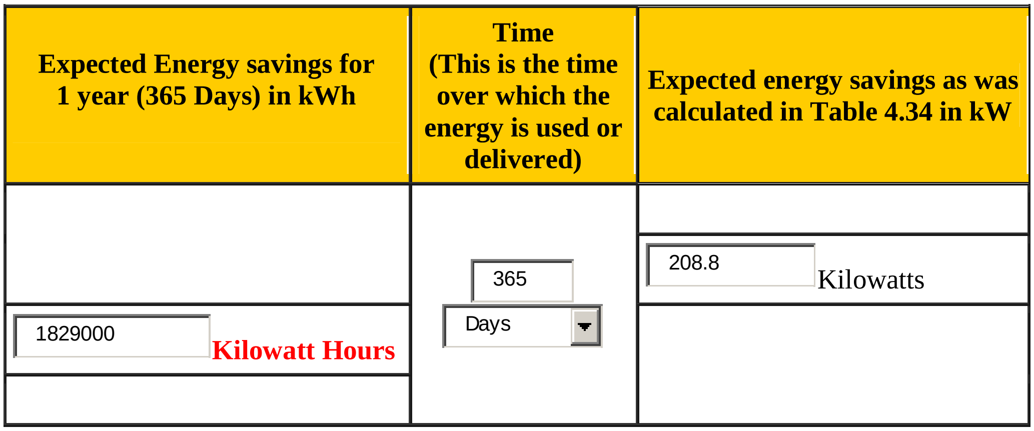
Expected Energy savings for 1 year (365 Days) in kWh	Time (This is the time over which the energy is used or delivered)	Expected energy savings as was calculated in Table 4.33 in kW
2355000 Kilowatt Hours	365 Days ▾	268.8 Kilowatts

Table 4.36 – Expected ac wattage savings with Optimised lay-ratios/lay-lengths at a load current of 875A (For 1 year)



Expected Energy savings for 1 year (365 Days) in kWh	Time (This is the time over which the energy is used or delivered)	Expected energy savings as was calculated in Table 4.34 in kW
704300 Kilowatt Hours	365 Days	80.4 Kilowatts

Table 4.37 – Expected ac wattage savings with Optimised Production lay-ratios/lay-lengths
at a load current of 750A (For 1 year)



Expected Energy savings for 1 year (365 Days) in kWh	Time (This is the time over which the energy is used or delivered)	Expected energy savings as was calculated in Table 4.34 in kW
1829000 Kilowatt Hours	365 Days	208.8 Kilowatts

Table 4.38 – Expected ac wattage savings with Optimised Production lay-ratios/lay-lengths
at a load current of 875A (For 1 year)

4.3 Summary of Key Findings

The discussions as presented in section 4.2, in terms of the lay-lengths and lay-ratios, are summarized in Table 4.39 below.

KEY :

s – Steel,
a1 – First Aluminium layer,
a2 – Second Aluminium layer,
a3 – Third Aluminium layer,
LL – Lay-ratio
D – Outer diameter
LR – Lay-ratio

Lay-length (mm)		**Outer Diameter (mm)**		**Lay-Ratio**	
A. Tern Conductor (Current/Original) (Applied to Computer simulation scenarios 1 & 2)					
LLs	110.97	Ds	6.75	LRs	**16.44**
LLa1	182.93	Da1	13.51	LRa1	**13.54**
LLa2	240.20	Da3	20.27	LRa2	**11.85**
LLa3	290.30	Da4	27.03	LRa3	**10.74**
B. Optimised Tern Conductor (Initial Software Simulation) (Applied to Computer simulation scenarios 3 & 4)					
LLs	110.97	Ds	6.75	LRs	**16.44**
LLa1	216.16	Da1	13.51	LRa1	**16.00**
LLa2	202.70	Da3	20.27	LRa2	**10.00**
LLa3	270.30	Da4	27.03	LRa3	**10.00**
C. Optimised Tern Conductor (Post Production Consultation) (Applied to Computer simulation scenarios 5 & 6)					
LLs	110.97	Ds	6.75	LRs	**16.44**
LLa1	206.00	Da1	13.51	LRa1	**15.25**
LLa2	206.00	Da3	20.27	LRa2	**10.16**
LLa3	271.00	Da4	27.03	LRa3	**10.03**

Table 4.39 – Lay-lengths/Lay-ratios:
(Current TERN conductor lay-ratios,
Optimised TERN Conductor lay-ratios [Initial Simulation],
Optimised TERN Conductor lay-ratios [Simulation post Production consultation])

The preceding tables 4.15 – 4.32 and their associated Graphs 4.1 - 4.18 all showed decreasing trends for each of the key output parameters (for grouped scenarios 1, 3, 5 and 2, 4, 6) reflected in Table 4.1 **(i.e. Magnetic Induction [Bm], Magnetic field strength[H], ac-dc ratio [kred], Magnetic resistance [∆R], ac resistance [Rac], Magnetic losses [Pmagnetic] and ac losses [Itot^2 Rac]**), with the exception of the **dc resistance (Rcon)** and the associated **dc resistance loss component (Itot^2 Rcon),** which both showed an increasing trends.

The proposed set of Optimised lay-lengths (lay-ratios) for the TERN conductor sample is therefore that of the ‘<u>Optimised Production lay-lengths</u>’ which is summarised and presented in Table 4.39 part C. The proceeding analysis is based on the selection of this optimized set of lay-lengths for the 3 layers of aluminium wires of the TERN ACSR conductor sample (the detailed computer simulations for this selection of optimised lay-lengths, at load currents of 750 and 875 A have been shown previously for scenarios 5 & 6, the detailed results of which are reflected in Tables 4.13 and 4.14 respectively).

The key parameters that impacted /influenced the effective ac resistance were found to be that of hysteresis & eddy current power losses and the redistribution of the layer currents for the TERN ACSR conductor sample, when the lay-lengths of its aluminium layers were varied. The **Magnetic Induction [Bm]** in the steel core showed a reduction of 35.5 – 36.64 % and the **Magnetic field strength [H]** show a reduction of 18.66 – 18.68 %.

As a result of the reduction in the effective magnetic induction in the steel core, the **ac-dc resistance ratio [kred]** showed a reduction of 0.69 to 0.98 % and the total **ac power losses [Itot^2 Rac]** were reduced by 0.27 – 0.52 %, as the load current was varied. It was also found that the **ac resistance [Rac]** of the TERN ACSR conductor sample could be reduced 0.27 – 0.52 %, synonymous with that of the reductions noted in the ac power losses.

Therefore the addition of the conductor dc resistance value to the component resistances produced by the current redistribution and magnetic hysterisis & eddy current power losses, form the total effective ac conductor resistance. This is contrary to standard practice where assumption is made that the conductor ac and dc resistance values are equal.

With the ac-dc resistance ratio ranging from 1.005 – 1.007 (i.e. the ac resistance is 0.5 – 0.7% greater than the dc resistance), it is evident that the magnetic core losses accounts for 0.2 – 0.25% of the increase in the ac resistance value and the current redistribution accounts for the remaining 0.3 – 0.43% of the increase in the ac-resistance value, based on the load current (i.e. 750A or 875A).

Based on a 100 (hundred) kilometer twin-circuit transmission line, with a single conductor being used per phase, the reductions in power loss would amount to approximately 704 300 kWhs – 1 829 000 kWhs over a one year period, based on the load current at a constant core temperature of 75 degrees celcius (Refer to tables 4.37 and 4.38). If the assumption of R1.55 is used as the cost/kWh, the expected savings would amount to R1, 091,665.00 – R2, 834,950.00 per year. If these values were to be extrapolated to reflect the possible savings that could be achieved over the life expectancy (+/- 50 years) of overhead transmission lines, then the savings in terms of electrical losses becomes hugely considerable.

The findings described above therefore confirmed the hypothesis of this research study as well as effectively satisfied the objectives of this research study.

5. CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

The primary objective of this research study was aimed at investigating the technique of optimising ACSR conductor lay-lengths to reduce electrical losses experienced by ACSR conductors, in order to optimise the electrical performance characteristics of bare ACSR conductors, in overhead line applications.

The hypothesis in carrying out this study was: The variation of stranding lay-lengths (i.e. pitch) will result in optimised service operation of multi-layered ACSR overhead-line conductors (Aluminium Conductor Steel Reinforced), through reduced power losses, in comparison to that, which would otherwise be experienced with the use of current conventional ACSR conductor lay-length constructions/designs.

The specific outcomes of this research study were to determine whether the effective ac resistance, ac-dc resistance ratio and ac power losses of overhead ACSR conductors could be reduced by varying the lay ratios or lay lengths, of the non-ferrous/metallic layers of aluminium wires that make up the ACSR conductor.

In order to determine and test the specific outcomes of this research study (i.e. evaluation of effective ac resistance, ac-dc resistance ratio and ac power losses of overhead ACSR conductors), a suitable research and analysis tool needed to be identified/developed. Having identified that there are several variables (i.e. the ferro-magnetic properties of the steel core, the physical construction of the conductor, the conductor operating/core temperature, the load current and the electrical system frequency) that interact simultaneously with lay-length variations to alter the effective ac resistance of the conductor, it was decided that the most effective research tool would be to develop a computer simulation program to perform and compute the outputs of these complex interactions.

Through in-depth literature review it was identified that the most suitable theoretical model on which to base and develop the computer simulation model, bearing in mind the primary research objectives, was the **Electromagnetic Model** as presented by Morgan and Price [6] and Barrett, Nigol, Fehervari & Findlay [7].

The selected theoretical model [7]

was then used as a basis to develop the computer software simulation program, using MATCAD 13 ® as the programming software. Several software simulation exercises were performed for a set of varied scenarios (described fully in Chapter 4). Using the developed software simulation program, a proposed set of optimised lay-lengths (lay-ratios) for the identified ACSR conductor research sample, was developed. The scenarios for which each of the computer simulations were performed, simulated what one could expect primarily in terms of electrical losses as a result of effective ac resistance variations, by changing or varying the lay ratios or lay lengths, of the non-ferrous/metallic layers of aluminium wires that make up the ACSR conductor. At the same time the behaviour of other critical parameters (i.e. magnetic induction, magnetic field strength and current re-distribution factors [i.e. ac-dc resistance ratio]) were noted and assessed for both cases of current lay-lengths versus optimised lay-lengths, for the identified ACSR conductor research sample.

5.2 Research Conclusions

The key parameters that impacted /influenced the effective ac resistance were found to be that of hysteresis & eddy current power losses and the redistribution of the layer currents for the TERN ACSR conductor sample, when the lay-lengths of its aluminium layers were varied. The **Magnetic Induction [Bm]** in the steel core showed a reduction of 35.5 – 36.64 % and the **Magnetic field strength [H]** show a reduction of 18.66 – 18.68 %.

As a result of the reduction in the effective magnetic induction in the steel core, the **ac-dc resistance ratio [kred]** showed a reduction of 0.69 to 0.98 % and the total **ac power losses [Itot² Rac]** were reduced by 0.27 – 0.52 %, as the load current was varied. It was also found that the **ac resistance [Rac]** of the TERN ACSR conductor sample could be reduced 0.27 – 0.52 %, synonymous with that of the reductions noted in the ac power losses.

Therefore the addition of the conductor dc resistance value to the component resistances produced by the current redistribution and magnetic hysterisis & eddy current power losses, form the total effective ac conductor resistance. This is contrary to standard practice where assumption is made that the conductor ac and dc resistance values are equal.

With the ac-dc resistance ratio ranging from 1.005 – 1.007 (i.e. the ac resistance is 0.5 – 0.7% greater than the dc resistance), it is evident that the magnetic core losses accounts for 0.2 – 0.25% of the increase in the ac resistance value and the current redistribution accounts for the remaining 0.3 – 0.43% of the increase in the ac-resistance value, based on the load current (i.e. 750A or 875A).

5.3 Recommendations for Future and Further Research

Using the developed a software simulation program (i.e. the research tool) that defines and computes the interactions between lay-length (Lay-ratio) variations and its impact on ac resistance for multi-layered ACSR conductors, one is now able to quite accurately predict the expected electrical power losses based on the total effective resistance of the conductor.

Having developed a proposal that specifies optimal lay-lengths, for the TERN ACSR conductor sample, based on computer simulation, a recommendation for further research would be to actually manufacture the TERN ACSR conductor using these 'Optimised Production lay-lengths', as presented in this research study. In this regard, and based on the research findings contained in this research report, Aberdare Cables Pty Ltd. has already initiated a development project which will be aimed at trial production/manufacturing runs and testing of the TERN ACSR conductor samples, using the proposed set of 'Optimised Production lay-lengths' **(Refer to Appendix C – PACE Project number: 00412).** The aim of this process would be to validate the projected/simulated savings in terms of electrical losses and reduction in ac resistance.

With successful validation results, it is further recommended that the lay-lengths of all other ACSR conductors manufactured by Aberdare Cables Pty. Ltd. be evaluated for possible optimisation, with the use of the developed software simulation program. The factory trial and testing processes should then be applied to each ACSR conductor identified for lay-length optimisation, as will be applied to the TERN conductor research sample.

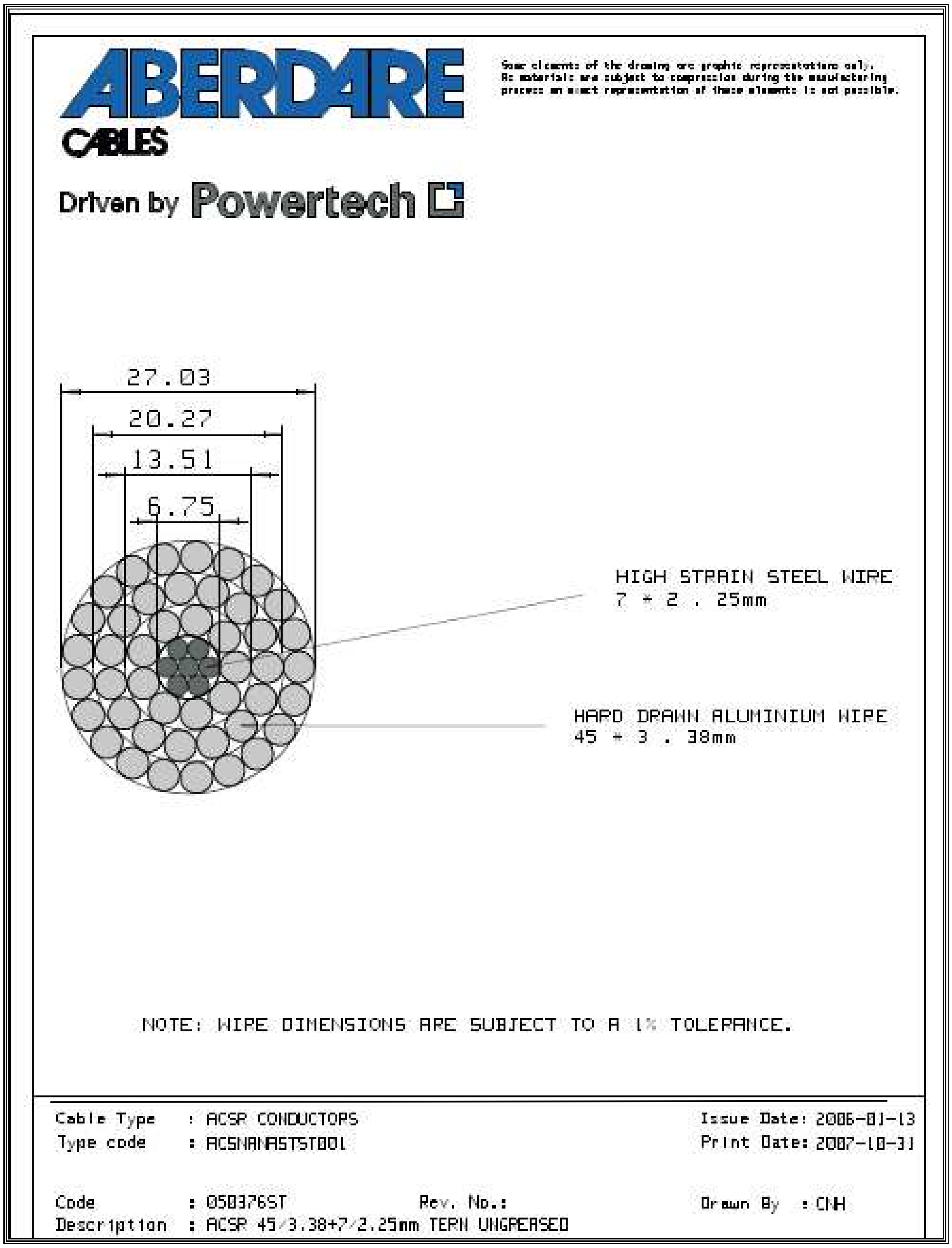
5.4 Conclusion

The results and findings produced by this research study show that the magnetic induction produced by the steel core in ACSR (Aluminium conductor, steel reinforced) conductors cause in increase in the ac power losses, associated ac-dc resistance ratio and the effective ac resistance of the conductor, whilst the conductor is energised during normal operation. More specifically, the key parameters that cause this increase in the effective ac resistance of the conductor, as a result of the magnetic induction produced by the steel core, are those of hysterisis and eddy current power losses in the steel core and an added power loss caused by the non-uniform redistribution of current in the layers of aluminum wires, due to the ‘transformer effect’. Therefore the addition of the conductor dc resistance value to the component resistances produced by the current redistribution and magnetic hysterisis & eddy current power losses, form the total effective ac conductor resistance. This is contrary to standard practice where assumption is made that the conductor ac and dc resistance values are equal.

The factors which influence the magnetic induction, include amongst others; the ferro-magnetic properties of the steel core, the physical construction of the conductor, the conductor operating/core temperature, the load current and the electrical system frequency. A computer simulation program was developed to calculate the effective ac resistance of multi-layer ACSR conductors and was largely based on determining the impact of varying these key factors, by evaluating its effect on the ac resistance of the conductor. It was found through manipulation of these factors that the total effective ac resistance of the conductor could be reduced and significantly so with higher load currents. The conductor sample used in this research study is commonly known as TERN ACSR conductor in the South African market and it was shown that with practical changes in lay ratios or lay lengths, one is able to reduce the total effective ac resistance of the conductor and associated power losses.

APPENDIX A

Drawing of TERN ACSR conductor



Some elements of the drawing are graphic representations only.
As materials are subject to compression during the manufacturing
process an exact representation of these elements is not possible.

NOTE: WIRE DIMENSIONS ARE SUBJECT TO A 1% TOLERANCE.

Cable Type : ACSR CONDUCTORS
Type code : ACSNANASTSTDOL
Issue Date: 2006-01-13
Print Date: 2007-10-31

Code : 050376ST
Rev. No.:
Drawn By : CNH
Description : ACSR 45/3.38+7/2.25mm TERN UNGREASED

Unless otherwise stated all Dimensions are Nominal and are Subject to Manufacturing Tolerances.
Aberdare reserves the right to make changes to this data as and when required.

APPENDIX B

TECHNICAL DATA SHEET

ABERDARE
CABLES

Code Name	**TERN**	**CONDUCTOR DETAILS**
Specification	**IEC 61089**	
Stranding and Wire Diameters	**45/3.38+7/2.25**	**No. AL/No. St/mm**
Diameter over Steel	**6.75**	**mm**
Overall Diameter	**27.03**	**mm**
Strand Build-up	**1St-6St–9Al-15Al-21Al**	
Type of Grease	**Ungreased**	
Grease Drop Point	**n/a**	**°C**
Aluminium Area	**403.77**	**mm^2**
Steel Area	**27.83**	**mm^2**
Total Area	**431.60**	**mm^2**
Aluminium Mass	**1114.91**	**kg/km**
Steel Mass	**220.04**	**kg/km**
Grease Mass	**N/A**	**kg/km**
Total Mass	**1334.95**	**kg/km**
DC Resistance at 20°C	**0.07154**	**ohm/km**
Ultimate Tensile Strength	**98710**	**Newtons**
Breaking Load	**10065**	**kg**
Coefficient of Linear Expansion	**21.22**	**per °C *10^{-6}**
Initial Modulus of Elasticity	**42900**	**N/mm^2**
Final Modulus of Elasticity	**66600**	**N/mm^2**
Current Rating (as per Operating Conditions stated below)	**875**	**A**
Short Circuit Rating (Temp rise from 75 to 200°C)	**34.28**	**kA for 1 Second**

Conductor - Black and Exposed to Sun	**OPERATING CONDITIONS**	
Operating Temperature	**75**	**°C**
Ambient Temperature	**25**	**°C**
Wind Speed	**0.44**	**m/s**
Solar Radiation	**0.089**	**W/cm^2**

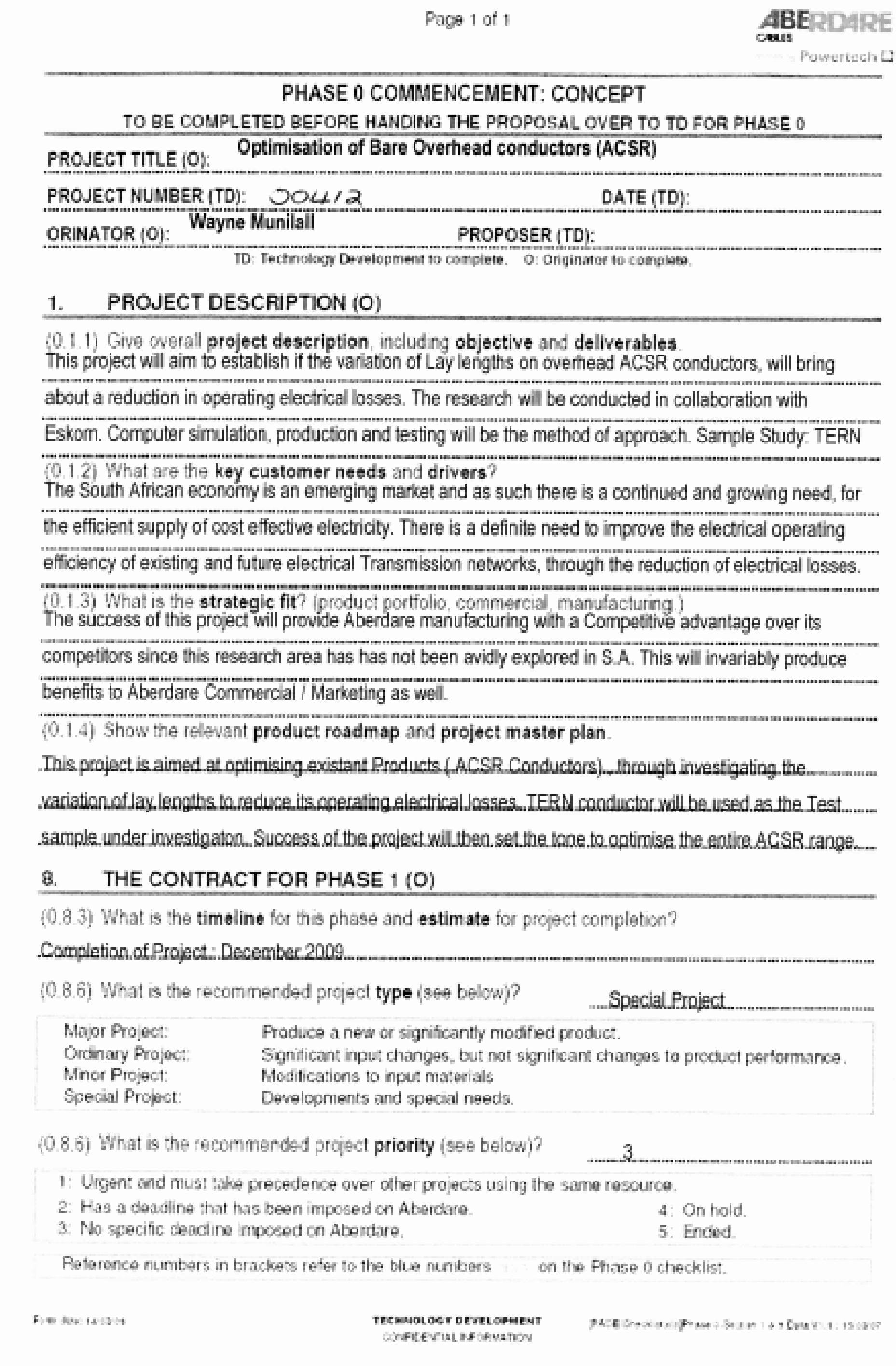
	DRUM DETAILS	
Offered Length	**4000**	**m**
Diameter over Flange Battens	**2476**	**mm**
Overall Drum Width	**1252**	**mm**
Gross Mass	**6025**	**kg**
Drum Material	**WOOD**	
Treated (i.e. Resistant against Biological attack).	**NO**	

Unless otherwise stated all Dimensions are Nominal and are Subject to Manufacturing Tolerances.
Aberdare reserves the right to make changes to this data as and when required.

ISO 9001 SABS

APPENDIX C

PACE DEVELOPMENT PROJECT



Page 1 of 1

PHASE 0 COMMENCEMENT: CONCEPT

TO BE COMPLETED BEFORE HANDING THE PROPOSAL OVER TO TD FOR PHASE 0

PROJECT TITLE (O): **Optimisation of Bare Overhead conductors (ACSR)**

PROJECT NUMBER (TD): 004/2 DATE (TD):

ORINATOR (O): **Wayne Munilall** PROPOSER (TD):

TD: Technology Development to complete. O: Originator to complete.

1. PROJECT DESCRIPTION (O)

(0.1.1) Give overall **project description**, including **objective** and **deliverables**.

This project will aim to establish if the variation of Lay lengths on overhead ACSR conductors, will bring about a reduction in operating electrical losses. The research will be conducted in collaboration with Eskom. Computer simulation, production and testing will be the method of approach. Sample Study: TERN

(0.1.2) What are the **key customer needs** and **drivers**?

The South African economy is an emerging market and as such there is a continued and growing need, for the efficient supply of cost effective electricity. There is a definite need to improve the electrical operating efficiency of existing and future electrical Transmission networks, through the reduction of electrical losses.

(0.1.3) What is the **strategic fit**? (product portfolio, commercial, manufacturing.)

The success of this project will provide Aberdare manufacturing with a Competitive advantage over its competitors since this research area has has not been avidly explored in S.A. This will invariably produce benefits to Aberdare Commercial / Marketing as well.

(0.1.4) Show the relevant **product roadmap** and **project master plan**.

This project is aimed at optimising existant Products (ACSR Conductors) , through investigating the variation of lay lengths to reduce its operating electrical losses. TERN conductor will be used as the Test sample under investigaton. Success of the project will then set the tone to optimise the entire ACSR range.

8. THE CONTRACT FOR PHASE 1 (O)

(0.8.3) What is the **timeline** for this phase and **estimate** for project completion?

Completion of Project : December 2009

(0.8.6) What is the recommended project **type** (see below)? Special Project

Major Project:	Produce a new or significantly modified product.
Ordinary Project:	Significant input changes, but not significant changes to product performance.
Minor Project:	Modifications to input materials
Special Project:	Developments and special needs.

(0.8.6) What is the recommended project **priority** (see below)? 3

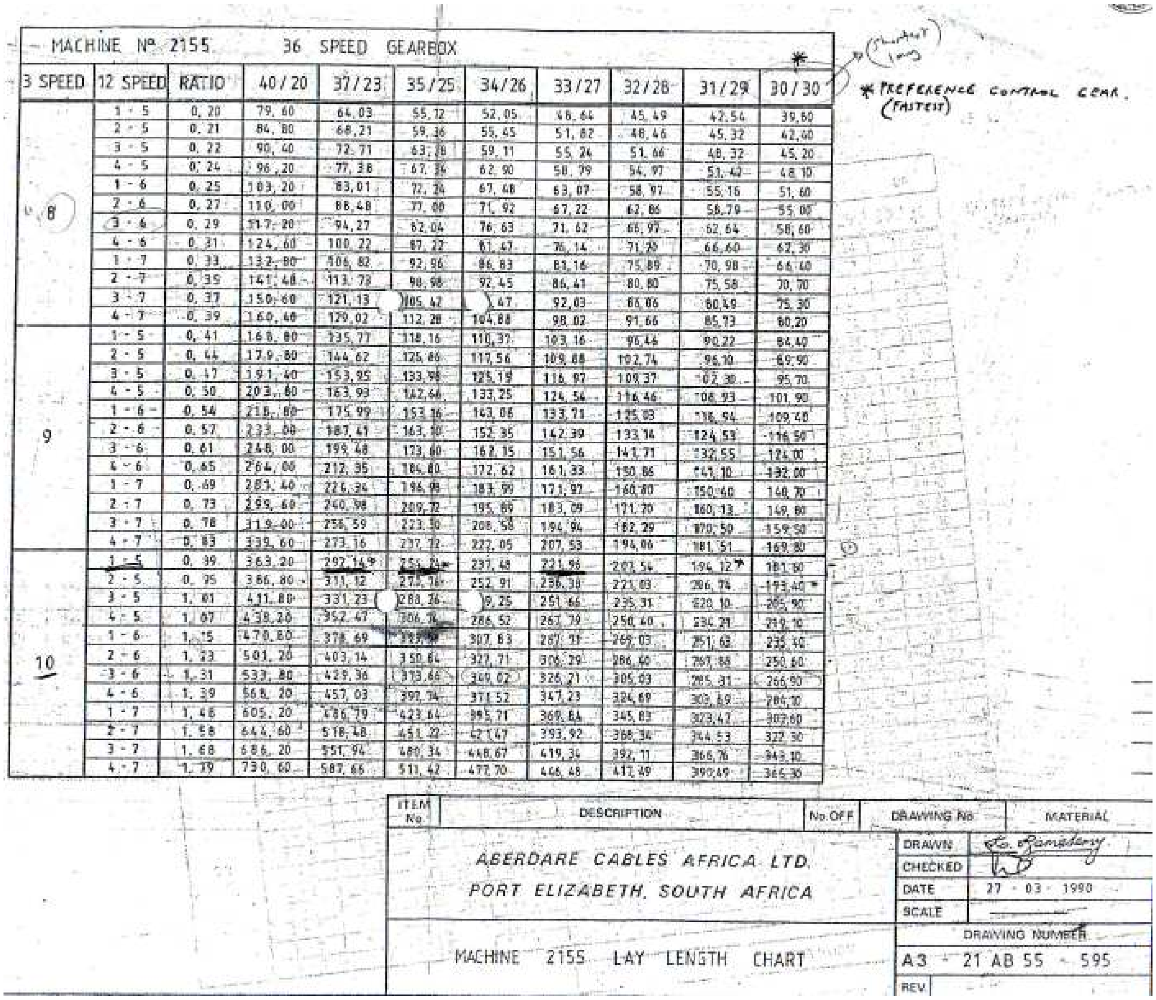
1: Urgent and must take precedence over other projects using the same resource.
2: Has a deadline that has been imposed on Aberdare.
3: No specific deadline imposed on Aberdare.
4: On hold.
5: Ended.

Reference numbers in brackets refer to the blue numbers on the Phase 0 checklist.

TECHNOLOGY DEVELOPMENT
CONFIDENTIAL INFORMATION

APPENDIX D

MACHINE GEARING RATIO CHART



MACHINE Nº 2155 36 SPEED GEARBOX

3 SPEED	12 SPEED	RATIO	40/20	37/23	35/25	34/26	33/27	32/28	31/29	30/30 *
8	1 - 5	0,20	79,60	64,03	55,12	52,05	48,64	45,49	42,54	39,60
	2 - 5	0,21	84,80	68,21	59,36	55,45	51,82	48,46	45,32	42,40
	3 - 5	0,22	90,40	72,71	63,28	59,11	55,24	51,66	48,32	45,20
	4 - 5	0,24	96,20	77,38	67,34	62,90	58,79	54,97	51,42	48,10
	1 - 6	0,25	103,20	83,01	72,24	67,48	63,07	58,97	55,16	51,60
	2 - 6	0,27	110,00	88,48	77,00	71,92	67,22	62,86	58,79	55,00
	3 - 6	0,29	117,20	94,27	82,04	76,63	71,62	66,97	62,64	58,60
	4 - 6	0,31	124,60	100,22	87,22	81,47	76,14	71,20	66,60	62,30
	1 - 7	0,33	132,80	106,82	92,96	86,83	81,16	75,89	70,98	66,40
	2 - 7	0,35	141,40	113,73	98,98	92,45	86,41	80,80	75,58	70,70
	3 - 7	0,37	150,60	121,13	105,42	[illegible]	92,03	86,06	80,49	75,30
	4 - 7	0,39	160,40	129,02	112,28	104,88	98,02	91,66	85,73	80,20
9	1 - 5	0,41	168,80	135,77	118,16	110,37	103,16	96,46	90,22	84,40
	2 - 5	0,44	179,80	144,62	125,86	117,56	109,88	102,74	96,10	89,90
	3 - 5	0,47	191,40	153,95	133,98	125,19	116,97	109,37	102,30	95,70
	4 - 5	0,50	203,80	163,93	142,66	133,25	124,56	116,46	108,93	101,90
	1 - 6	0,54	218,80	175,99	153,16	143,06	133,71	125,03	116,94	109,40
	2 - 6	0,57	233,00	187,41	163,10	152,35	142,39	133,14	124,53	116,50
	3 - 6	0,61	248,00	199,48	173,60	162,15	151,56	141,71	132,55	124,00
	4 - 6	0,65	264,00	212,35	184,80	172,62	161,33	150,86	141,10	132,00
	1 - 7	0,69	281,40	226,34	196,98	183,99	171,97	160,80	150,40	140,70
	2 - 7	0,73	299,60	240,98	209,72	195,89	183,09	171,20	160,13	149,80
	3 - 7	0,78	319,00	256,59	223,30	208,58	194,94	182,29	170,50	159,50
	4 - 7	0,83	339,60	273,16	237,72	222,05	207,53	194,06	181,51	169,80
10	1 - 5	0,89	363,20	292,14*	254,24*	237,48	221,96	207,54	194,12*	181,60
	2 - 5	0,95	386,80	311,12	270,76	252,91	236,38	221,03	206,74	193,40*
	3 - 5	1,01	411,80	331,23	288,26	[illegible]	251,66	235,31	220,10	205,90
	4 - 5	1,07	438,20	352,47	306,74	286,52	267,79	250,40	234,21	219,10
	1 - 6	1,15	470,80	378,69	[illegible]	307,83	287,71	269,03	251,63	235,40
	2 - 6	1,23	501,20	403,14	350,84	327,71	306,29	286,40	267,88	250,60
	3 - 6	1,31	533,80	429,36	373,66	349,02	326,21	305,03	285,31	266,90
	4 - 6	1,39	568,20	457,03	397,74	371,52	347,23	324,69	303,69	284,10
	1 - 7	1,48	605,20	486,79	423,64	395,71	369,86	345,83	323,47	302,60
	2 - 7	1,58	644,60	518,48	451,22	421,47	393,92	368,34	344,53	322,30
	3 - 7	1,68	686,20	551,94	480,34	448,67	419,36	392,11	366,76	343,10
	4 - 7	1,79	730,60	587,66	511,42	477,70	446,48	417,49	390,49	365,30

(Shortest lay)

* PREFERENCE CONTROL GEAR.
(FASTEST)

ITEM No.	DESCRIPTION	No. OFF	DRAWING No	MATERIAL

ABERDARE CABLES AFRICA LTD.
PORT ELIZABETH, SOUTH AFRICA

MACHINE 2155 LAY LENGTH CHART

DRAWN	
CHECKED	
DATE	27 - 03 - 1990
SCALE	
DRAWING NUMBER	A3 - 21 AB 55 - 595
REV.	

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