DYNAMIC MODELLING OF
AC POWER LINES FOR RAILWAY TRACTION

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DECLARATION

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no materials previously published or written by another person nor material which has been accepted for the award of any other degree or diploma of the university or other institute of higher learning, except where due acknowledgement has been made in the text.

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Date : 27-6-2017

THESIS COMPLETION CERTIFICATE

This is to certify that the thesis entitled **DYNAMIC MODELLING OF AC POWER LINES FOR RAILWAY TRACTION** submitted by **RAVI KUMARAN NAIR.C** to **UNIVERSITY OF PETROLEUM AND ENERGY STUDIES, DEHRADUN** for the award of the Degree of Doctor of Philosophy (Engineering) is a bona fide record of the research work carried out by him under our supervision and guidance. The contents of this thesis, in full or parts have not been submitted to any other Institute or University for the award of any other degree or diploma.

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EXECUTIVE SUMMARY

Railway is considered to be the most suitable mode of bulk inland transportations for energy efficient operation, because of its ability to transit large volume of freights to longer distances with lesser duration of time, with lesser risks. Besides, any mode of traction used in railways shall be more energy efficient than that of road traffic with the reasons, like; lesser wind resistance due to trains' snake shape configuration, avoidance of frequent breaking due to the presence of lesser number of obstructions on its running path, avoidance of quick acceleration of the vehicles, absence of steep gradients & curves on the railway tracks etc,.

A comparative study made on the energy efficient operation of various types of tractions used in railways (A1) brought to light that the high voltage alternating current (ac) electric traction is the best system of traction for railways [20]. The figures on the cost effectiveness of Diesel Traction and Electrical Traction of Indian Railways organization for the year 2011-12[39], which is indicated below to substantiate it.

Diesel-Electric Power

Percentage consumption of energy	42.56 %
Percentage sharing of traffic load	39.08 %
Percentage sharing in energy cost	55.257%
(@ Rs 40/- litter of High Speed Diesel, HSD)	

Electric Traction Power

Percentage consumption of energy	57.36 %
Percentage sharing of traffic load	61.10 %
% sharing of energy cost (on national average basis)	44.143%
(cost of energy @ Rs 6.0/kWh)	

Even though the high voltage electric traction is the best choice for the energy efficient operation of train traffic, a literature survey made on the statistics of railway networks [38] in developed as well as in developing countries revealed that the interest shown by the developed countries in electrifying their railway tracks are too poor, except by Germany (A2), whereas, the momentums in electrifying their railway tracks in developing countries are very high. Despite being a poor country, South Africa takes the leading role in the railway track electrification, in percentage wise.

Unlike in fossil fuel driven train locomotives, cost involved in constructing the infrastructures for feeding electric power to traction power networks in railway is highly capital intensive. Recurring expenditures are also required for its regular operation & maintenance. No tangible difference is there in the costs of fuels in electric traction and in diesel traction. Besides, the constraints added on the railway systems with the electrification of the railway tracks drastically reduces the flexibility in modifying the railway system, and increases risks on safety issues.

However, it became mandatory to electrify their railway tracks in developing countries due to risks on energy security, which shall always be under the influence of policy changes made in the production of crude oil by the Organization of Petroleum Exporting Countries (OPEC) & developed countries. It is obvious that developing countries prefer to switchover to other fuels from petroleum products. Availability of other sources of energy like coal & hydroelectricity, other factors like political, environmental and local economic reasons are also the contributing factors in adding momentum in electrifying the railway tracks in developing countries. The main constraint involved in railway track electrification is that, once the railway tracks electrification works begin, there shall not have any other options, except to complete the electrification of track at that region, because of the technical & operational constraints evolve with the partial electrification.

Railway network is the integral form of so many inter-dependent functional sub networks. Some of them are; Train Traffic Control or Section Control, Communication Fault Control, Crew Control, Ballast & Track Control, Commercial Control, Carriage & Wagon Control, Locomotive Control etc. One more functional sub network, termed as Traction Power Control (TPC),is added to the railway system with the electrification of railway tracks.

Functions of the TPC are; to ensure uninterrupted power supply to the electric traction network, to arrange facilities for the field units for the maintenance activities, to ensure the co-ordinations of electric traction branches with other functionary branches, to arrive at quick & apt decision for the disaster management actions etc.

Except the TPC, all other control networks function on human command mode. TPC is the man-technology sandwiched 'decision making' systems, with the aid of computer hardware & software, sensors and agent technologies for ensuring the safety and reliability in the electric traction system.. Those types of system are integrated with several basic functional modules. One such module shall usually caters more than 300 kilo meters length of electrified rail route. The human (Traction Power Controllers) who are assigned the responsibility for making decisions on such systems in crucial time should have; sound working knowledge of the systems, proper information about the sections of railway route, keen intelligence, knowledge on the latest statutory provisions & restrictions, ability to diagnosis the fault symptoms, ability to take appropriate decision in-time etc. for ensuring the effective system safety & reliability management. Major disasters may happen if the controller of the system malfunctions or fails to diagnosis the crisis on real time basis.

Developed countries used to electrify their suburban rail routes only. Whereas, developing countries already had electrified non-suburban rail routes to a large extent, and continue to electrify rest of the railway tracks also. Electrified non-suburban areas of tracks are prone to risk to railway systems' reliability. Persisting traction supply failure happen due to vandalism on the electric traction lines, earth faults happen on it due to the presence of foreign bodies like; tree branches, birds, animals, human etc. shall lead to the train traffic detention for prolonged duration (A3). As the quantum of railway electrification done in developing countries at rural areas are very high, the risk on the railway systems' reliability shall also be very high.

It is needless to say that obtaining of uncorrupted & reliable data on such vulnerabilities, that too, from the primary sources in time are essential for the apt decision making process in pinpointing the persisting faults on electric traction lines. Else, even if the Traction Power Controller is a careful & intelligent man, the potential unintentional or unnoticed threats prevail in the electric traction power system can cause abnormal disruption to the railway traffic, and endanger the system reliability & safety.

With the survey made at the sampling region of an actual electric traction railway system (A4), it is understood that the wrong indication of the location of the persisting earth fault occurred on them is the prime cause of concern of the railway system. It is observed from the field survey that the pin pointing of locations for many persisting faults on the railway electric traction system by the computer-agent technology aided fault locating system were largely deviated from the actual fault position.

Once the faults persist on the high voltage railway electric traction lines, traction supply could not restore until those faults are cleared off. Every railway organization will have quick response teams equipped with breakdown vehicles &equipment to clear such faults. But, it is very important that correct position of the persisting fault(s) on the electric traction lines are to be informed to the breakdown attending team. Deviation of one kilometre in the informed fault location from the actual shall consume 40 to 50 minutes extra to clear those faults off, which shall be highly embarrassing to the railway system at that region in total.

Further, with the intensive study made at the sampling region revealed that the variation happened in the parasite capacitance in the ac high voltage traction line is primarily responsible for the erratic pinpointing of the persisting earth fault position on electrified railway system. The said factor is found to be attributed by the various topographical features like; presence of hillocks, earth cuttings, tunnels, over line structures etc. at the proximity of the high voltage ac electric traction lines. Since all those features are present in irregular manner, the variations in the parasite capacitance are also found irregular.

Hence, the experimental studies conducted with the help of table top as well as prototype models of high voltage ac traction lines for the identification& quantification of those vulnerabilities causing the changes in the parasite capacitance on ac electric traction system, and the subsequent re-modelling of it are detailed in this report. Further, this research work suggest the feasible algorithm to mitigate railways’ risk in pinpointing the persisting earth fault on high voltage ac power traction lines with the dynamically modelled high voltage ac electric railway traction line.

LIST OF SYMBOLS

$\mu\Omega$	micro ohm
Ω	ohm
$\prod$	pai
X_C	capacitive reactance
I_f	earthfault current
ℓ	earth fault distance
X_L	inductive reactance

LIST OF ABBREVIATIONS

AT	Auxiliary Transformer
ATD	Automatic Tensioning Device
ac	alternating current
AIC	Akakine Information Criteria
BG	Broad Gauge
BIC	Basiyan Information Criteria
Coef.	Coefficient
DPR	Distance Protection Relay
EHV	Extra High Voltage
F	Farad
FEP	Front End Processor
GDP	Gross Domestic Product
H	Height
I_f	Fault current
INR	Indian National Rupee
km	kilo metre
kgf	kilogram force
km/h	kilometre per hour
kV	kilo volt
L	Length
m	metre
mm	millimetre
MG	Metre Gauge
MODEM	Modulator & Demodulator
MVA	Megavolt Ampere
nF	nano farad
NG	Narrow Gauge
OPEC	Organization of Petroleum Exporting Countries
pF	Pico Farad
RCA	Relay Critical Angle

RCC	Remote Control Centre
R&D	Research & Development
RDSO	Research Design and Standard Organization
RTU	Remote Terminal Unit
SCADA	Supervisory Control And Data Acquisition
SoD	Schedule of Dimensions
SP	Sectioning Post
SSP	Sub Sectioning Post
sq.mm	millimetre square
TPC	Traction Power Control
TPCR	Traction Power Control Room
TSS	Traction Sub Station
viz.	namely
WAN	Wide Area Network
WS	Work Station
Z_f	Fault Impedance
z	Impedance of 100 long block of OHE

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CHAPTER 1
INTRODUCTION

1.1 STATISTICS ON THE ELECTRIC TRACTION NETWORKS IN VARIOUS RAILWAY ORGANIZATIONS

Almost all the developing countries are tending to go for electrifying more and more rail routes with high voltage ac electric power, mostly with 25kV, 50 Hz electric, mainly due to the energy security reasons, and the risks attributed by the policy changing by the OPEC and developed countries. The statistics [1] on the electrified rail routes of various countries substantiate it. Even though the United States of America has the biggest railway networks with approximately 2,50,000 kilo metres (km) rail route, total length of electrified track is only 1,600 km. Similar is the cases in almost all developed countries, except in Germany, whereas, almost all the developing countries have large electrified tracks in their railways networks. China has electrified 65,000 km railway track out of total 121,000 km track length. South Africa has electrified 80 % of their railway tracks by this time. India has already electrified 44,950 km railway track out of 115,000 km, and continues to electrify 3000 km of railway tracks in every year.

1.2 IMPORTANCE OF AC ELECTRIC TRACTION SYSTEMS IN RAILWAYS.

The Gross Domestic Product (GDP) of any nation directly depends on the mobility of the raw materials and finished goods from sources to destinations. The stagnation of raw materials, fuels, food grains and other commodities will lead to war-like situations and shall breaks out the direness in the nation. Wider railway networks play key roles in promoting GDP. Obviously, the drooping of railway electric traction power network systems' reliability will directly results to deep negative impact on the growth of the GDP. In the context of developing countries, electric traction power networks act as the booster of rail transportation system. Evidently, in India, railway traffic dealt on electrified routes is around 68 % of the total, whereas the length of electrified track is only around 35 % of the total [2]. Obviously, traffic interruption in electrified rail routes can give enormous setback on the GDP of the developing countries.

Railway Electrification system is the integral form of various facilities that are made to transit electrical energy from high tension electric power network to the electric locomotive (load). It has many similarities with the transmission & distribution system of electric power sector. The main differences between electrified railway system and the general electric power system lie on the arrangement of feeding the electric power to the load. Unlike the electric power transmission and distribution system, railway electrification system feeds power to the moving load (electric locomotives) and there exists many general safety as well as reliability aspects which are not able to be complied as it is the case of general power transmission systems. However, Railway electrification networks are constructed at overhead of the railway tracks, which are considered to be isolated system from the remaining power networks, as well as from the public. Railway electrification system shall ordinarily be linear in general layout (Fig.1.1)

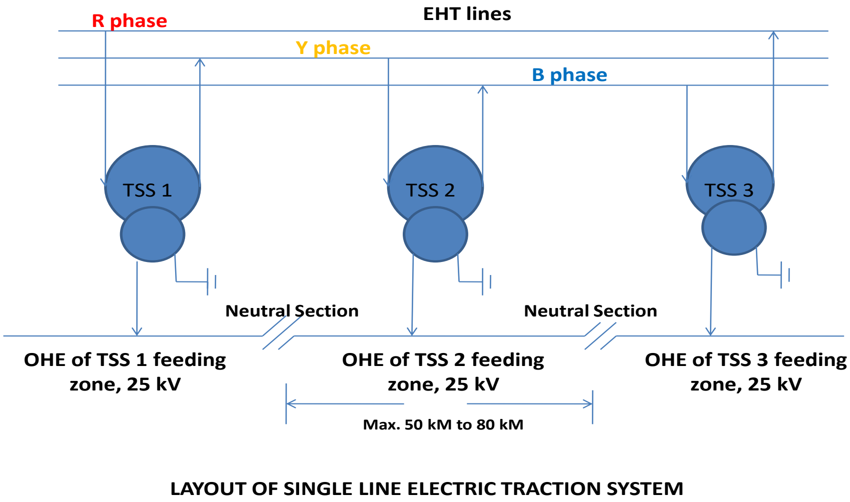

Fig. 1.1 Single line diagram of high voltage ac electric traction system

Most of the railway electric traction network systems are of high voltage ac power, and the most ongoing electrification projects are also of the same nature.

1.3 MAIN COMPONENTS OF RAILWAY ELECTRIC TRACTION SYSTEM

Traction Power Supply System includes three main components, viz. Traction Sub Station (TSS), Traction Power Distribution Lines (also called as Over Head Equipment or OHE), and the Traction Current return paths.

1.3.1 INCOMING POWER SUPPLY ARRANGEMENTS FROM THE EHV ELECTRIC POWER NETWORKS TO THE RAILWAY ELECTRIC TRACTION SYSTEM

The incoming supply to the Traction substation shall be from the locally available three phase power grid of power generation/distribution companies, whose voltage shall normally be 66 kV, 110kV, 132kV, 220kV or 400 kV. The inter spacing of high voltage ac TSSs shall vary in between 50km to 80 km. Standard designed TSS normally needs two phases to fed with. Hence the asymmetry in loading due to the TSS is likely to occur on the EHV power grid. The percentage of asymmetry due to the railway traction load to a grid is calculated as the ratio of asymmetric load on the two phases to the three phase fault level of the grid. The value of this fraction should ideally be zero. However, a maximum 3% of such load asymmetry is found permitted in many countries. As such, it shall be advisable to feed the Traction substation through two phases from a three phase grid system of voltage 66 kV or above, whose fault level shall be in the order of many thousands MVA [3]

1.3.2 GENERAL LAYOUT OF TRACTION SUB STATION

Traction Sub Station (Fig.1.2) receives the power from the EHV electric grid and transforms it into the voltage rating of the electric locomotives. TSSs in general are designed to receive the power through two phases and to feed the power supply arrangements to locomotive in single phase. Hence it is obvious that the TSSs are designed as single phase except at the receiving point. Two pole circuit breaking arrangements are provided at the incoming power side and single pole circuit breakers are provided at the outgoing side. Single phase transformer with high impedance voltage (in the order of 12 to 15%) shall be used as the traction power transformer. The secondary voltage of ac power traction transformer shall be 25kV at its normal working tap. The primary windings are tailor-made in accordance with the available grid voltage at the incoming side. There shall be two such parallel standby arrangements (bays) available at most of the TSSs with equipment for proper coupling of bays

1.3.3 EQUIPMENTS AT TRACTION SUB STATION

Traction Sub Stations (TSSs) located along the railway track at theoretically equal distance. This inter-distance may slightly vary with the factors like; availability of Extra High Voltage (EHV) lines nearby the railway track, availability of suitable lands to construct TSS, road approachability to proposed site etc.. Each TSS will have all the commonly available components of an electric substation, like; Power Transformers, switchgears, protective relays, other protective systems like lightning arrestors & overhead earth screens, instrumental transformers (Potential Transformer & Current Transformers), buried earth grids etc. (Fig. 1.2)

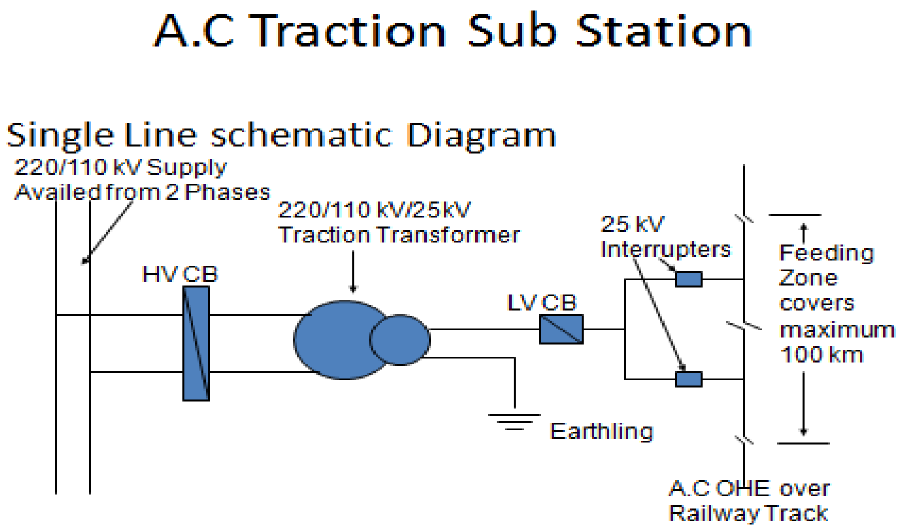

Fig. 1.2 Single line schematic diagram of an EHV/25 kV ac TSS

TSS is designed to work on single phase. The incoming supply shall be the two phases from the EHV grids. Outgoing is single phase only, with the neutral conductor solidly earthed and connected to the railway track. Phase line will be connected to the Traction Power Distribution Line. The traction circuit is completed through the secondary winding, OHE, the electric locomotives and the return path of traction current, which is theoretically, shall be the rails (Fig. 1.3)

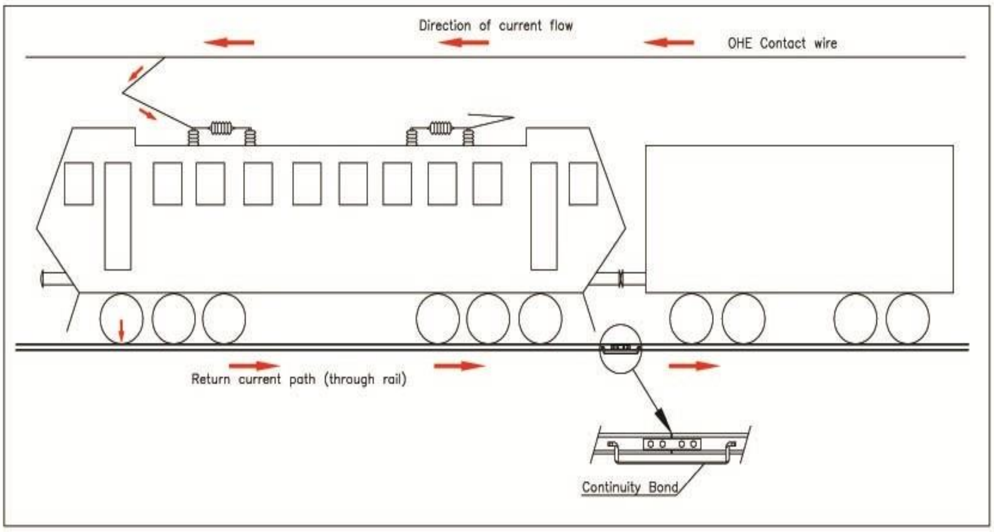

Fig. 1.3 Flow of railway traction current

1.3.4 TRACTION POWER DISTRIBUTION LINES

Traction power distribution lines are also termed as Over Head Equipments (OHE) since it is deployed exactly at the overhead of the railway tracks (Fig 1.4).

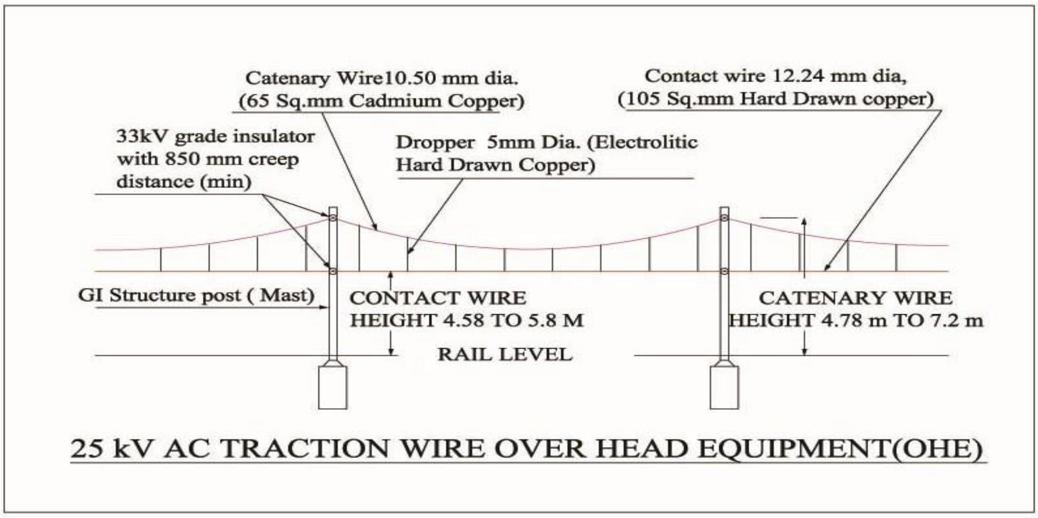

Fig.1.4.Dimensional details of conventional high voltage OHE

OHE is fed at single point with the high voltage electric power from TSS (most probably at the end point of the feeding sector). It consists of the catenary system, along track feeder system, intermediate auxiliary transformer stations (ATSs) and Sectioning Posts (SP). Maximum length of the OHE fed with electric supply through switchgear associated with protective relays usually shall be 30 to 40 km, and the working voltage shall be below 27.5 kilo volts (kV).

1.3.5 TRACTION CURRENT RETURN PATHS

Traction power return paths comprise of the running rails, various traction bonds like; inter rail bonds which ensures the even distribution of return track currents through both the rails in normal case, and ensure the availability of at least one path for the return traction current when one rail is defective, impedance bond which ensures the flowing of return traction only through the traction rails at track circuited signal areas, cross bonds which interconnect two or more railway tracks to ensure the alternative paths for the return traction currents or fault currents, in case of other railway tracks are defective etc. (Fig. 1.5)

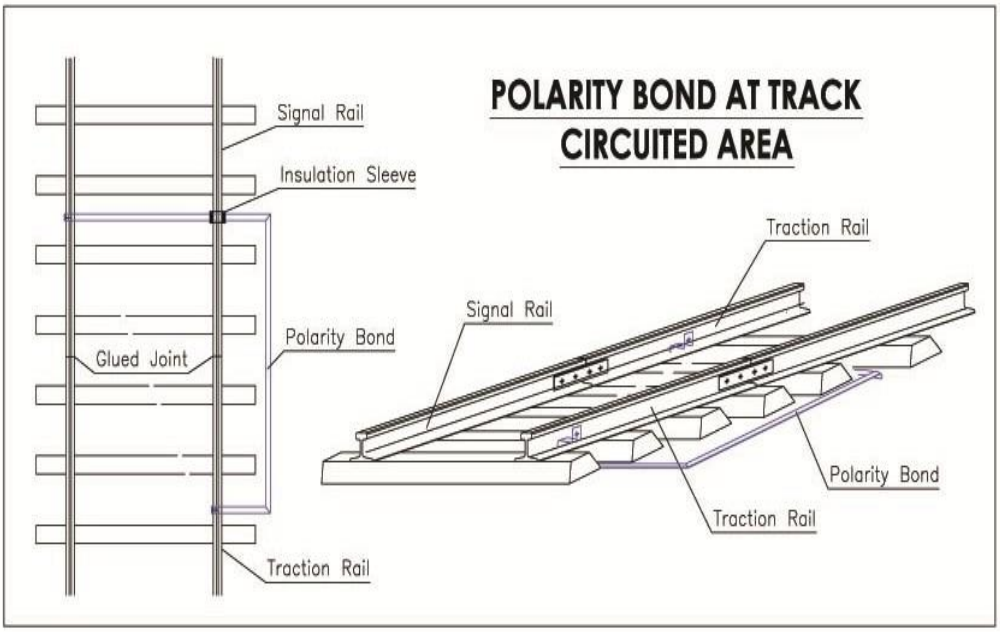

Fig. 1.5 Various bonds used in railway electric traction system

The ground (earth) itself acts as the return path for traction current from the locomotives to the TSS.

1.3.6 TRACTION POWER CONTROL SYSTEM

Electric traction power network's assets on every 300 to 400 km of electrified tracks are under the direct operational control of a supervisory electrical engineer, called Traction Power Controller (TPC). He acts as the 'master' of the network. His place of work, called Traction Power Control Room (TPCR) shall be at centrally located in every regional railway systems. TPC has to act as the supreme controller of the high voltage electrical traction power networks comprising of four to six extra high tension sub stations (called, Traction Sub Station, TSS with 220 kV or 110 kV or 66 kV incoming supply) and ten to fifteen intermediate high tension (25 kV) switching stations, termed as Sub Sectioning & Paralleling post ie. SPs and SSPs (Fig. 1.6).

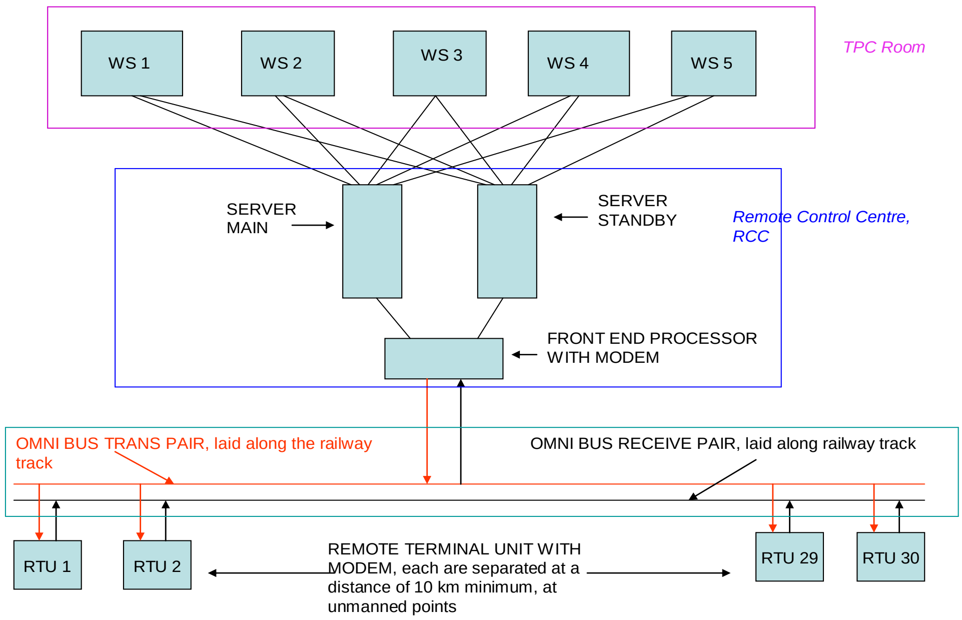

Fig 1.6 Computer aided control network of Electric Traction Power system

There shall be around 100 extra high tension/high tension switchgears to be controlled by the TPC for various system related functions. Several nodes with sensors for sensing the real time conditions and abnormalities are incorporated in this network. All these are being effectively managed with Supervisory Control And Data Acquisition (SCADA) system [4]. Three to five numbers of Works Stations (WS, the Personal Computers with mimic diagrams) are made available for the use of TPC in the TPCR Those work stations provides primary information about the conditions of the equipment and lines in traction power network to the Traction Power Controller in the form of verbal and pictorial messages with the inputs received from various nodes. Servers (main & Stand by) and Front End Processors (FEP) with MODEM are kept in a separate locked room called Remote Control Centre (RCC). Omni bus trans and receive pair of wires (usually optical fibre cables), are buried along side of the railway track with surface mounted connecting nodes at certain intervals, called Remote Terminal Units. The Omni bus will have more than 300 kilo meter length, which connect almost all the controlled nodes of the WAN.

Remote Terminal Unit (RTU) along with Modulator & Demodulator (MODEM) are provided for each TSS , SSP and SP. SCADA WAN is generally designed of catering maximum 30 RTUs. The RTU gathers information about the equipment under their service area in round robin fashion (polling) , and send to server. Also, they receive supervisory command from the TPCR & actuate the field equipment. The information thus passed to server by RTUs are voltage, current, open/close condition of switchgears, actuation of protective relays and alarms etc. Traction Power Controller is able to assess the condition of the traction power line under his control only through the information passed by the equipment and relays only. If the TPC gets misleading or incorrect information from these sensors, it may lead to hours longing train traffic block or even disasters.

1.4 CHALLENGES FACED BY THE ELECTRIC TRACTION SYSTEM

Developing countries are the promoters of high voltage ac electric traction in railways. They already had electrified non-suburban rail routes to a large extent, and continue to electrify rest of the railway tracks also. Electrified non-suburban areas of tracks are prone to risk to railway systems' reliability. Persisting traction supply failure happen due to miscreant actions on the electric traction lines, or earth faults happen on it due to making of continuity with earth by foreign bodies like; tree branches, birds, animals, human etc. shall lead to the train traffic interruption for prolonged period. Quantity of electrification done on railway tracks in developing countries at non-suburban areas are very large, the chances of traffic interruption due to persisting earth fault on electric traction lines shall also be very high.

Occurrence of the faults persist on railway electric traction lines will automatically interrupt the traction supply could, which could not be restored until those faults are cleared off. It is very essential to correctly locate the position of the persisting fault(s) on the electric traction lines for clearing them off with minimum possible time. Difference in indicating the fault location by one kilometre from the actual shall consume nearly 45 minutes extra to clear those faults. Such situations are highly detrimental to the railway systems' reliability at that region in total.

1.4.1 IMPORTANCE OF FLAWLESS THEORIES IN FAULT PINPOINTING PROCESS IN DECISION MAKING

Every electric traction system are equipped with fault locating modules. The fault locating module of electric traction power network aims to support the decision making process of the Traction Power Controller to direct the breakdown attending group to the affected part of electric traction lines at the fastest means.

The causes of occurring prolonged fault on electric traction lines are essentially to be avoided. But, it is not feasible to establish a fault-free electric traction system, as they are opened to all kind of external vulnerabilities. The faults occurred on OHE can be classified as 'momentary' and 'persisting'.

Momentary faults

These types of earth faults occur when conducting materials like; tree branches, animals, birds etc. come in contact with the live electric traction lines, and burned off itself within fraction of a second. Naturally occurring lightning surges on electric traction lines also cause the monetary faults. It happens because the high frequency lightning impulses grounded through the lightning arrester. Even though the momentary faults are vulnerable, they are not much detrimental to the railway system as a whole as they don't become the cause of railway traffic interruption.

Persisting faults

These types of faults are likely to be happened due to mechanical collapse of the traction lines & its fixtures, electrical puncture of insulators, permanent puncture of lightning arrestors & pole assembly of switch gears, bypassing of insulators provided on the metallic supports (masts) of electric traction lines with the sticking of electrocuted bodies etc, Those fault will disrupt the entire train traffic at that region till those are cleared off. Statistical data on the persisting and non-persisting faults occurred at the sampling region of 635 km long rail route for a period of one year from July 2015 and June 2016 (A3) indicate that the chances of occurring persisting faults are around 10 % of the total on an average.

1.5 RESEARCH MOTIVATION

Risk on nation's energy security is mitigated to a large extent in non-oil producing countries with the electrification of railway track. On the other hand, the risk on reliability of train traffic increases due to persisting earth faults occurred on it. The prevailing technology developed for fault pinpointing is found made on ideal working conditions of electric traction system. But in actual, the working conditions of high voltage traction lines vary widely at non-suburban & topographically challenged areas. Those situations add risk on to the reliability of the railway electric traction systems.

1.5.1 INADEQUACY OF EXISTING FAULT LOCATING SYSTEM

The necessity to precisely locate the faults on the railway electric traction line arises only when the earth fault persists on it with zero impedance. It is obvious that the impedance offered by many earth faults shall be theoretically very high, because the material caused the earth fault will get burned off with the heat developed (I^2R loss) during the flow of enormous fault current though it. The fault with the zero impedance occurs only when the (un-insulated) electric traction line makes firm contact with the earth or earthed structures directly. So that, the prevailing algorithm to locate the distance of fault persist on OHE from the feeding point of it is developed based on the loop impedance of OHE only. The impedance of the OHE is assumed to be uniformly distributed throughout its length. The voltage and the short circuit current generated during such earth faults are being used to derive the loop impedance in between the supply point (at the Traction Sub Station) and the point of fault on the OHE. The distance of fault from the supply point is arrived by the arithmetical division of the loop impedance with the per unit length impedance of the OHE. The conventional methods for pin pointing of fault on electric traction power line is build up on theories made on four simple assumptions as follows,

Assumption 1

For single-end direct power supply traction system, the fault is mainly embodied as contact grounding phenomenon (impedance contact of traction line with earth). A transient resistance generated when the fault occurred between the fault point and earth. It is randomly varying, and has no correlation to the distance of the fault point. Magnitude of this will be decided by the earth resistance and the arc resistance evolved during the short circuit period

Assumption 2

The short-circuit reactance is normally decided by the material of the conductor, structural space, impurities at the contact of material conductivity etc.. Basic line reactance is arrived after the traction line has been erected, which shall not be influenced by the means of short-circuit and power supply.

Assumption 3

The fault (position of earth contact on traction line) can be determined with the current and voltage value at the power supply point of the electrical traction line.

Assumption 4

From the value obtained in the previous step, the impedance/reactance at the measurement point is calculated and is divided by the per-unit-length resistance/ reactance. Thus the distance from the measurement point to the fault point is determined.

It was observed from the survey (A4) that the fault locations indicated by the system incorporated fails to precisely pin point the persisting earth fault positions on OHE at different places.

1.5.2 UNSATISFACTORY FISCAL FEATURES OF OHE

Another aspect is the extra fiscal burden. The power demands by the electric traction systems from the power grid lines are not consistent. It varies irregularly. The suppliers of electric power to railway traction system are from different entities. They usually enforce stringent conditions over railway organizations in using the electric power to keep certain factors like power factor, load factor, harmonic distortions, reactive power etc. within specific limits; and penalize the consumer heavily if not adhered to those conditions. Such serious unsatisfactory feature was noticed in the sampling region [5], that the Railways organization was penalized around 9.9 million Indian Rupees (INR) by the one Electric Supply Company, upto March 2014 for drawing excessive reactive power by the electric traction system (Table 1.1), by adding the modulus value of lagging and leading reactive power of the high voltage ac traction power system. Those much penalties were found paid by the railway organization for drawing excessive reactive power by 60 km long 25 kV OHE. Usually, electric supply companies consider the difference of those two figures to calculate the reactive power drawn by the consumers, and to impose penalty on this aspect. If the electric power supply company insist the consumers to maintain power factor close to unity at any load conditions will add fiscal burden to the consumers like railway organizations because the shifting of reactive power from lagging to leading and vice versa with the sudden variations in load in unpredictable manner is very common in railway electric traction.

Table 1.1 Penalty levied by Electricity Supply Company

Month	Monthly Average Power Factor	Penalty imposed by Supplier, in INR		Month	Monthly Average Power Factor	Penalty imposed by Supplier, in INR
April 2012	0.86	1,08,045		July 2013	0.86	1,89,541
May 2012	0.43	12,83,147		Aug. 2013	0.85	3,18,756
June 2012	0.62	9,89,450		Sept. 2013	0.84	5,40,702
July 2012	0.75	3,72,765		Oct. 2013	0.85	2,97,849
Aug. 2012	0.79	2,60,438		Nov. 2013	0.85	3,14,642
Sept. 2012	0.82	1,64,145		Dec. 2013	0.85	3,38,931
Oct. 2012	0.83	1,60,243		Jan. 2014	0.84	5,48,260
Nov. 2012	0.84	1,59,213		Feb. 2014	0.84	5,73,178
Dec. 2012	0.85	1,18,111		Mar. 2014	0.84	5,42,107
Jan. 2013	0.85	1,06,724		April 2014	0.83	6,84,348
Feb. 2013	0.87	1,04,876		May 2014	0.76	8,43,356
Mar. 2013	0.85	1,27,839		June 2014	0.90	0
April 2013	0.84	2,05,485		July 2014	0.83	5,69,597
May 2013	0.83	3,69,111		Aug. 2014	0.83	5,82,819
June 2013	0.85	1,90,350				

It is learned [6] that the lagging reactive power in electric traction is only seriously considered for design purpose. Generation of leading reactive power at OHE is found ruled out in the design stage itself. Provision of fixed capacitors at supply point is found suggested to compensate the lagging reactive power as a result of it in the prevailing designs. It is worth to note that the leading reactive power generated by those capacitors dominates in electric traction system when the traction load is zero.

Further, it was observed from the month of May 2012 that the power factor was as low as 0.43. It was come to light that fixed capacitors were put in continuous service at that particular TSS for seven days on trial basis in May 2012 for power factor improvement. But instead of improving power factor, it went down. In another trial conducted in the month of June 2014 by connecting a 21.6 MVA Traction Transformer (acted as reactive load) continuously for five days to the said traction line, the power factor was found improved to 0.9. Usually the power factor of electric traction load varies between 0.65 to 0.8 lag. But the power factors were found slightly higher than 0.85 in most of the days, even when no capacitor banks were connected to OHE for the power factor improvement at the sampling region.

With the two phenomenon, it is conceived that the irregular variations in the capacitance of OHE plays a crucial role in determining its loop impedance as well as the generation of leading reactive power, at areas where earth potential surfaces like, earth cuttings, tunnels etc. are available at the proximity of it.

1.6 OVERVIEW OF RESEARCH APPROACH

1.6.1 EXPERIMENTAL STUDY CONDUCTED TO DETERMINE THE INFLUENCING FACTORS OF PARASITE CAPACITANCE OF ELECTRIC TRACTION LINES

Persisting earth faults on high voltage ac electric traction line were created with zero impedance at two different places where difference in topographies is extreme to determine the factors influencing the impedance of the ac high voltage electric traction lines.

Sections selected for experimentation

Two distinct sections with the two extreme topographical features where high voltage ac railway traction lines erected are selected for conducting experimentation. One was at the railway section between Eraniel and Thovala in Tamilnadu state of India, where railway tracks are laid on level ground. Other was the railway section between Eraniel and Balaramapuram , where railway tracks are laid through steep earth cuttings & tunnels made through the valley of Western Ghats, in India.

Test conditions

Experiments were conducted only on non-rainy days duly ensuring no rolling stocks or trains were present in the entire zone of experiments, ie, from the supply point to the farthest point of OHE, and all other power lines run in parallel and across at the vicinity of OHE (owned by other organizations) were switched off.

Ten trials were conducted in the period ranging from 2nd October 2014 to 12th October 2015, by creating the earth faults on OHE. Table 1.2 shows the actual distance of persisting earth fault locations, and distance of location indicated by the Distant Protection Relay for two different places.

Table 1.2 Actual Earth fault distance and the fault distance indicated by DPR for the two extremely different terrains

Actual fault distance and fault distance indicated by DPR Distance					
at plane area			at terrain with earth cuttings & tunnels		
Date	Actual fault distance	Indicated Fault distance	Date	Actual fault distance	Indicated Fault distance
02/10/2014	35 km	40 km	14/06/2015	34 km	33 km
29/10/2014	20 km	23 km	27/06/2015	16 km	18 km
06/02/2015	14 km	16 km	30/06/2015	37 km	37 km
26/03/2015	20 km	23 km	22/08/2015	19 km	19 km
02/07/2015	19 km	22 km			
12/10/2015	9 km	10 km			

Variations in the fault distance indicated by the DPR for the two extremely different topography are plotted (Fig. 1.7) against the theoretical fault distances.

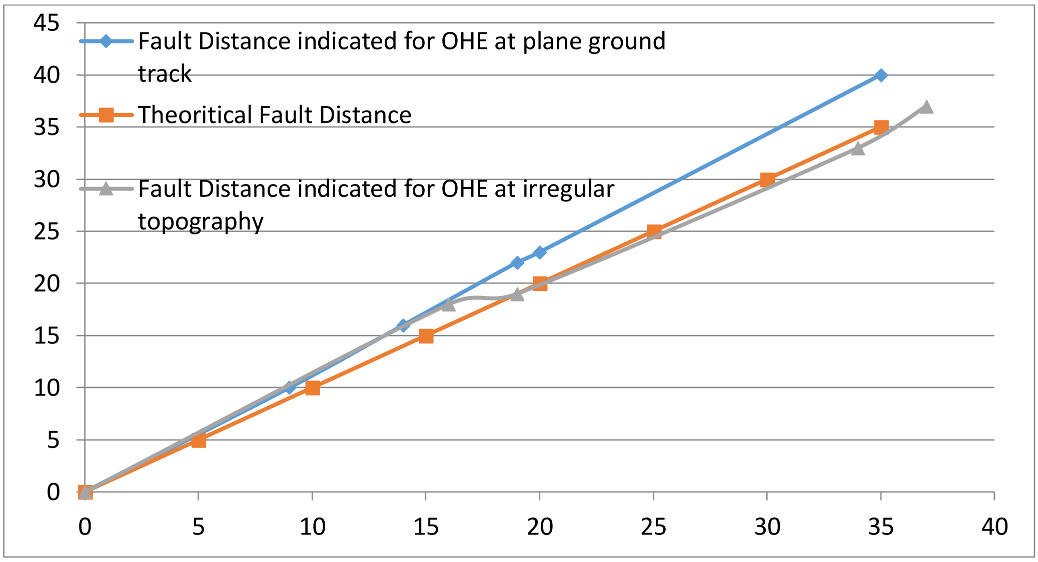

Fig. 1.7 Plots on actual fault distances and the indicated distances for the two extremely different terrains

Analysis of the outcome of field experimentations

The variations in the fault distance are observed to be more or less linear with progressing offset value in the section where tracks are laid on plane areas, which is indicated in blue in fig 1.7. The continuous consistent positive diversion is contributed by the uniformly distributed shunt admittance present in the entire length of OHE and the ground.

The least variations, but in highly irregular manner, were observed at the sections where railway tracks are laid at terrain where steep slope earth profiles & tunnels are present at the proximity of OHE, which is indicated in green in fig 1.7. The earth fault distance indicated by the DPR for the OHE at terrain where steep earth cuttings and tunnels are present is almost linear with cumulative offset from the actual at its initial 15 km long stretch due to the reason that topography at those stretch is generally plane ground with some minor gradual slope profiling of short lengths and a short length tunnel. A sudden shift towards the theoretical value is observed at 15 km to 19 km, due to the reason that many steep earth cuttings of high altitude & length, and two lengthy tunnels are available in this stretch. In the remaining stretches upto 37 km, combinations of plane grounds, few minor slope earth cuttings, large number of steep earth cuttings, and one tunnel of length 201 metre are available en-route.

From the table 1.2, it can be presumed that the shut admittance between the electric traction lines and the surrounding geographical features gave significant influence on the fault distance locating algorithm of the DPR. Hence, it is hypothetically accepted that the parasite capacitance of high voltage ac railway traction line / over head equipment (OHE) varies with the presence of surrounding earth, and earthed structures; and the variations are decided by various physical measurements like, area of earth/earthed structure, its clearances from OHE, angle of slope, alignment of track etc.

1.6.2 FACTORS INFLUENCING THE PARASITE CAPACITANCE OF AC ELECTRIC TRACTION LINE

From the detailed survey (A4), and from the experimentation conducted at the sampling region of the research work, it is affirmed that the height of OHE from ground and the features of the topography of the area where the railway tracks are laid are responsible for the variations in the shunt admittance (or parasite capacitance) of high voltage ac electric traction lines. Those are tangible from the variations in the height of the electric traction lines in the survey regions.

Variations in the height of the electric traction line

Electric traction lines are usually made in two types, viz. conventional and non-conventional. The non-conventional lines shall only have one conductor, which are made only at yard lines at railway stations and at railway tracks leading to some factory premises. Maximum operational speed of ac locomotives trains at the non-conventional electric traction line (also called as tramway line) is restricted to 90 km/h. Conventional traction lines shall have minimum two conductors, viz. the contact wire at the bottom and the catenary wire at the top. They are electrically bonded through copper conductors, called droppers, and their configuration resembles a hanging bridge (Fig.1.4). The said arrangement is able to feed the electric supply to locomotives which run upto a speed of 180 km/h. The bottom conductor (contact wire), is kept perfectly horizontal by stretching its either ends with a tensile load of 1200 kgf. Height variation in the contact wire is restricted in between 4.58 m and 5.8 m [3]. The top conductor (catenary wire) got the name from its shape. It provides mechanical support to the contact wire. This wire is also stretched with a tensile load 800 kgf. Height of the catenary wires varies in between 4.78 metre and 7.2 metre, as per the site conditions.

The variations in height of the electric traction lines between minimum and maximum values are warranted to keep safety clearance with the fixed over head structures like; tunnels, bridges, pipe line etc No regular pattern in the height variation of OHE is noticed.

Height of the faces of the earth cuttings

Earth cuttings become necessary to lay the railway tracks at undulated earth surfaces, to keep the gradient of the railway track within the permissible limit, and to avoid the sudden variations in the gradient of railway tracks. Abrupt variations in gradients of the tracks are not allowed due to the poor coefficient of adhesion of locomotives' wheels and the railway track. Coefficient of adhesion (or friction) between wheel and railway track shall around 0.35 to 0.5 only. Presence of some lubricating materials like grease, water etc on rail top or on locomotive wheel further reduce the coefficient of friction, which in turn will reduce the tractive effort of the locomotives drastically. The train will stall (stopping the train even when locomotives' wheels rotate) at such occasions, and the subsequent wheels slip will burn & perish the railway track.

Variations in vertical heights of earth cuttings were observed to be from a few centimetres upto 18 m. Heights above 18 m are not permitted for earth cuttings in order to avoid the land slide [7].For a height above 18 m, either the earth will be removed in full & refill after constructing the tunnel (cut & cover) if the bearing capacity of the soil is not adequate, or the tunnel will be carved through hard rocks. In almost all the earth cuttings, the faces of the cuttings have bell shape. The differences exist only in its base lengths and in its heights (Fig. 1.8)

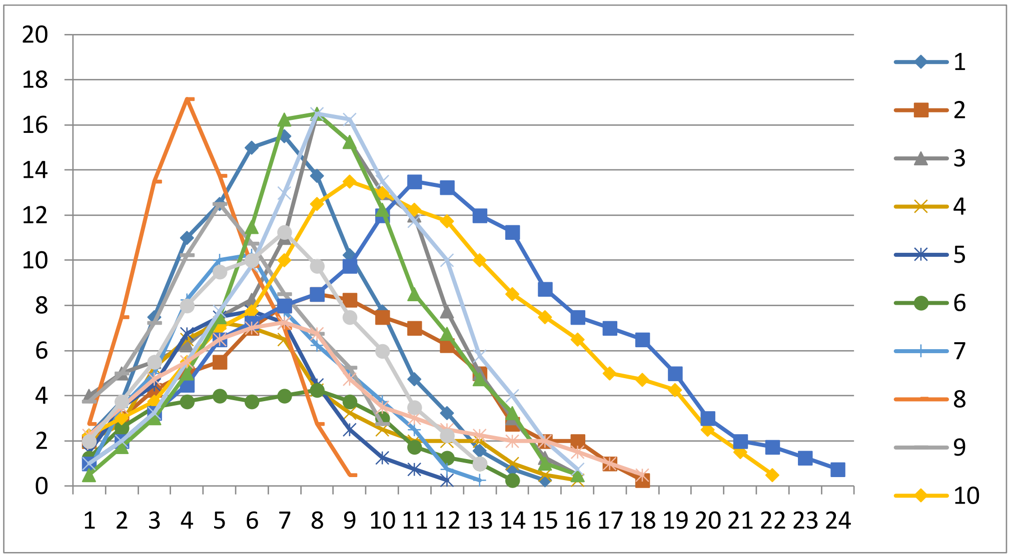

Fig. 1.8 Common profile of earth cuttings' walls

There exists no correlation between the base length and the height of the earth cuttings.

Slope of the earth cutting

Even though the variations in the slopes of the earth cuttings are in existence in between perfect horizontal (0 degree) to perfect vertical (90 degree), the slopes at earth cuttings made for laying railway tracks are found to be fixed to some specific slopes (the tangent value of the angle, in the form of ratio, except for vertical cuttings). They are 1:1 (angle of slope, 45^0), and 1: ½ (angle of slope, 76^0). The factor deciding the slope of earth cutting is the hardness (bearing capacity) of the soil only. Slope 1:1 is usually adopted where earth cuttings were made on laterite, and 1: ½ slope is adopted where earth cuttings are made at hard rock. Some old vertical earth cutting are also present in railway system where the very hard rocks are available.

Base width of the earth cuttings

Base width of earth cuttings are decided based on the gauge (laying distance of the rails) of the railway track. There exist four common railway gauges worldwide , viz, Broad Gauge or BG (1.678 m), Metre Gauge or MG (1 m), Cape Gauge (1.05 m, exiting at African Countries), and Narrow Gauge or NG (0.76 m). In earlier days, electrifications were done in MG areas also. But, as of now, the electrification works are in progressing phases on BG lines only, as the existing MG lines are being undergone conversion to BG lines in many countries.

The minimum requirement of base width of the earth cuttings are decided by several factors, those include; the minimum setting distance (the distance between the nearest face of any rising object from the rail level and to the centre line of the track), requirement as per the gauges adopted for laying the track, requirement of draining the rain water, construction of robust drainage for continuous seepage water, chances of landslides etc. It is observed that the base widths of the earth cuttings vary in between 6.16 m to 8.96 m in the sampling region. Some exceptions (earth cuttings with wider base widths), due to fear of land slide in heavy rainy seasons, were also noticed on this aspect.

Clearance of traction lines from the walls of the tunnel

Since the progressing of electrification works of railway track for introducing ac electric traction nowadays are concentrated on BG lines, cross sectional dimensions of tunnels available at BG line area were verified in detail and were found that almost all the tunnels have standard cross section in their shape and dimensions. Slight variations, in the order of few centimetres, were noticed at some tunnels due to the lesser precision in the masonry works.

Heights & clearances of the contact wire and catenary wires from the rail level, and from the wall & roof of tunnels were found varying in accordance to the feasibility available for the erection of the cantilever assemblies (the metallic structure with insulator at its fixing point provided to hold the electric traction wire) inside the tunnel walls.

1.7 OBJECTIVES OF THE RESEARCH WORK

1.7.1 CONSTRUCT MODELS OF ELECTRIC TRACTION LINES TO CONDUCT EXPERIMENTAL STUDIES ON VARIATIONS OF PARASITE CAPACITANCE OF ELECTRIC TRACTION LINES

To construct 50 m similitude model of ac railway traction line with its exact surroundings at different topographies to study the parasite capacitance (shut admittance) variations of ac electric traction line with respect to the surroundings, by manipulating one parameter at a time, keeping others controlled.

1.7.2 FORMULATE EMPIRICAL EQUATIONS FOR PARASITE CAPACITANCE OF OHE FOR VARIOUS TOPOGRAPHICAL CONDITIONS.

To formulate empirical formula for parasite capacitance of ac traction power lines duly including the effect noticed factors noticed from the sampling region.

1.7.3 DESIGN DYNAMIC MODEL OF OHE

To design dynamic model for high voltage ac traction line by incorporating the findings on the variations in the parasite capacitances of it.

1.7.4 MODIFY THE ALGORITHM FOR FAULT LOCATION

To modify the prevailing algorithm for pinpointing the faults on OHE

1.8 CONTRIBUTION OF RESEARCH

The research work aim to dynamic model the high voltage ac electric railway traction lines, which shall help in fine tuning the line parameters for different topographical conditions, which in turn helps to design compensatory systems to minimize the variations in the power factor, and enhances the accuracy in persisting earth fault pinpointing process.

1.9 OUTLINE OF THE THESIS CHAPTERS

Chapter 1

Chapter 1 introduces the research problem and the objectives of the research works.

Chapter 2

Chapter 2 describes the literatures (journals, texts and internet sites) reviewed in connection with the research works.

Chapter 3

Chapter 3 narrate the experimentation conducted to gather data to formulate the variations in the parasite capacitance of the railway electric traction lines at its various heights from the ground level with the help of similitude model, and the validation tests conducted on a real electric traction line.

Chapter 4

Chapter 4 narrates the data collection from the experimentation done on the similitude model to formulate the influence of the variations in the base widths at different slopes (angles) of earth cuttings on the parasite capacitance of the electric traction lines, at controlled heights of OHE and earth cuttings.

Chapter 5

Chapter 5 narrates the data collection from the experimentation done on the similitude model to formulate the influence of the variations in the heights of earth cuttings at different slopes (angles) of it, at controlled base width of cutting and height of OHE.

Chapter 6

Chapter 6 narrates the data collection from the experimentation done on a 50 metre long similitude model of electric traction line inside a BG railway tunnel of standard dimensions suitable, to determine the nature of the influence of different heights of the electric traction line within the tunnel on its parasite capacitance.

Chapter 7

Chapter 7 presents the dynamic model of the high voltage ac traction line duly incorporating the variations in the parasite capacitance in accordance with the variations in height of traction wire at open place, and inside the standard railway tunnels, and suggests an algorithm to precisely calculate the fault distance on OHE.

Chapter 8

Chapter 8 presents the conclusions and limitations of this research works, along with the scope exists for further research.

Journals, Text books and the Internet sites referred in connection with this research works are given in the reference section.

Data collected through surveys and experiments are appended as the last part of this report.

CHAPTER 2

LITERATURE SURVEY

2.1 CHAPTER OVERVIEW

Experimental studies of the changes in the characteristic of line parameters of high voltage ac electric traction power line is the core activity and, dynamically modelling the electric traction line duly incorporating the changes in line parameter (s) is the main objective of this research work. The literatures survey made for getting clear understanding of the prevailing theories, and the gaps noticed in the related knowledge are explained in this chapter.

2.2 LITERATURE SURVEY

Literatures are available in abundant in the form of texts, journals and web sites on the study made on the parameters and modelling of electric power transmission lines. All those literatures categorize the alternating current high voltage electric power transmission lines as ‘short’, ‘medium’ and ‘long’ [8][9][10][11][12][13][14][15][16] based on the modelling done them with line parameters.

2.2.1 SHORT TRANSMISSION LINE

Extra High Voltage (EHV) lines those have length 100 km or less, and working voltage of 110 kV or below are classified as short transmission lines (Fig.2.1)

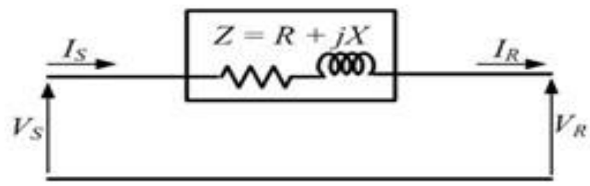

Fig. 2.1 Model of short transmission line

Effect of shunt admittance exits in between power line and earth is conveniently neglected in short transmission line, due to the reason that the height of lowest live conductor itself is strung at considerably high altitude from the earth, which practically eliminates the effect of shunt admittance.

2.2.2 MEDIUM TRANSMISSION LINE

Transmission lines of length ranges from 100 km to 250 km is classified as medium transmission lines. As the charging current due to shut admittance can't be neglected in medium transmission lines, line admittance in lump is incorporated in its modelling considered in the modelling. Two types of modelling are made for the medium line. Shut admittance is lumped at the middle of the line in one model (Fig.2.2), termed as T model.

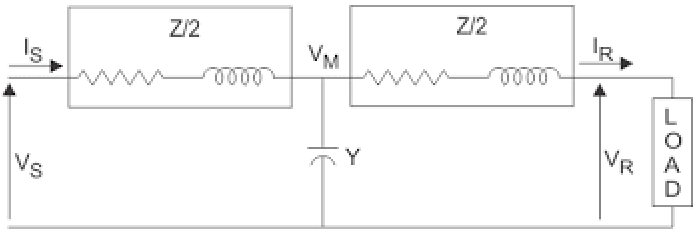

Fig.2.2 T model of medium transmission line

The shut admittance is divided into two equal parts and lumped at the sending end and receiving ends of the transmission line (Fig.2.3). This model is termed as ∏ (pai) model.

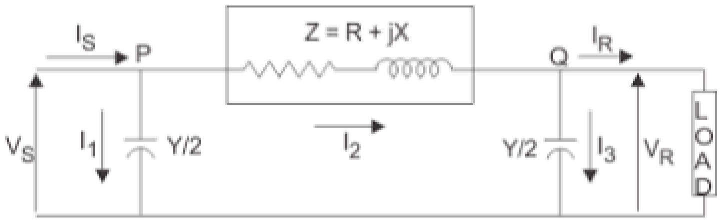

Fig. 2.3 ∏ model of medium transmission line.

2.2.3 LONG TRANSMISSION LINE

Transmission lines over 250 km length are classified as long transmission lines.

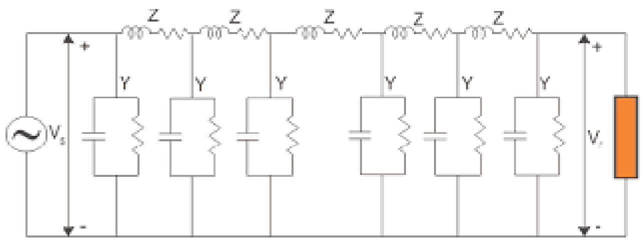

Fig. 2.4 Model of long transmission line

The parameters (resistance, inductance and the capacitance) of the long transmission lines are not lumped, but distributed uniformly throughout its length (Fig. 2.4).

2.2.4 ANALOGY OF AC POWER ELECTRIC TRACTION LINE

Even though the physical appearance of high voltage ac power line of railway traction has no similarity with the short the electric power transmission line, its modelling is done at par with the short length ac power transmission line (Fig.2.1) as, the length of high voltage ac electric traction lines shall be less than 50 km, and the working voltage shall not go beyond 27.5 kV.

2.2.5 SHORTFALL IN THE PREVAILING MODEL OF AC TRACTION LINES

Presence of earth or earthed structures shall not be there at the proximity of electric power transmission lines. Hence, the effect of line capacitance is neglected in short transmission lines. The same concept is adopted in ac electric traction line model also. But, unlike in power transmission lines, ac traction line often drew closer to earth potential surface to a considerable length. As the capacitance of a power line varies inversely with its distance from the earth/earthed surface, the effect of capacitance of ac traction lines will be many times higher. As such, the generalized model (Fig. 2.1) can't be fit as it is on high voltage ac electric traction lines, and for developing the algorithm for its protection scheme, despite the working voltage and the length of high voltage ac traction line is far below the levels stipulated for short transmission lines.

2.2.6 PREVAILING THEORIES FOR FAULT LOCATION ON ELECTRIC TRACTION LINES

From the theories available [8][9][10][11] for pinpointing the persisting fault location (methods for fault location) on electric power lines, it is learned that those were made on some loop impedance theory for electric traction power network. Fig. 2.5 is the model of an OHE with zero impedance persisting earth fault on it. Since it is essential to pin point the exact fault position on the OHE for the early restoration of the railway traffic, a scheme for fault locating algorithm is incorporated in the line protection schemes. The scheme of locating the fault is clubbed with the impedance relay (or MHO relay) developed based on the principle of loop impedance of the ac railway electric traction line [17][18]

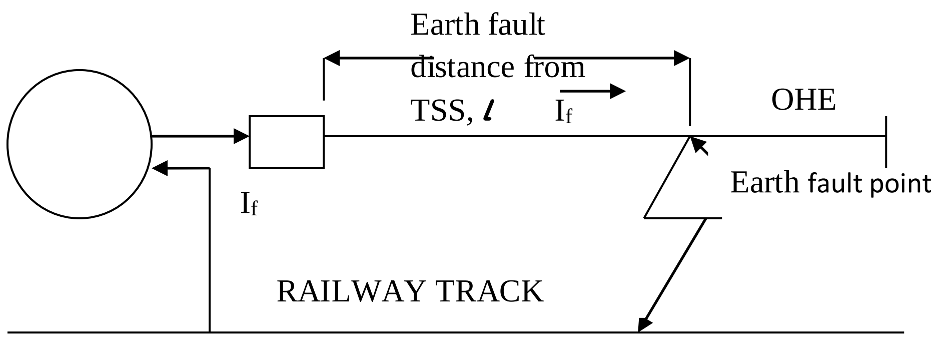

Fig. 2.5 Model of an earth fault persisting traction system

'*l*' is the distance of earth fault from the TSS, and 'I_f' is the earth fault current. The traction line parameters are assumed to be uniformly distributed [6], where the per unit length resistance, inductance, and capacitance are R_0, L_0, C_0 respectively, where R_0 is 0.1 to 0.3Ω/km, L_0 is 1.4 to 2.4 mH/km and, C_0 is 10 to 14 nF/km [19]

The theories [20][21][22][23][24][25][26][27][28] used to make prevailing algorithms for locating the fault distance measurement by the Distance Protection Relay (DPR) are based on the measurement of loop impedance under different types of fault condition of electric traction lines. The assumption is made that the impedance angle of OHE is constant in all fault conditions, duly considering the line parameters are uniformly distributed [23] in all models, despite the impedances of traction line are different (Table 2.1) for different layouts of railway tracks.

Table 2.1 Impedances of OHE for different layout of railway tracks

Sl. No.	Type of track & OHE	Impedance / km
1	Single line track OHE with return conductor	$0.70 \angle 70^0\,\Omega$
2	Single line track OHE without return conductor	$0.41 \angle 70^0\,\Omega$
3	Double line track OHE with return conductor	$0.43 \angle 70^0\,\Omega$
4	Double line track OHE without return conductor	$0.24 \angle 70^0\,\Omega$

The magnitude of the impedance is calculated using general expression,

$$Z = V/I \ \Omega \qquad \text{Eqn.(2.1)}$$

where ‘V’ is the traction line voltage, and ‘I’ is the current occurred during the fault. The distance of fault ‘L’ is occurred on OHE is calculated using the general formula;

$$L = Z/z \ \text{km} \qquad \text{Eqn.(2.2)}$$

where ‘Z’ is the total loop impedance in Ω upto the point of persisting earth fault on OHE in Ω, and ‘z’ is the unit impedance of the OHE per unit length, in Ω/km

The Relay Characteristic Angle (RCA) (Fig.2.6) plays the crucial role in differentiating a fault current in high voltage ac electric traction lines, and the load current contributed by the electric locomotives. It shows how the resistive reach settings are arrived.

The impedance relay is also called Distant Protection Relay (DPR), which works on the principle of overshooting the impedance parallelogram by the traction current vector.

The phase angle of load current of the locomotive shall be around 40^0 lagging, and the angle of earth fault current shall be around 72.5^0 lagging for all fault distance calculations [29]. The Relay Critical Angle (RCA) is so determined that the relay does not actuate at the higher traction load current contributed by the electric locomotives, and shall acts when earth fault current occurs even with lesser magnitude. The angle of the earth faults current, which is determined by the angle of loop impedance of OHE, if varies; the magnitude of minimum current required to actuate the DPR shall also vary. Distance between dead earth fault point/area and the source of supply is being arrived from the loop impedance, which is derived from the magnitude of the fault current and the instantaneous voltage of the OHE. The prevailing method, which was developed based on the existing theories of locating the fault position on electric traction lines shall succeed only if the two conditions are satisfied. One is the fault on OHE should be stationary and is having continuous earth contact, and the other is, impedance of OHE is uniform throughout its length

Documents on persisting earth faults kept by electric traction department of railway organization [5] highlight significant variations in the fault distances indicated by the relay from the distance of actual fault occurred. Variations in the data in irregular manner so happened were at railway track laid at hilly area where a lot of earth cuttings and tunnels are. Single optimized value of capacitance of OHE for the fault distance calculation defies the chances of significant variations in the capacitance with the variations in topography.

2.2.7 UNIQUE FEATURES OF HIGH VOLTAGE AC ELECTRIC TRACTION LINES

High voltage ac electric traction lines' (OHE) altitude is as low as 4.58 metre from the ground at some critical places, and slope profiled faces of earth cuttings made through hillocks to lay railway tracks, may be available within 3 m to 4 m radial distances for a longer stretch [29]. The presence of tunnels on rail routes will further reduce the clearance between traction conductors to earth as low as 0.25 m, for very lengthy stretches in hilly terrain.

Chronological order of research done

2.3 CHRONOLOGICAL ORDER OF RESEARCH WORK DONE

Table 2.2 Chronological order of research work done

Period	Work done	Contribution
January 2013 to September 2013	Literature survey.	Prevailing model of high voltage ac railway electric traction at par with general model of ac power transmission line is found misfit due to unique features of OHE.
October 2014 to October 2015	Earth faults created at ten occasions on actual high voltage ac electric railway traction lines for comparing the actual and indicated fault distances.	Fault distances indicated by the agent technology (fault distance indicating relay) of railway electric traction system are found deviating much in irregular manner at hilly terrain.

July 2015 to June 2016	Intensive survey conducted at 630 km long stretch of railway electric traction lines. Experiments conducted on table top models.	Variations in the indicated fault distances are mapped along with the geographical features, where persisting faults occurred naturally in the past.
June 2016 to October 2016	Experiments were conducted with similitude model at geographically different places to measure the line parameters of ac electric traction lines.	Parasite capacitances of ac electric traction lines are found different for different places. Empirical formulae for calculating the capacitance of high voltage ac electric railway traction lines were generated for different topographies.

2.4 CHAPTER SUMMARY

On reviewing the available literatures on the railway electric traction, it is noticed that no specific attention is given for modelling the railway traction lines. All the analysis is made by considering the railway electric traction lines at par with short length transmission line only.

Fault distances indicated by the agent technology of railway traction systems are found much deviating from the actual in irregular manner at topographically challenged areas. Drastic variations in the features of topography at close proximity of railway traction lines, especially the presence of railway tunnels, which can cause the variation of shunt admittance of OHE is found not considered in system analysis. The uniformly distributed line parameters of railway electric traction lines are found used for creating algorithm for fault distance pinpointing processes.

Tests conducted on actual railway traction lines by creating earth faults on them at several occasions confirmed that the changes in topographical features at close proximity of OHE will cause error in fault pinpointing processes.

CHAPTER 3

RELATION OF PARASITE CAPACITANCES OF 25 kV AC RAILWAY ELECTRIC TRACTION LINES WITH THE HEIGHT FROM RAILWAY TRACK

3.1 CHAPTER OVERVIEW

It is pertinent that in the prevailing model of the short power transmission line (Fig 1.4), the effect of shunt admittance (or the parasite capacitance) exits in between power line and earth is conveniently neglected. It is noticed from the study made in railway networks that the same generalized model is in use for analysing the high voltage ac electric traction also.

In practice, with the many unique features of OHE, the theoretically calculated parasite capacitance using mirror imaging principle [30] are found not matched with the actual. It is so happened with some of the special features in railway systems which influence the line parameters of OHE.

From the previous chapter, it is understood that the height of the OHE from the ground level, and the presence of earth or earthed structure at the proximity of OHE can influence the parasite capacitance of it. This chapter explains the methodology adopted for data collection and the analysis made thereon for formulating the parasite capacitance of high voltage ac traction lines where the railway track is laid at plane area.

3.2 UNIQUE CHARACTERISTIC OF AC HIGH VOLTAGE ELECTRIC TRACTION LINE

Altitude of the bottom conductor (contact wire) of OHE varies between 4.58 m to 5.8 m, and the top conductor (catenary wire) varies between 4.78 m to 7.0 m from the ground (rail level). Also, there present earthed structure (metallic structure holding the cantilever assembly of the OHE) just at a distance 0.3 m apart from the live part of OHE. There shall be such 20 metallic supports (OHE masts) on an average in every kilometre length of. Besides, the catenary wire is strung in parallel to the centre line of the railway track, but the contact wire is strung in a horizontally staggered manner with a maximum +0.3 M to -0.3M deviation from the centre line of the railway track at alternate supporting masts (Fig. 3.1).

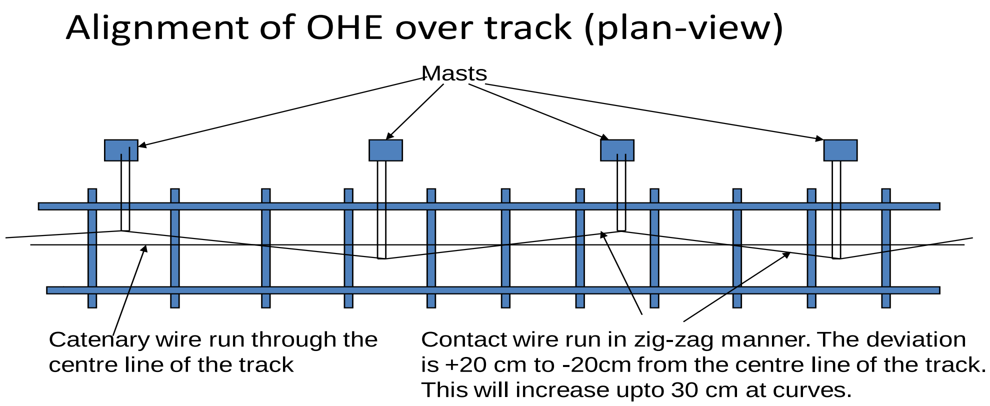

Fig. 3.1 Horizontal alignment of Contact wire and Catenary wire of OHE

Since the OHE is considered to be a single conductor, the formula for capacitance by mirror imaging method [30] is used for calculating the theoretical value of the parasite capacitance of it. Capacitance for single conductor power line with the earth in mirror imaging method is,

$$C = 10^{-9} / (18 * l_n (2h/r)) \text{ F /m} \qquad \text{Eqn.(3.1)}$$

where 'h' is the height of conductor from earth, 'r' is the radius of conductor, and 'l_n' is the natural logarithm. It is obvious that the formula (Eqn. (2.1)) is not apt to precisely calculate the capacitance between OHE and the earth due to the several unique features associated with the OHE, as detailed above in this chapter.

3.3 DATA COLLECTION

A 50 m long specimen of OHE with its actual components was setup (Fig. 3.2) for the measurement of capacitances for various heights of OHE.

Fig.3.2 Experiment conducted on a 50 m long prototype of conventional OHE

Data collected from a 50 m long specimen of conventional OHE setup (Fig.3.2) at outdoor area, which is subject to all kinds of stray nuisances produced by nearby power lines, telecommunication towers, high frequency equipment etc., similar to that of the actual electrical traction lines in use. The experiments were repeated for various heights of OHE ranging from 3.00 m to 5.50 m (A5) on the level ground. Readings are shown in Table 3.1.

Table 3.1 Parasite capacitances of conventional OHE at its various heights from railway track on level ground.

Height of contact wire of OHE from rail level, in m	Parasite capacitance of 50 m long OHE, in nF
3.00	0.990
3.25	0.902
3.50	0.860
3.75	0.831
4.00	0.809
4.25	0.786
4.50	0.768
4.75	0.754
5.00	0.739
5.25	0.727
5.50	0.718

3.4 CURVE FITTING

Fig. 3.3 is the plots obtained through the regression analysis made on the parasite capacitances of 25 kV ac traction line with the earth at varying height of OHE, at level ground with the help of a curve fitting &analysing tool [31].OHE height in M are on X axis and Parasite capacitances are on Y axis in nF/km.

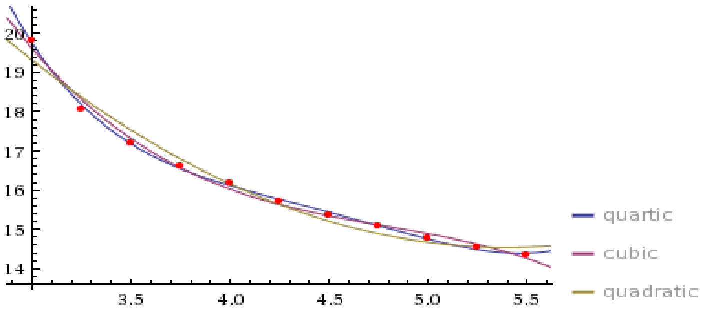

Fig. 3.3 Parasite capacitances for different heights of OHE at level surface

Percentage variations of the theoretical value of parasite capacitance from the value obtained in the experiment setup are given in Table 2.2.

Table 3.2 Comparison of theoretically calculated parasite capacitance and the value measured from the specimen OHE

Height of contact wire, in m	Capacitance of OHE as per mirror imaging formula, in nF/km	Capacitance measured directly from the proto type of OHE, nF/km	Variations in theoretical value from the actual
3.00	15.858	19.80	- 19.91 %
3.25	14.84	18.04	- 17.71 %
3.50	14.479	17.20	- 15.82 %
3.75	14.3032	16.62	- 13.94 %
4.00	14.232	16.18	- 12.04 %
4.25	14.1245	15.72	- 10.15 %
4.50	14.0913	15.36	- 8.26 %
4.75	14.1195	15.08	- 6.37 %
5.00	14.1171	14.78	- 4.48 %
5.25	14.1635	14.54	- 2.59 %
5.50	14.20	14.36	- 0.7 %

Quadratic equation (Eqn. (3.2)) for the parasite capacitance is also obtained with the equation generating tool [40] for different heights of OHE from rail level on level ground. Generic form of Quadratic equation is ax^2+bx+c, where 'a' and 'b' are the coefficients of different powers of the independent variable X (varying height of measured at contact wire level of conventional OHE), and 'c' is the constant term (Y intercept of the curve),

$$Y = 0.83333X^2 - 8.999\,X + 38.33 \text{ nF/km} \qquad \text{Eqn. (3.2)}$$

An empirical equation for the Parasite Capacitance of OHE (C_p) duly incorporating the length of OHE in quadratic form (Eqn. (3.3)) is framed duly incorporating the length of it.

Parasite capacitance of OHE at plane level geographical area,

$$Cp = \frac{L}{3} 10^{-12}(2.5\,H^2 - 27H + 115) farads \qquad \text{Eqn. (3.3)}$$

Where 'C_p' is the parasite capacitance of conventional OHE on plane geographical area, 'L' is the length of OHE in m, and 'H' is the height of contact wire of OHE from the ground, in m.

3.5 STATISTICAL ANALYSIS

The Akaike Information Criterion (AIC) &the Bayesian Information Criterion (BIC) [32], the R^2 (coefficient of correlation regression) and the adjusted R^2 (adj.R^2) are also calculated for the new equation (Table 2.3)

Table 3.3 AIC, BIC, R^2 and adj. R^2 for various equations

Form of equation	AIC	BIC	R^2	adj.R^2
Quadratic	+ 7.219	+ 8.811	0.978	0.973

In the statistical analysis, the ideal values of R^2 and the adj.R^2 should be ONE, and the values of AIC & BIC should be closer to zero, if it is positive. However, if the R^2 and adj.R^2 are above 0.9, and AIC & BIC are small positive integers for any curves, the equations framed can be accepted empirically. R^2 and adj.R^2 are above 0.97, and the values of AIC & BIC are small positive real numbers for the newly formed empirical equation (Eqn. (2.3)). Hence it is found statistically significant.

3.6 VALIDATION TEST

Validation test for verifying the level of acceptance of the newly generated formula for the parasite capacitance of the actual 25 kV ac OHE of railway system, where the track is laid on the level ground, were also conducted at Thovala – Nagerkoil section of Indian Railways by isolating three segments of OHE with different length and heights (Fig. 3.4).

Contact wire heights were 5.6 m, 5.3 m and 5.0 m, for the lengths of OHE 1234.2 m, 1410 m and 1081 m respectively, and the parasite capacitances measured are 17.81 nF, 20.616 nF and 16.21 nF respectively for those three segments of OHE. The readings obtained in the validation tests and the theoretical values arrived through the new empirical equation Eqn. (3.3) are given in Table 2.4

Table 3.4 Comparison of actual value measured and the value arrived using new empirical equation (Eqn. (2.3)) for the parasite capacitance of OHE

Height of Contact wire, in m	Length of OHE, in m	Parasite capacitance measured, in nF	Parasite capacitance of ONE km,in nF	Parasite capacitance calculated (Eqn.2.3)	
				Value, in nF/km	% variation from actual
5.6	1234	17.81	14.43	14.16	- 1.9 %
5.3	1410	20.95	14.85	14.61	- 1.7 %
5.0	1081	16.21	14.99	14.75	- 1.6 %

The calculated values show the variation in between – 1.6 % to -1.9 % only from the actual values obtained in validation tests. It is noted that very thin layer of dusts deposited on supporting insulators of actual OHE system is the reason for higher value of capacitance obtained in the validation test.

Fig.3.4 Validation test conducted on an actual 25 kV electric traction system.

3.7 CHAPTER SUMMARY

The statistical analysis and the validation test results indicate that the quadratic equation generated (Eqn. (3.3))with the data collected through the experimentation on the prototype of OHE for modelling the parasite capacitance of it at plane area for different heights is acceptable empirically. Besides, the equation with smaller degree of power of independent variable contributes the least complexity in making algorithm for the numeric Distance Protection Relay for pin pointing the fault on 25 kV ac electric railway traction.

CHAPTER 4

FORMULATING PARASITE CAPACITANCES OF 25 kV AC RAILWAY ELECTRIC TRACTION LINES AT EARTH CUTTINGS FOR ITS VARIOUS WIDTHS & ANGLES

4.1 CHAPTER OVERVIEW

It is experimentally proved (section 3.2) that the parasite capacitance of the railway high voltage ac electric lines significantly vary from the theoretical value in between upper and lower permissible heights of the OHE (Table 2.2). Hence, the calculation of the impedance (Z) of high voltage ac traction power lines of railways comprising including an inductive reactance (jX_L) in series with the line resistance (R), and by neglecting the effect of parasite capacitance (or the shunt admittance) as per the generalized model of short transmission line (Fig.1.4) is proved to be erratic. The algorithms made thereon for fault distance calculator of the Distance Protection Relay (DPR) in 25 kV ac electric traction line [33][34][35][36][37] are also found inadequate to precisely pinpoint the persisting earth fault on OHE.

The impedance is considered to be uniformly distributed in all the prevailing calculations [6]. Even though, the magnitude of the impedances are different for different configuration of railway tracks, impedance angle of OHE is taken as constant; ie $\llcorner 70^0$.

Fault distance indicated by the DPR has vital role in determining the degree of reliability of electrified railway transportation system. Algorithm developed using erratic data often mislead the judging process of pinpointing the persisting faults on the high voltage ac electric traction lines.

It is an accepted fact that surrounding topography will have influence on the parameters of high voltage electric lines. The field experimental study conducted (Table 1.2) made on the behaviours of the high voltage ac electric railway traction lines in conjunction with the earth fault occurred on them affirmed revealed that the topographical features at the proximity of OHE significantly influence the accuracy of the fault distance locating algorithms. The angle of the earth faults current shall be the angle of loop impedance of OHE also. If it varies, the distance indicated by the DPR will also vary.

It is understood from previous chapter that the shut admittance contributed by the parasite capacitance exists between the OHE and earth depends on the height of OHE from rail level.

This chapter refers the experiments conducted with a 50 m long similitude model of OHE at various earth cuttings for collecting data for formulating the parasite capacitance of OHE at earth cuttings with varying base widths and angle of cuttings.

4.2 REVIEW OF THE EXISTING SYSTEM

Earth cuttings made for railways shall have many unique features. Since the trains have snake like shape, the cross section of the earth cutting (Fig.4.1) shall not be wide as much as those made for inland roadways.

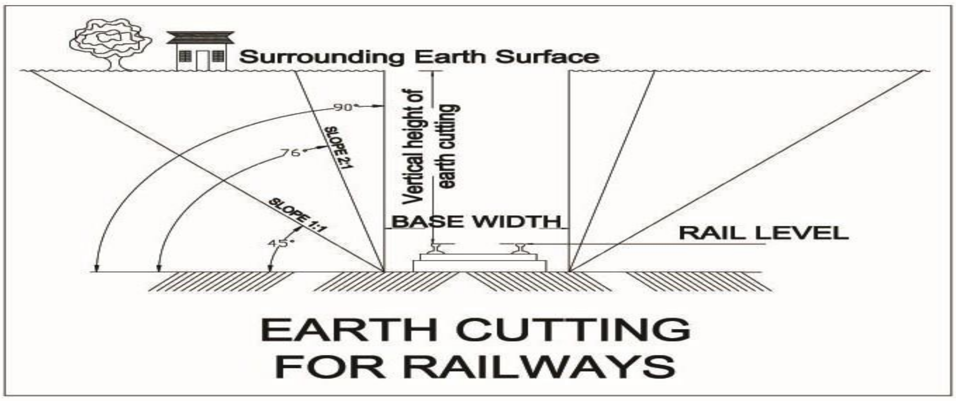

Fig. 4.1 Theoretical earth cutting for railways

The area of the earth cuttings available at the proximity of the OHE depends on the base width of the earth cuttings. The area, horizontal distance of OHE from the earth, the angle of the cuttings etc. will also quantitatively influence the parasite capacitance of OHE. Eqn.(3.3) is capable to formulate the parasite capacitance of OHE were the earth is at the bottom of OHE with infinite plane area only. It is found inadequate to precisely calculate the parasite capacitance of OHE at earth cuttings of random variations in their dimensions.

Fig. 4.2 Electrified track through the earth cutting

Actual earth cuttings (Fig. 4.2) are made to lay the railway track where the geography in undulating. It becomes necessary to remove soil/rock to lay the railway track because the gradient of the track could not be made beyond the certain limit. This limit is defined by several factors like; gauge of the track, humidity in atmosphere, presence of sharp curves, coefficient of adhesion of the wheels of the locomotives on railway tracks etc. Coefficient of adhesion is around 0.35 only in broad gauge railway track. Higher gradient on the track shall bring the train under risk, either by stalling or by rolling back.
Angle of the soil excavation at earth cutting is determined by the bearing capacity of the soil. The maximum angle that can be given for the earth cuttings are decided as per the indices defined by soil technique engineering. Even though, the variations in the angle of cuttings (slopes) are feasible in between 0^0 to 90^0, railway organizations usually maintain the earth cuttings at some specific angles only. More precisely, the slopes are referred instead of angles. Cuttings with slopes 1/1 (45^0 cutting) and 2/1 (76^0 cutting) are generally available at laterite and at hard rock areas respectively. Vertical cuttings (cutting with 90^0) are found strengthened by concrete wall. The maximum heights of earth cuttings were found permitted upto 18 m only.

Railway organizations are interested in reducing the slopes of earth cuttings to the possible extent, to avoid landslides in rainy seasons.

4.3 DATA COLLECTION

Experiments were conducted in two steps, viz, data collection from table top model, and from the similitude model of an actual traction system.

4.3.1 DATA COLLECTION FROM TABLE TOP MODEL

Experiments conducted on the similitude model of OHE set up at laboratory (Fig.4.2) for data collection on the parasite capacitance exists between OHE and earth cuttings, for different angles and different base widths of it at the proximity of OHE, keeping the height of OHE and earth cutting controlled.

Fig.4.3 Experiment on model of OHE at laboratory at different angles and different base widths.

The model is setup using two hardboard sheets hinged on a base wooden sheet, pasted with metal foil inside, connected to an earth pit to create uniform electrical potential surface analogous to earth surface, and by placing a miniature size of OHE inside the experiment setup (Fig 4.3). Length of the model is one metre.

Parasite capacitances in between the earth and the OHE of one meter length, for different angle of the uniform electrical potential surfaces were measured, in six trials. Average readings of the trials obtained for different angles for different heights of the model traction wires are shown in Table 4.1

Table 4.1 Parasite capacitances of traction wire model with same potential surface, at its different angles.

Ht. of wire in m	Parasite capacitance of the model traction wire measured for different angles of the same potential surface, in pF/m									
	0^0	10^0	20^0	30^0	40^0	50^0	60^0	70^0	80^0	90^0
0.10	37.93	38.09	38.30	38.51	38.83	39.27	39.72	40.48	41.67	42.77
0.11	37.84	37.99	38.21	38.42	38.74	39.18	39.63	40.39	41.57	42.67
0.12	37.76	37.91	38.12	38.33	38.65	39.09	39.54	40.30	41.48	42.58
0.13	37.67	37.83	38.03	38.24	38.56	38.99	39.44	40.21	41.38	42.48
0.14	37.58	37.74	37.94	38.15	38.47	38.91	39.35	40.11	41.28	42.38

On analysing those readings statistically using the software tool [31] , the relation of the angle of cutting surfaces and the parasite capacitance for OHE of height 0.1 m is obtained as,

$$C = 0.00068\, x^2 - 0.01\, x + 38.09 \text{ pF/m} \qquad \text{Eqn. (4.1)}$$

where 'x' is the angle of cutting in degree (Fig.4.4)

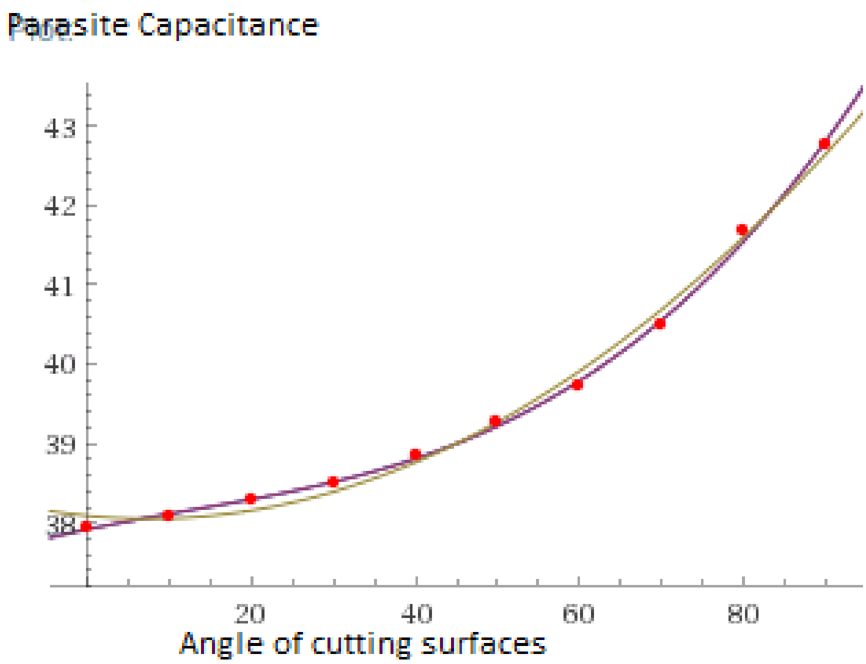

Fig. 4.4 Characteristic curve of capacitance of traction wire at earth cuttings

The AIC & BIC [32], R^2 and adjusted R^2 are -4.63, -3.42, 0.993 and 0.991 respectively. It is revealed that, the variations in the parasite capacitance of OHE at earth cuttings in accordance with variations in the slopes of earth cuttings are non-linear.

4.3.2 DATA COLLECTION FROM ACTUAL HIGH VOLTAGE TRACTION SYSTEM

The capacitance of the traction wire varies inversely proportional to the height of it from the ground (rail level) in accordance with the newly established relation (Eqn.(3.3)). However, it is unable to calculate the parasite capacitance of the OHE at earth cuttings, since they don't have common profiles, except in the cases of their slopes. Hence, further data collection for different base widths of the earth cuttings are done by conducting the experiments at various locations (Fig. 4.5) of earth cuttings with various base widths with the aid of a 50 metre long model of high voltage ac railway traction wire

Fig.4.5 Data collection from the actual high voltage traction line at railway earth cutting

Averages of the readings obtained in the experiments' trials conducted at earth cuttings of various widths (A7 – A9) are shown in Table 4.2. Standard angles of earth cuttings available in railway systems are 30^0 for ordinary soil, 45^0 for laterite, 76^0 for rocks, and 90^0 for concrete walls. In all the cases, the vertical height of earth cutting is kept more or less 7.8 m and height of lower conductor OHE (contact wire) 5.6 m, as controlled variables.

Table 4.2 Parasite capacitance between OHE and earth at cuttings

Angle of cutting	Average of parasite cap. in nF/km at , measured in 6 trials at earth cuttings for its various base widths				
	Base width 6.72 m	Base width 7.28 m	Base width 7.84 m	Base width 8.40 m	Base width 8.96 m
30^0	14.59	14.55	14.53	14.51	14.50
45^0	14.77	14.74	14.70	14.65	14.60
76^0	15.45	15.34	15.23	15.10	14.95

4.4 CURVE FITTING

All the data collected from the experiments conducted at the actual high voltage ac traction lines at different earth cuttings of different base widths are subjected to the curve fitting process & statistical analysis using the software tool [31]

Fig. 4.6 to 4.8 are the plots obtained from the statistical analysis made on the parasite capacitances of 25 kV ac traction line with the varying profiles (base widths) of earth cuttings at different angle of cuttings, ie. 30^0, 45^0, 60^0, 76^0 and respectively, with the aid of the statistical tool [31]

Y axis represents the parasite capacitance measured, in nano farad / kilo metre (nF/km), and X axis represents the base width of earth cutting, in metre (m)

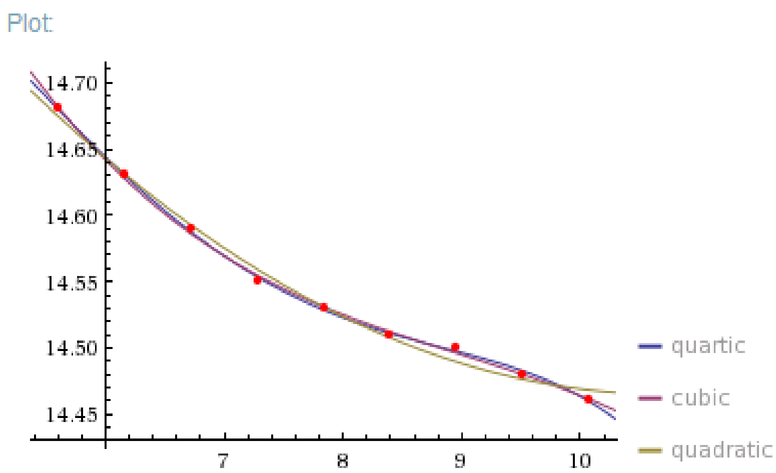

Fig 4.6 Plot on the parasite capacitances of OHE run through at a 30 degree earth cutting, for different widths of it, at controlled height of earth cutting height & OHE.

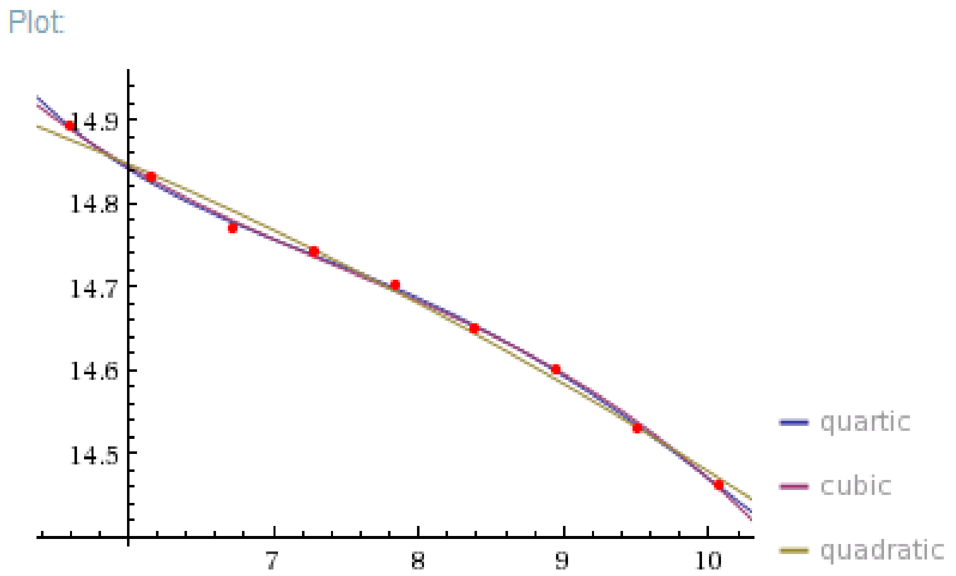

Fig 4.7 Plot on the parasite capacitances of OHE run through at a 45 degree earth cutting, for different widths of it, at controlled height of earth cutting height & OHE.

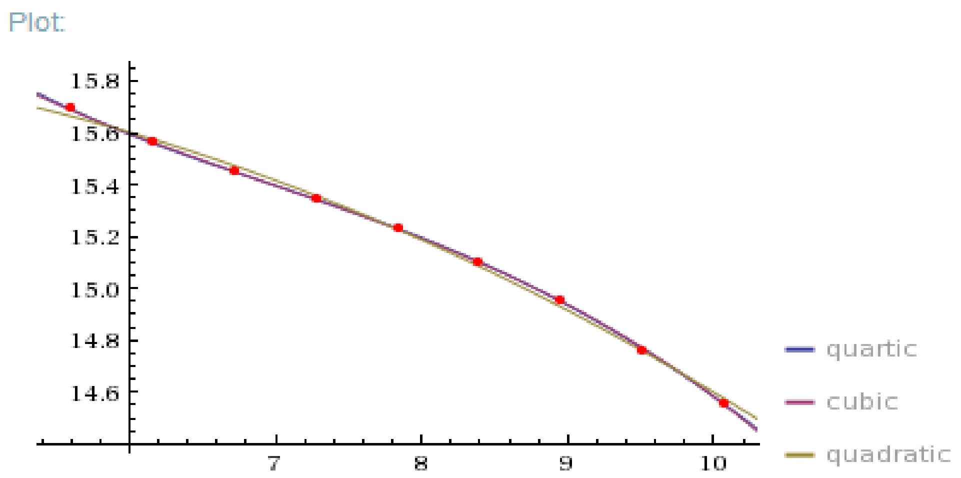

Fig 4.8 Plot on the parasite capacitances of OHE run through at a 76 degree earth cutting, for different widths of it, at controlled height of earth cutting height & OHE.

As the results of the statistical analysis, three non-linear forms of equations, viz. Quartic, Cubic and Quadratic with approximate fit to the curves are also generated for different angles of earth cuttings, viz. 30^0, 45^0, 76^0 and 90^0 whose base widths varies from 5.6 m to 8.96 m

Height of earth cutting and the height of lower conductor of OHE were kept controlled at 7.8 m, and 5.6 m respectively. Equations thus generated in Quartic, Cubic and Quadratic forms are given in tabular form in Tables 3.3, 3.4 & 3.5 respectively. 'w' is the width of earth cutting, in metre,

Quartic form of equation, $C = aw^4+bw^3+cw^2+dw+k$ nF/km Eqn.(4.2)

Cubic form of equation, $C = aw^3+bw^2+cw +K$ nF/km Eqn.(4.3)

Quadratic form of equation, $C = aw^2+bw +K$ nF/km Eqn.(4.4)

Table 4.3 Quartic equations generated for various angles of earth cuttings,

Angle of cut	Coefficient of w^4, a	Coefficient of w^3 , b	Coefficient of w^2, c	Coefficient of w, d	Constant term, k
30^0	- 0.0008	+0.218	-0.216	+0.816	+13.8
45^0	+0.0011	-0.039	+0.506	-2.88	-20.9
76^0	+0.001	-0.039	+0.536	-3.235	+22.9

Table 4.4 Cubic Equations generated for various angles of earth cuttings

Angle of cut	Coefficient of w^3 , a	Coefficient of w^2, b	Coefficient of w, c	Constant term, k
30^0	-0.0024	+0.0645	-0.606	+16.476
45^0	-0.0043	+0.097	-0.801	+17.09
76^0	-0.0032	+0.0633	-0.541	+16.767

Table 4.5 Quadratic equations generated for various angles of earth cuttings

Angle of cut	Coefficient of w^2, a	Coefficient of w, b	Constant term, k
30^0	+0.0081	-0.173	+15.391
45^0	-0.0044	-0.022	+15.137
76^0	-0.0218	+0.0979	+15.799

4.5 STATISTICAL ANALYSIS OF DATA

The AIC & BIC [32], R^2 and the adjusted R^2 calculated for all those three equations given separately in Tables 4.6 to 4.8

Table 4.6 AIC, BIC, R^2 and adj. R^2 for Quartic equations

Angle of cut	AIC	BIC	R^2	(adj.R^2)
30^0	-74.49	-73.30	0.999	0.998
45^0	-64.40	-63.21	0.999	0.998
76^0	-74.31	-73.12	0.999	0.999

Table 4.7AIC, BIC, R^2 and adj. R^2 for Cubic equations

Angle of cut	AIC	BIC	R^2	(adj.R^2)
30^0	-70.45	-69.47	0.998	0.997
45^0	-61.81	-60.83	0.999	0.998
76^0	-67.70	-66.71	0.999	0.999

Table 4.8AIC, BIC, R^2 and adj. R^2 for Quadratic equations

Angle of cut	AIC	BIC	R^2	(adj.R^2)
30^0	-58.61	-57.82	0.992	0.989
45^0	-48.42	-47.63	0.993	0.991
76^0	-38.48	-37.69	0.997	0.996

4.6 CHAPTER SUMMARY

In the statistical analysis of all sets of data of all the different angles of earth cuttings, the coefficient of determination R^2 and the adjusted R^2 are found more than 0.9, which are above the minimum acceptance level in curve fittings. Besides, the AIC and BIC are negative for all those equations, which further enhances the degree of acceptance level of those empirical formulae. Hence the empirical formulae generated in Quartic, Cubic and Quadratic forms of equations (Table 4.3, 4.4 & 4.5) are statistically significant.

The highest R^2 is obtained in the Quartic equations, which will give highest accuracy if utilized in creating fault locating algorithm. However, the quadratic equations are also having very high R^2 value, in the order of 0.99 and above.

From the interactions made with the official of Traction Distribution branch of various railway organizations, it is learned that the variation in accuracy of pinpointing the persisting fault location on OHE within a range upto 250 metres is generally tolerable by the electric traction departments. Hence, using of quadratic equations (Table 4.5) for finding the parasite capacitance of OHE at the earth cuttings of various standard slopes are also acceptable for modifying the algorithm for pin pointing the fault location on OHE.

CHAPTER 5

EFFECT OF VARYING HEIGHT OF EARTH CUTTINGS ON THE PARASITE CAPACITANCE OF AC HIGH VOLTAGE ELECTRIC TRACTION LINES

5.1 CHAPTER OVERVIEW

It is understood from the previous chapters that the persisting earth fault on OHE due to various reasons like; non-clearing of electrocuted bodies (of birds, animals, reptiles etc,) from the live portion of OHE, permanent touching of trees or its branches to OHE, insulator flashing due to dirt deposited or algae formed over them, falling of other metallic structures or power line crossing conductors of grid lines on them etc. will cause automatic shut down of traction power of OHE. This situation will lead to serious interruption of train traffic at a wide area till such time those faults are cleared from the OHE. Hence, removal of persisting faults from the OHE is paramount important action for restoring the train traffic.

Pinpointing the exact position of persisting earth fault on railway electric traction lines is inevitable in mobilizing the breakdown attending teams to clear those faults, for which, fool proof algorithms developed duly formulating the variations of the line parameters, mainly the parasite capacitance (or the shunt admittance) of OHE at vulnerable areas like; earth cuttings, tunnels etc. are essential. However, all the prevailing theories ignore the effect of topographical features at the vicinity of the high voltage ac traction line on its shut admittance.

Not all the earth cuttings (soil removed from the hillocks to lay railway tracks (Fig. 4.1), are having all the profiles similar. Its base width, angle of cuttings, and the height vary from place to place in tune with various factors like; drainage arrangement at water stagnate areas, stability of soil in accordance with its bearing capacity, water table at the place from where the soil is to be removed for laying tangent railway track etc.

Data published by Research Design and Standard Organization (RDSO) of Indian Railways [7] for making of earth cuttings prescribes to adopt 1:1 slope at laterite soil area, and 2:1 slope for hard rock area for its better stability. Those two slopes are having angles 45^0 and 76^0 respectively. Construction of vertical concrete walls is also suggested for the places where space constraints are experienced. It is specifically described that the maximum height of any earth cuttings shall not exceed 18 m.

It is discussed in the previous sections that the parasite capacitance exists between the OHE and earth will vary with the variations in the heights of OHE from rail level, base with of the earth cutting available at the proximity of the OHE, the angle of the cutting etc.

Since the data collection from the laboratory model cannot exactly replicate the actual effects of the earth cuttings on the parasite capacitance of OHE due to the irregular surfaces of earth cuttings at hard rock area, experiment conducted with a 50 m similitude model of OHE by placing it at actual railway earth cuttings of various height and of various slopes is adopted as the methodology for data collection, and to formulate the parasite capacitance of OHE at different vertical heights and angles of earth cuttings, by keeping base width and OHE height are controlled variables.

5.2 DATA COLLECTION

Series of experiments were conducted on similitude models of OHE set up at the railway tracks laid through the earth cuttings of different angles viz. 30^0, 45^0, 76^0 and 90^0, and for various heights of it, which vary from 5.6 to 15.12 m, by keeping the base width 5.6 m and contact wire height of OHE 5.6 m as controlled variables.

Averages of the readings obtained in the trials (A10 - A12) are arranged in Table 5.1

Table 5.1 Parasite capacitance between OHE at various heights of earth cuttings, at standard slopes (keeping OHE height at 5.6 m and base width of cutting at 5.6 m)

Height of earth cutting, in m	Capacitance of OHE at 30^0 slope, in nF/km	Capacitance of OHE at 45^0 slope, in nF/km	Capacitance of OHE at 76^0slope, in nF/km
5.60	14.41	14.42	14.54
6.16	14.49	14.52	14,84
6.72	14.58	14.68	15.23
7.28	14.66	14.80	15.53
7.84	14.70	14.85	15.74
8.40	14.76	14.96	15.90
8.96		15.03	16.04
9.52		15.08	16.14
10.08		15.11	16.22
10.64			16.28
11.20			16.32
11.76			16.36
12.32			16.38
12.88			16.40
13.44			16.41
14.00			16.41
14.56			16.41
15.12			16.41

5.3 CURVE FITTING

Fig.5.1 to 5.3 are the plots obtained through statistical analysis for curve fittings made on the parasite capacitances of 25 kV ac traction line with the earth at varying heights of cuttings at slopes 30^0, 45^0 and 76^0, with the help of the online curve fitting &analysing tool [31]. Earth cutting's heights in metre are shown on X axis in metre (m), and the corresponding parasite capacitances are on Y axis in nF/km,

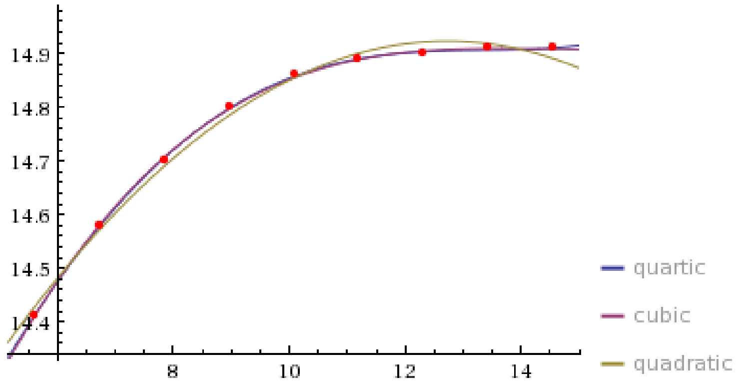

Fig. 5.1 Plot on parasite capacitance for different heights of earth cuttings at 30^0

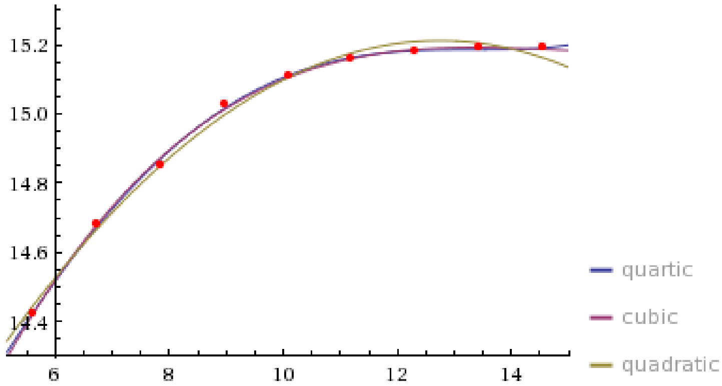

Fig. 5.2 Plot on parasite capacitance for different heights of earth cuttings at 45^0

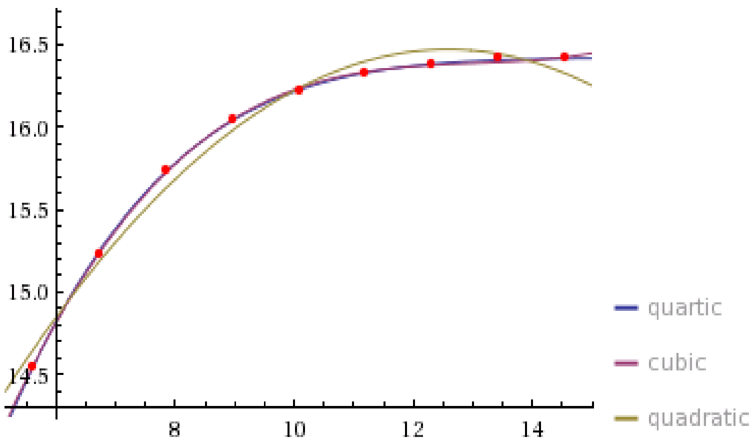

Fig.5.3 Plot on parasite capacitance for different heights of earth cuttings at 76^0

Non-linear equations of the forms Quartic (Eqn.(5.2)), Cubic (Eqn.(5.3)) and Quadratic (Eqn.(5.4)) are also generated with the aid of the statistical tool [31] for different slopes of cuttings, viz. 30^0, 45^0, 76^0 and 90^0 whose heights vary from 5.6 m to 15.12 m.

Since the shapes of the Quartic equation and cubic equations in all the graphs (Fig.5.2 - 5.5) almost resemble each other for all the standard slopes of earth cuttings, the analysis of Quartic equation is omitted from the scope the analysis. The quadratic equations generated are shown in Table 5.2

5.3.1 CUBIC FORM OF NEWLY FORMULATED EQUATIONS FOR PARASITE CAPACITANCES OF OHE FOR VARIOUS STANDARD SLOPES OF EARTH CUTTINGS.

$C = 8x10^{-4}\ h^3 – 3.3x10^{-2}h^2 + 4.74x10^{-1}h + 12.668$ nF/km Eqn. (5.1)

$C = 1.1x10^{-3}\ h^3 – 4.7x10^{-2}h^2 + 6.69x10^{-1}h + 11.844$ nF/km Eqn. (5.2)

$C = 4.3x10^{-3}\ h^3 – 1.67x10^{-1}h^2 + 2.1723h+ 6.831$ nF/km Eqn. (5.3)

Equations, Eqn. (5.1), Eqn. (5.2) and Eqn. (5.3) are for finding the parasite capacitance (C) of OHE at earth cuttings with angles (slopes) of walls 30^0, 45^0 and 76^0 respectively, where 'h' is the height of the earth cuttings in metre.

Table 5.2 Equations generated in Quadratic form for various slopes of earth cutting at its different heights (h)

Slope of earth cutting	Coefficient of h^2	Coefficient of h	Constant term, k
30 degree	-0.00978	+0.249	+13.3391
45 degree	-0.01509	+0.3847	+12.7611
76 degree	-0.03744	+0.94207	+10.5427

5.4 STATISTICAL ANALYSIS OF DATA

The Akaike Information Criterion (AIC) & the Bayesian Information Criterion (BIC) [32], the R^2 , and the adjusted R^2 (adj.R^2) are also calculated for all those equations and shown in Tables 4.3 & 4.4

Table 5.3. AIC, BIC, R^2 and adj. R^2 for Cubic equations for various slopes of earth cutting

Angle of earth cutting	AIC	BIC	R^2	(adj.R^2)
30 degree	-65.93	-64.95	0.999	0.999
45 degree	-47.19	-46.21	0.998	0.997
76 degree	-43.67	-42.68	0.999	0.999

Table 5.4 AIC, BIC, R^2 and adj. R^2 for Quadratic equations for various slopes of earth cuttings

Angle of earth cutting	AIC	BIC	R^2	(adj.R^2)
30 degree	-43.27	-42.48	0.993	0.990
45 degree	-35.90	-35.12	0.993	0.991
76 degree	-12.84	-12.06	0.985	0.979

5.5 CHAPTER SUMMARY

In the analysis, R^2 and the adjusted R^2 are found above 0.9 for the two forms of equations, which imply that all the two forms of equations generated are statistically significant. The highest R^2 is obtained in the cubic form of equations. This form of equations shall give highest accuracy in calculating the parasite capacitance of OHE at earth cuttings. However, the quadratic equations also give very good R^2 value, in the order of 0.97 at the minimum. But it is noted from the graphs (Fig. 4.2 to 4.5) that the quadratic equations have significant variations from the actual trace of the curve at heights of cuttings above 10 metres. Hence, using of quadratic equations (Table. 4.2) for finding the parasite capacitance of OHE at earth cuttings of height lesser than 10 M is acceptable. Cubic form of equations ((Eqn.(4.1) - Eqn.(4.4)) are recommended the height of earth cuttings above 10 m.

CHAPTER 6

PARASITE CAPACITANCE OF AC HIGH VOLTAGE ELECTRIC TRACTION LINES INSIDE RAILWAY TUNNELS

6.1 CHAPTER OVERVIEW

Railway tunnels are usually constructed where the height of earth cuttings exceed 18 metres. However, there is no hard & fast rules in deciding to construct tunnels in lieu of earth cuttings for a height lesser than 18 metres. Bearing capacity of the soil to be excavated, chances of avalanche in rainy seasons, availability of land to construct wider earth cuttings (lesser angle of slope) etc. are other deciding factors of it. It is observed in the research regions that tunnels are made even for 13 metre high earth cuttings, mainly due to the poor bearing capacity of soil.

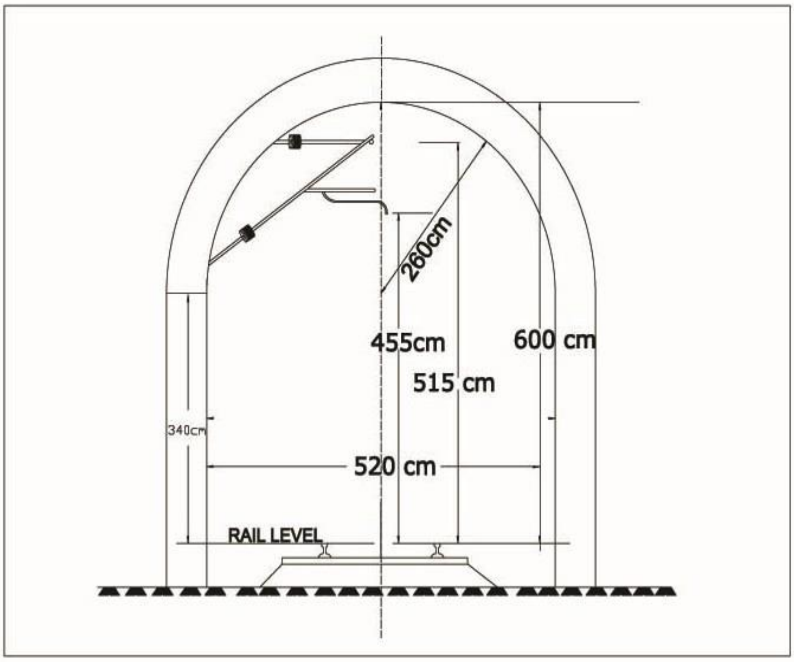

Fig. 6.1 Dimensional details of Broad Gauge railway tunnel

As there is no laid down theory for the calculation of variation of the parasite capacitance of OHE within a railway tunnel, this chapter explains the experiment conducted with the help of a 50 m long model of OHE inside the BG railway tunnel with standard dimensions to formulate the parasite capacitance of OHE

6.2 TYPES OF RAILWAY TUNNELS

Railway tunnels are of two types viz. cut & cover and carving through.

6.2.1 CUT AND COVERED TUNNEL

These tunnels are made at laterite soil or soil with lesser bearing capacity. The entire volume of earth will be excavated from that area in ‘V’ shape, and tunnels with flat base, vertical walls and semi-circular head room wall (6.1) will be constructed either with reinforced cement concrete or with brick masonry. Those tunnels are covered thereafter with the soil, which was removed earlier. Interior of such tunnels shall be smooth, and no much deviation will be there in its dimensions from the standards stipulated for railway tunnels (Fig. 6.2).

Fig. 6.2 Cut and covered railway tunnel

6.2.2 CARVED TUNNEL

Tunnels are carved for laying railway tracks at hard rock area. This process was done earlier with manual labours. Interior of such carved tunnels shall not be smooth (Fig.6.3). Its dimensions shall also have slight variations from the standard values. There exists the chance of rock felling inside such tunnels as the result of the hairline cracks penetrated through the tunnel walls with the hammering or explosions made on them while removing the rocks for tunnel constructions. Such cracks may lead to the collapse of tunnel walls when the trains pass through them with high velocity. In such areas, additional lining with cement concrete mix will be made on the tunnel walls.

Fig. 6.3 Railway tunnel carved through hard rock

Most of the modern railway tunnels are being constructed with the rock carving machines. Interior of such tunnels shall be smooth, and there exists little chances for the wall collapse. Whether it is a cut & cover tunnel or a carved tunnel, water drainage arrangements will be constructed by the side of the tracks. The track is laid on the ballast cushion bed. Five such cut & cover tunnels constructed with reinforced cement concrete are available at research region.

6.2.3 ANALOGY OF RAILWAY TUNNEL WITH EARTH CUTTINGS

Railway tunnel can be imagined as an earth cutting of vertical walls (90^0 slopes) covered with semi-circular roof for its entire length. However, there shall not ordinarily be various base widths and heights due to standardization of its cross sectional dimensions of tunnels (Fig 6.1)

6.3 UNIQUE FEATURES OF HIGH VOLTAGE AC TRACTION WIRES INSIDE RAILWAY TUNNELS

OHE is drawn through the specially designed supports fitted under the curved head room wall of the tunnel. OHE in the tunnels has many unique features, which make the assessment of parasite capacitance of OHE within the tunnel very complex. Since the broad gauge railway tunnels have the standard height of 6 m, the top conductor of traction wire (catenary wire) is strung at the maximum height of 5.5 m from the ground (rail level), and the bottom conductor (contact wire) is strung further at 0.3 m below to it (Fig. 6.4).There shall not be such an arrangement to run a high tension ac power electric un insulated conductors so close to the earth potential surface anywhere else in electric power transmission or distribution sectors.

Fig. 6.4 Bare conductors of OHE run close to earth potential surface

Railway tunnels shall have lengths in the order of few metres to many kilometres. Evidently, very long railway tunnels are present in India and China. Konkan railway route in India is the typical example for it. Konkan Railway is constructed through the west coast (also called Konkan coast) of India on 741 kilo metre stretch. Since it passes through (and often crosses also) the Western Ghats, there available 92 tunnels of total length around 83.6 kilometres, one with around 7 kilometre length. It is already decided by the India Government to electrify railway tracks at Konkan Railway route at its full stretch [38]. With the railway track electrification, length of the un insulated high voltage ac traction wires will run closer to earth potential around 83.6 km. Besides, there available a large number of sharp earth cuttings. It is obvious that the parasite capacitance of the OHE at the stretch pf lengthy tunnels will vary significantly from the standard design values, and shall cause serious error in the fault distance calculation.

6.4 DATA COLLECTION

A standard similitude model of conventional OHE with 50 m length, and with dip (vertical distance between the catenary and contact wire) 0.3 m is made for data collection, and placed inside a BG railway tunnel (Fig.6.5)

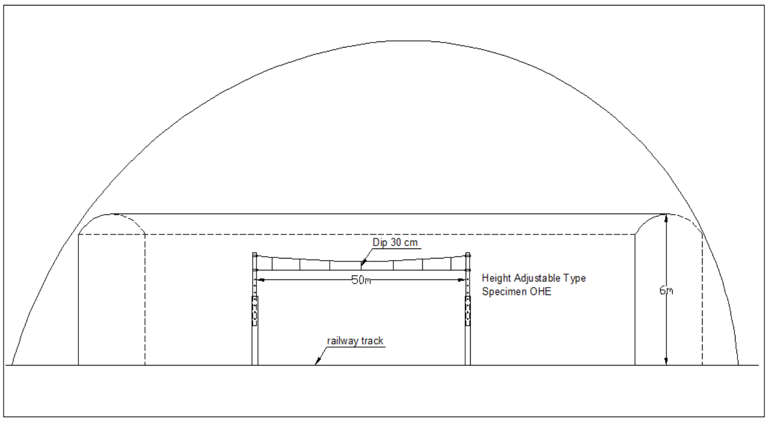

Fig. 6.5 Measurement of parasite capacitance of OHE within railway tunnel

Arrangements to adjust the height of the model OHE in 0.25 meter steps were also incorporated to the model. The model is placed inside a BG railway tunnel of length 200 m, in the research region. Readings of parasite capacitances for every 0.25 M steps in its heights are measured, each in 6 trials (A15). Average of the measurements obtained through the experiment trials are shown in Table 6.1

Table 6.1 Parasite capacitances of similitude model of OHE of length 50 m, inside a railway tunnel having standard dimensions.

Height of Contact (H_t) wire, in m	Height of Catenary wire, in m	Capacitance (Cp) of 50 m long conventional OHE in nF, with fixed dip 0.3 m	Cp, made out of 1000 m long OHE, in nF
0.50	0.80	1.905	38.1
0.75	1.05	1.757	35.94
1.00	1.30	1.71	34.2
1.25	1.55	1.659	33.18
1.50	1.80	1.595	31.9
1.75	2.05	1.565	31.3

2.00	2.30	1.525	30.5
2.25	2.55	1.517	30.34
2.50	2.80	1.495	29.9
2.75	3.05	1.513	30.26
3.00	3.30	1.53	30.6
3.25	3.55	1.553	31.06
3.50	3.80	1.605	32.1
3.75	4.05	1.638	32.76
4.00	4.30	1.705	34.1
4.25	4.55	1.768	35.36
4.50	4.80	1.86	37.2
4.75	5.05	1.943	38.86
5.00	5.30	2.055	41.1
5.25	5.55	2.163	43.25
5.50	5.80	2.271	45.42

6.5 CURVE FITTING

The plots (Fig.6.6) obtained through the analysis made on the parasite capacitances of 25 kV AC traction line for the varying heights of the OHE inside a standard dimensioned railway BG tunnel with the help of the curve fitting & analysing tool [31]. OHE heights in metre are shown on X axis in metre (m), and the corresponding parasite capacitances are on Y axis in nF/km.

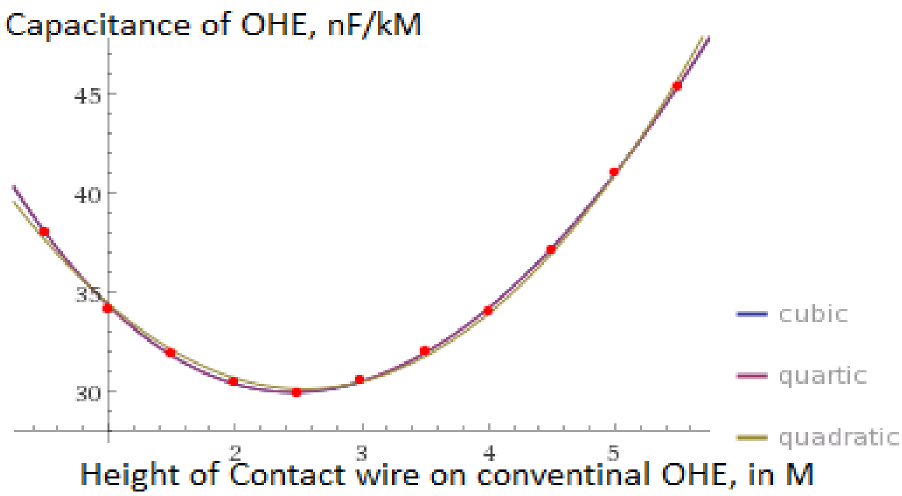

Fig. 6.6 Plot on capacitance of conventional OHE inside the railway tunnel

Three types of equations, viz. Quartic, cubic and quadratic forms were also generated as the result of the statistical analysis (Table 5.2)

Table 6.2 Three forms of equations generated for the parasite capacitance of OHE within railway tunnel of standard dimensions

Form of equations	*Coef.of H_t^4	Coef. of H_t^3	Coef. of H_t^2	Coef. of H_t	Constant term, K
Quartic	0.007459	-0.17125	2.8802	-11.4737	43.09
Cubic		-0.08174	2.524	-10.9479	42.87
Quadratic			1.79	-9.1	41.75

*Coef. = Coefficient. H is the height of the bottom conductor of conventional OHE from the rail level, in metre.

6.6 STATISTICAL ANALYSIS OF DATA

The statistical indices, viz, AIC, BIC, R^2 and adjusted R^2 [32] were also determined for all the three types of the equations (Table 5.2)

Table 6.3 Statistical indices of equations generated for the parasite capacitances of conventional OHE inside a railway tunnel.

Form of equations	AIC	BIC	R^2	adj.R^2
Quartic	-9.04072	-6.65335	0.9996	0.9994
Cubic	-10.0513	-8.06182	0.9998	0.9994
Quadratic	9.66045	11.252	0.9969	0.9962

From the plots (Fig. 6.5) of all the tree types of the equations (Table 5.2), it is understood that curves generated for three types of equations are almost resemble one another.

In the statistical analysis, the values of 'R^2' and the 'adjusted R^2' are found above 0.99 for all the three forms of empirical equations obtained. Also, the AIC & BIC are obtained in negative real numbers for the Quartic and Cubic forms of equations. Those indices are close to zero for the Quadratic equations also (Table 6.3). Hence, the quadratic equation is considered feasible for making empirical equation for the parasite capacitance of OHE inside the railway tunnel. Newly generated empirical quadratic equation for the parasite capacitance of high voltage ac electric railway traction line inside a railway tunnel with the standard dimensions shall almost equals to,

$$C_{pt} = 10^{-12} L_t \, (1.79H_t^2 - 9.1H_t + 41.75) \text{ farads} \qquad \text{Eqn.(6.1)}$$

Where, 'C_{pt}' is the parasite capacitance of conventional 25 kV ac electric traction wire within a railway tunnel of standard dimension in 'farad', 'L_t' is the length of the railway tunnel in metre, and 'H_t' is the height of the bottom conductor (contact wire) of OHE from the rail level in m.

6.7 CHAPTER SUMMARY

From the experimentations, it is revealed that the parasite capacitance of high voltage ac electric traction lines (OHE) drawn inside the railway tunnels is around three times higher than that of the traction lines drawn at plane surface area for its normal height. Also, it is came to light that the variation in the parasite capacitance of OHE is not decaying as the height increases, but it traces a parabolic path. There available an optimum point (height of OHE) at which the parasite capacitance is the minimum. But, the said minimum value itself is about two times higher than the lowest parasite capacitance of OHE at plane area. The minimum parasite capacitance of OHE inside the BG railway tunnel is obtained at around 2.5 m high from rail level. However, the said height of OHE is unacceptable in high voltage ac electric traction system on safety & operational points of views. The minimum height of OHE is prescribed is 4.98 m from the year 2004 onwards (which was 4.58 m prior to 2004). Hence, it is important to note that the traction line impedance will vary significantly inside the railway tunnels, which is turn will give erratic input to the distance protection relay for judging the distance of persisting earth fault on OHE at hilly areas. Such situations shall be highly detrimental to railway organizations while actions initiated for restoring the train services, if persisting faults are occurred on high voltage ac OHE.

These findings upheld the necessity to dynamically model the high voltage ac railway traction lines duly incorporating the actual values of the line parameters for different geographical conditions for pin pointing the persisting fault location on it.

CHAPTER 7

DYNAMIC MODELING OF LINE PARAMETERS OF AC HIGH VOLTAGE ELECTRIC TRACTION LINES FOR VARIOUS TOPOGRAPHICAL FEATURES

7.1 CHAPTER OVERVIEW

From the Chapter 1 it is understood that the distances of persisting earth faults on high voltage railway ac electric traction wire (OHE) indicated by the Distant Protection Relay (DPR) varies significantly from the theoretical values. Such variations happen in unpredictable manner at earth cutting & tunnel areas.

From the Chapter 3, it is understood that the parasite capacitance of OHE varies inversely with the variations in its height. An empirical equation (Eqn.(3.3))connecting the parasite capacitance of OHE and its height is also derived through experimental studies conducted on similitude model and on actual OHE systems.

From Chapters 4 & 5, it is understood that the parasite capacitance of the OHE varies significantly with the presence of earth cuttings at its proximity. Those variations are found to be happened in tune with the variations in the base length, base widths, cutting heights and the angle of earth cuttings (slopes). Empirical formulae for establishing the relations of parasite capacitance of OHE with those variables are also derived vide equations in Quadratic, Cubic and Quartic forms (Tables 4.3, 4.4, 4.5 and 5.2).

From the Chapter 6, it is understood that the parasite capacitance of OHE within the railway tunnel shall be three times higher to that of at plane area. Also, its characteristics curve is quite different from that of at plane ground (Fig6.6). The height of OHE at which the parasite capacitance is obtained as minimum is unacceptable in high voltage ac electric traction system on safety &

operational points of views. The minimum height of OHE is specified as 4.98 metre with effect from the year 2004. Hence, it is obvious that the traction line impedance will vary significantly inside the railway tunnels, which is established through an empirical equation (Eqn. (6.1))

Those findings highlight the necessity to dynamically model the high voltage ac railway traction lines duly incorporating the actual values of the line parameters for different geographical conditions for pin pointing the persisting earth fault locations on it.

This chapter explains the dynamic modelling of high voltage electric ac electric traction lines of railways duly incorporating the findings presented through the previous chapters on the variations of parasite capacitance of OHE in accordance with the changes in topographical features.

Besides, a suitable algorithm, which is modified from the prevailing one, enabling the Traction Power Controller to precisely pinpoint the persisting faults on ac OHE is also suggested.

7.2 REVIEW OF THE EXISTING MODEL OF HIGH VOLTAGE AC ELECTRIC RAILWAY TRACTION

High voltage ac electric power railway traction line is analogous to a short ac power transmission line. A short electric power transmission line shall have the length less than 80 km, and working voltage shall be 66 kV or lesser. High voltage ac power electric traction line’s working voltage shall not go beyond 27.5 kV, and the maximum length shall ordinarily be in between 25 km to 40 km.

However, there exist differences also. The transmission lines (whether they are short, medium or long) are acting as the links of various power grids’ nodes. There shall not be direct connections of electrical loads to those lines, other than the power transformers available at sub stations. There shall be regular pattern of loads for every substation.

Railway electric traction lines (OHE) are acting as local linear distribution lines. Electric loads of high rating (electric locomotives) are directly connected to OHE. Also, there exists a unique feature of loading on OHE, ie. the position of the high rated loads shall always vary from time to time. Therefore, regular patterns of load curves can’t be made for the electric traction lines, mainly because running of unscheduled freight carrying trains with heavy loads.

Resistance and inductive reactance are the two line parameters considered for modelling the short ac power transmission line (Fig. 1.8).Shunt admittance of such lines are neglected from the modelling stage itself due the reason that the effect of shut admittance is negligibly small at the height where the conductors are strung above the minimum statutory level prescribed for power transmission lines. Line parameters of transmission lines are assumed to be uniformly distributed throughout its length, since there shall not be much variation in its heights in accordance with geographical conditions.

Maximum height of the ac high voltage traction lines is limited to a value much lesser than that of transmission line. It is limited in between 5.8 m and 4.58 m (High reach OHE with height 7 m are also in use at few freight transportation railway corridors)

Besides, the height of OHE in most of the cases varies in between permitted maximum and minimum levels randomly in accordance with the presence of over line structures like; bridges, tunnels, aqua ducts, water pipe lines, petroleum pipe lines etc. above the OHE at the geographically challenged areas. Hence, no pattern could be noticed in the variations of the height of OHE also.

7.3 PROPOSED MODEL OF HIGH VOLTAGE AC ELECTRIC RAILWAY TRACTION LINE

From the survey, and the subsequent experiments conducted at various electrified railway sections, it is discovered that the variations in the parasite capacitance of OHE happens mainly due to the variations in its clearances from the earth or earthed structures. Since those variations in the clearance of OHE from earth/earthed structures are not regular, the entire length of OHE is proposed to subdivide into several blocks, and distinct line parameters are assigned for each blocks of OHE (Fig.7.1)

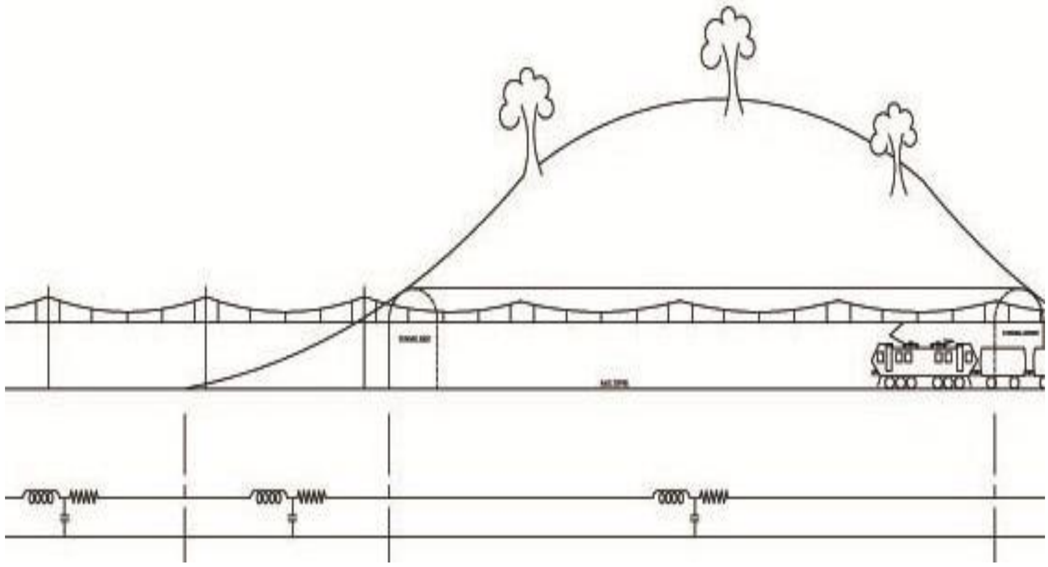

Fig.7.1 Segregation of line parameters of OHE in tune with changes in topographical features

Further, for easy assessment of line parameters, the entire length of the OHE is subdivided into 100 long blocks for the theoretical calculations of line impedance per unit length (100 metre), duly incorporating the average parasite capacitances of OHE for every 100 metre length at various topographical features, like ; plane area, earth cuttings, tunnels etc. Resistance (R_o) & inductive reactance (L_o) per unit length are directly adopted from the prevailing theoretical values [19].

Capacitive reactance of every 100 metre blocks, viz. c_1, c_2, $c_3 ... c_n$, are assessed separately by using the newly formed empirical formulae (Eqn. (2.3)to Eqn. (5.1)) for different topographical features, and made conceptual dynamic model for OHE (Fig. 7.2)

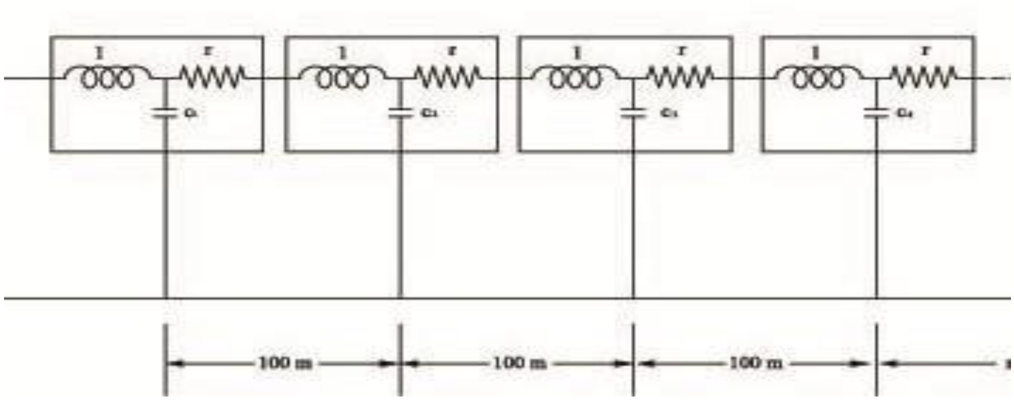

Fig 7.2 Conceptual dynamic model of OHE with varying line capacitance

7.4 APPLICATION OF DYNAMIC MODEL OF OHE IN MODIFYING FAULT LOCATING ALGORITHM

7.4.1 PROCESSES INVOLVED IN FAULT DISTANCE PINPOINTING IN PREVAILING ALGORITHM

Collecting the fault current and the real time volage from the outputs of current transformer (CT) and Potential transformer (PT) is the first step. Impedance of OHE upto the point of fault is calculated in the next step by deviding the real time voltage by the the fault current. Distance of fault is arrived at the last step by deviding the loop imepedance obtained from the preceding step by the per unit standard value of impedance of OHE, as shown in Table 1.2, which is incorporated in the software program of the Distance Protection Relay.

It is proved that the prevailing algorithm for pinpointing the earth faults on OHE lacks the accurancy (Fig.1.8), and is dicovered that the varying papasite capacitance of OHE in accordance with the the changes in the topographical features is the root cause of the inaccuracy of it.

7.4.2 PROCESS STEPS IN FAULT DISTANCE PINPOINTING IN MODIFIED ALGORITHM.

A modified algorithm for calculating the fault disance on OHE for the accurate calculation of earth fault distance is suggested herewith, in the following steps (Fig. 7.3)

Step 1

Segregate the entire length of OHE into many blocks of 100 m long.

Step 2

Conduct detailed survay on every blocks to record the values of the physical variables, viz. height of OHE (bottom contact wire) for plane area & inside the tunnels, and height of OHE & mesurements of profiles (base width, height and slope) of earth cuttings.

Step 3

Calculate the parasite capacitances for each blocks using the newly discovred empirical equations (Eqn. (3.3), Tables 4.3, 4.4, 4.5 and 5.2, and Eqn. (6.1)) appropriately.

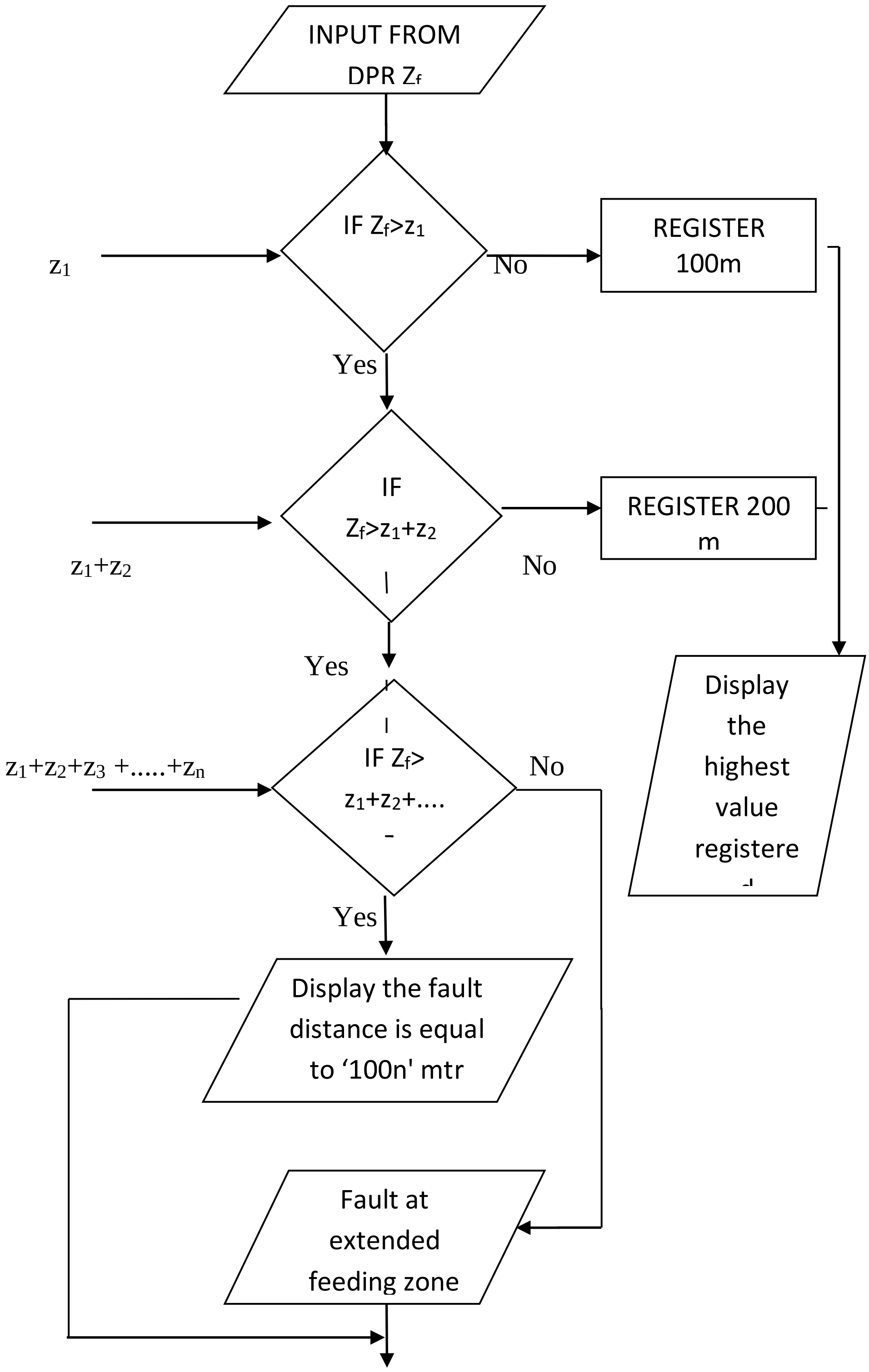

Fig. 7.3 Modified flow chart for earth fault pinpointing algorithm

Step 4

Calculate the impedances for every 100 metre blocks, viz. z_1, z_2, z_3, ..., z_n using the values obtained in step 3 along with the standard values of resistance and inductive reactance [13] of 25 kV ac OHE.

Step 5

Incorporate the distinct impedances obtained in the preceding step in the software programing.

Step 6

Derive the impedance Z_f, upto the faulty point using the established equation, Z=V/I, where V is the real time voltage and Iis the instantaneous current.

Step 7

Compare the value of loop impedance, Z_f with the value z_1. If Z_f is lesser than z_1, declare, "fault location is within 100 m" of the electric supply point. Else, go to next step (Fig.6.3)

Step 8

Compare the value of Z_f with the combined value of z_1 and z_2 in the next step . If Z_f is lesser than z1+z2, declare, "fault location is within 200 m" of the electric supply point. Else, go to next step

Further steps are the iteration of the previous step by comparing the combined values of z_1, z_2 and z_3 and so on till it arrived 'z_n', and declare, "fault locations within k*100 m" at the step when the Z_f is found lesser than the combined values of impedances upto and including 'z_k' block, where the value of 'k' varies from 1 to 'n'

7.5 CHAPTER SUMMARY

The modified algorithm for fault distance pinpointing suggested in this chapter is to be executed in two phases. One is the preliminary phase, which includes first four steps as detailed in section 7.3. It shall be a one time action for any particular feeding sector of OHE until otherwise there made some changes in the topographical features. It is to be executed through manual labour only.

Next phase can be executed either through software support or through mannual labour. Deatils of impedances of every 100 metre length block of OHE shall be available in Traction Power Control Room after the adoption of modified algorithm. The Traction Power Controller on duty, who is also an electrical engineer is able to receive the primary inputs of earth faults on OHE (viz. real time voltage and instantaneous fault current) through the SCADA [4] can do all other steps through simple arithmetical calculation. There shall not be any difference in the accuracy of calculation of fault distance in either ways. If software support is used, few minutes can be saved in the manual labour only, but is found not economical.

CHAPTER 8
CONCLUSIONS AND FUTURE RESEARCH

8.1 INTRODUCTION

It is brought to light from that the accuracy in calculating the distance of persisting earth fault on high voltage ac electric power railway traction lines should be of high degree for clearing those faults for the earliest restoration of train traffic at that sector. Since the railway is a huge network system in size, with lesser number of nodes, providing alternate routes for diverting train traffic in case of problem encountered at any one route is very difficult, hence is not often sorted to. Clearing the earth fault from OHE and the restoration of power supply to restart the train traffic is the foremost action to be initiated. Obviously, the stress on the Traction Power Controller to pinpoint the persisting earth fault of OHE shall be enormous if work with generalized fault locating methods.

Hence, dynamic modelling of high voltage ac electric traction line is set as the main objective. Setting up of dynamic models of ac railway traction line in tune with its exact surroundings with the aid of surroundings empirical formulae created for different topographical conditions for calculating the parasite capacitance ac traction power lines duly including the newly obtained parameters, and defining of new algorithm for pinpointing the persisting faults on OHE to help the Traction Power Controller were set as the sub objectives of this research work.

Applied research in three phases, viz. site survey at sampling region, experimentation on table top models & similitude models for data collection, and validation test conduct on actual system were explored for this research work.

8.2 SUMMARY OF RESEARCH FINDINGS

From the study conducted at the survey regions, it is observed that the accuracy of prevailing system for pinpointing the persisting faults on OHE is much deviates from the actual, due to various factors associated with the topography, which are explained in the previous chapters. Further, intensive study conducted on 640 km stretch of railway system in India at many geographically different places revealed that the root cause of the variations in the parasite capacitances of high voltage ac traction lines is the presence of earth/earth potential surface at the close proximity of un insulated high voltage ac traction lines, which is unique in power transmission/distribution system.

Through a series of experimentations conducted on models of OHE, the variations in parasite capacitances between earth/ earthed potential surfaces and the ac traction lines are quantified, and empirical equations to calculate the parasite capacitance of the ac traction lines for varying topographical features are created through this research work.

8.3 CONTRIBUTIONS OF THE RESEARCH

8.3.1 THEORETICAL CONTRIBUTIONS

Empirical equations are formulated to calculate the parasite capacitance of the ac railway traction line at areas of following topographical features,

At plane surface land

Variations in the parasite capacitance of electric traction line with height of it from earth is empirically established (Eqn.(3.3))

At railway earth cuttings of standard slopes (30^0, 45^0, 76^0, and 90^0)

Variations in the parasite capacitance of electric traction line at earth cuttings with the variations in base widths at constant heights of traction line & earth cuttings are established empirically (tables 4.3, 4.4, 4.5 in Quartic, cubic and quadratic forms), and those for different heights of earth cuttings at constant base widths are also empirically established (Eqn. (5.2))

At Broad Gauge Railway tunnel

Variations in the parasite capacitance of electric traction line with the variations in its heights from rail level tunnel of standard dimensions of Broad Gauge railway line is empirically established (Eqn. (6.1))

8.3.2 IMPLICATIONS FOR PRACTICE

An algorithm to pinpoint the persisting earth fault distance on high voltage ac traction lines duly incorporating the dynamic parameters of it is suggested in Chapter 7, section 7.3 (Fig. 7.3). The said algorithm is found useful to calculate the fault distance even without the help of software controlled module of Distance Protection Relay. It is practically implemented on trial basis, in parallel with the existing system of fault location of DPR, by making a chart for the impedances for every 100 length of OHE for a feeding sector of 35 km length (Eraniel and Balaramapuram), in the Traction Power Control Room at Trivandrum Division of Indian Railway organization for manually calculating the distance of earth fault occurred on (Table 8.1)

Table 8.1 Comparisons on actual distance of naturally occurred earth faults, distance of fault indicated by the DPR, and distance calculated with new algorithm.

Date of Earth Fault	Actual Distance of fault, in km	Fault distance indicated by existing system, in km	Percentage variation from actual	Fault distance calculated using new algorithm, in km	Percentage variation from actual, when new algorithm is used
16.06.2016	16.300	19	16.56 %	16.500	1.22 %
24.01.2017	21.500	25	16.27 %	21.200	1.42 %
10.04.2017	27.200	30	10.29 %	27.400	0.73 %
22.04.2017	06.700	07	04.48 %	06.700	0.00 %

The calculations made on the distance of naturally occurred earth faults from the supply feeding point with the help of newly developed algorithm (Fig.7.3) are found closely matching to the actual (Table 8.1)

8.4 LIMITATIONS & FUTURE RESEARCH

8.4.1 LIMITATIONS

Developed countries do not show much interest in electrifying their railway tracks. It is needless to mention that the electrification process of railway tracks shall invite many constraints to the railway system, which include the degradation in the flexibility of railway systems' modifications, safety aspects etc.

Electrification of railway tracks in developed countries were found done at the suburban sections only, where the challenges offered by the geographical features at the proximity of high voltage ac traction lines on its parameters are near to zero. Corporate/R&D Organizations, who design & develop the high voltage traction systems also do not show interest in developing the remedial solutions for the issues related to challenges raised by the topography of railway tracks, as it is the unique burden experience by some users (mainly, developing countries) only. Hence, all the design & developments made on electric traction systems are found generalized in nature, and are suitable for ideal working conditions.

There available very rare opportunity to conduct the experimentation on the real traction systems, as it consumes prolonged time duration, and may interrupt train traffic also. Besides, the literatures (texts & journals) and internet sites on quantifying the variations in the parameters of high voltage ac electric traction in tune with the changes in topographical features are hardly available for references.

Hence, all the experimentations were conducted for this research work with the help of similitude models. The research regions were hilly as well as at plane areas where tall trees grow thickly. Presence of some unwanted factors like; deposition of dusts on insulators, stray electromagnetic interference due to mobile phone communication towers etc. were could not be avoided from the experimentation. On the other hand, the presence of any other factors, which may have significant influence on the line parameters of high voltage ac electric traction system at a different geographical region, like snow fall, sand wind etc. could not be addressed in this work.

8.4.2 FUTURE RESEARCH

Further studies at regions with different types of geographical features can be conducted to bring out other variables, which may significantly influence the parasite capacitance of the high voltage ac traction lines, which are unnoticed in this research work. Empirical equations for the parasite capacitance of high voltage ac electric traction lines, which are generated through these experimental studies, can be fine tuned by conducting the experiments in more controlled ambiences by including those valid variables, and by eliminating the unwanted or fury factors.

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APPENDICES

APPENDIX. 1

COMPARISONS ON EFFICIENCIES OF VARIOUS TYPES OF TRACTION

Traction system	Percentage efficiency
Steam Traction locomotives	5 % to 7 %
Gas turbine electric traction locomotives	Upto 10 %
Diesel Electric traction Locomotives	26 % to 30 %
Electric Traction Locomotives receive power from Thermal plant	34 % to 36 %
Electric Traction locomotives receive power from Hydro electric power plant	40 % to 42 %

APPENDIX .2

STATISTICS ON RAILWAY TRACK ELECTRIFICATION IN DEVELOPED AND DEVELOPING COUNTRIES

Country	Developed/ Developing	Total track length, in kM	Length of electrified track, in kM	Percentage of electrified track
United States	Developed	2,50,000	1,600	00.64 %
China	Developing	1,21,000	65,000	53.72 %
India	Developing	1,15,000	44,950	39.08 %
Russia	Developing	86,000	50,000	58.14 %
Canada	Developed	46,552	129	00.28 %
Germany	Developed	43,468	19,973	45.95 %
Australia	Developed	38,445	2,715	07.06 %
Argentina	Developed	36,966	136	00.37 %
South Africa	Developing	31,000	24,800	80.00 %

APPENDIX. 3

EVENT OF TRACTION SUPPLY FAILURE AT SURVEY REGION

Shoranur – Thrissur sector

Month	No. of Faults	Type of tripping	Cause of faults identified
July-2015	01	Momentarily - 01	Bird menace - 01
Aug	04	Momentarily - 03 Persisting -01,	Lightning surge - 02 ,
Sept	03	Momentarily - 04	Bird menace - 01
Oct	04	Momentarily - 04	Bird menace - 01, Lightning surge - 01
Nov	Nil		
Dec	04	Momentarily - 04	Man electrocuted - 01
Jan-2016	04	Momentarily - 04	Bird menace - 01
Feb	04	Momentarily – 04	Bird menace-03, Loco roof trouble - 01
March	05	Momentarily - 05	Bird menace - 02
April	04	Momentarily - 05	Bird menace - 01
May	07	Momentarily – 06 Persisting- 01	Bird menace - 01, Tree fallen on OHE -01
June	05	Momentarily - 04	Lightning surge - 01, Locomotive trouble -01

Thrissur - Chalakkudi sector

Month	No. of faults	Type of tripping	Cause of faults identified
July-2015	01	Momentarily 01	
Aug	02	Persisting -02	Foreign body on Loco roof - 02
Sept	02	Momentarily 02	
Oct	01	Momentarily 01	
Nov	02	Momentarily 02	
Dec	03	Momentarily 03	Bird menace - 01
Jan	01	Momentarily 01	

Feb	02	Momentarily 02	
March	05	Momentarily 05	Bird menace - 01 Toddy cat menace - 01
April	02	Momentarily 02	Bird menace -02
May	03	Momentarily 03	Lightning surge - 01

Chalakkudi – Alway sector

Month	No. of faults	Type of tripping	Cause of faults identified
July	Nil	--	--
Aug	Nil	--	--
Sept	04	Momentarily 04	Bird menace-01, Lightning surge - 03
Oct	03	Momentarily 02 Persisting 01	Bird menace - 02, Lightning surge - 01
Nov	02	Momentarily 02	Lightning surges - 01
Dec	02	Momentarily 02	Lightning surges - 01
Jan 2016	01	Persisting 01	Tree fallen on OHE
Feb	03	Momentarily 03	Bird menace - 01
March	03	Momentarily 03	
April	02	Momentarily 02	Bird menace - 01, Lightning surges - 01
May	03	Momentarily 03	Bird menace - 01, Lightning surges - 01
June	01	Momentarily 01	

Alway - Ernakulam sector

Month	No. of faults	Type of tripping	Cause of faults identified
July	03	Momentarily 03	Bird menace - 01
Aug	06	Momentarily 03 Persisting 01	Bird menace - 01 Lightning surges - 01
Sept	10	Momentarily 08	Bird menace - 05 Lightning surges - 01,

		Persisting -02	Foreign body on OHE-02
Oct	Nil	--	--
Nov	07	Momentarily 05 Persisting 02	Bird menace – 06 Tree fallen on OHE - 01
Dec	08	Momentarily 08	Bird menace – 05 Lightning- 01
Jan 2016	05	Momentarily 05	Bird menace - 04
Feb	05	Momentarily 04 Persisting 01	Bird menace - 01, Locomotive trouble -01
March	05	Momentarily 05	
April	04	Momentarily 02 Persisting - 02	Locomotive trouble - 02
May	03	Mom. 03	
June	05	Momentarily 05	Lightning surges - 01, Foreign body on OHE-02

Ernakulam- Vaikkom Road sector

Month	No. of faults	Type of tripping	Cause of faults identified
July	Nil	--	--
Aug	02	Momentarily 02	Lightning surges -01
Sept	03	Momentarily 03	Man electrocuted -01 Lightning surges -03
Oct	04	Momentarily 03 Persisting 01	Bird menace -01 Lightning surges -01
Nov	03	Momentarily 03	Lightning-02
Dec	01	Momentarily 01	
Jan	03	Momentarily 03	
Feb	01	Momentarily 01	Bird menace -01
March	01	Momentarily 01	
April	05	Momentarily 03 Persisting 01	Bird menace -01 Lightning arrestor busted
May	02	Momentarily 02	

June	04	Momentarily 04	Lightning surges -01
Jan	03	Momentarily 03	

Ernakulam- Sherthala sector

Month	No. of faults	Type of tripping	Cause of faults identified
July	Nil	--	--
Aug	03	Momentarily 02 Persisting 01	 Snake bypassed insulator
Sept	01	Momentarily 01	
Oct	09	Momentarily 07 Persisting 01	Bird menace -02 Lightning -02 Locomotive trouble -01
Nov	03	Momentarily 03	Lightning surges -02
Dec	Nil	--	--
Jan	01	Momentarily 01	Bird menace -01
Feb	04	Momentarily 04	Bird menace -01
March	03	Momentarily 02 Persisting 01	Bird menace -01
April	Nil	--	--
May	03	Momentarily 03	Lightning surges -03
June	01	Momentarily 01	Lightning surges -01

Sherthala – Punnapra sector

Month	No. of faults	Type of tripping	Cause of faults identified
July	01	Momentarily 01	Bird menace -01 Lightning surges -01
Aug	03	Momentarily 03	Bird menace -01
Sept	02	Momentarily 02	
Oct	02	Momentarily 02	Lightning surges -01
Nov	01	Momentarily 01	Bird menace -01
Dec	01	Momentarily 01	Bird menace -01
Jan	Nil	--	--

Feb	01	Persisting 01	Lightning surges -01
March	01	Momentarily 01	Foreign body on OHE- 01
April	01	Momentarily 01	Bird menace -01
May	01	Persisting 01	Lightning surges -01
June	Nil	--	--

Punnapra – Cheppad sector

Month	No. of faults	Type of tripping	Cause of faults identified
July	02	Momentarily 02	
Aug	Nil	--	--
Sept	01	Momentarily 01	
Oct	04	Momentarily 04	Lightning surges -02
Nov	05	Mom. 05	Lightning surges -02
Dec	01	Persisting 01	Bird menace -01
Jan	Nil	--	--
Feb	01	Momentarily 01	Bird menace -01
March	Nil	--	--
April	02	Momentarily 02	Lightning surges -02
May	03	Momentarily 02 Persisting -01	Lightning surges -01 Tree fallen on OHE -01
June	03	Momentarily 02	Foreign body on OHE -02

Vaikkom Road - Chingavanam sector

Month	No. of faults	Type of tripping	Cause of faults identified
July	03	Momentarily 03	Bird menace -01
Aug	Nil	--	--
Sept	03	Momentarily 03	
Oct	01	Momentarily 01	Lightning surges -01
Nov	02	Momentarily 02	Bird menace -01
Dec	05	Momentarily 05	Bird menace -02 Lightning surges -01
Jan	03	Momentarily 02	

		Persisting -01	Foreign body on OHE -01
Feb	07	Momentarily 05 Persisting 01	Bird menace -01 Loco trouble -01
March	03	Momentarily 03	
April	03	Momentarily 02 Persisting 01	 Toddy cat menace -01
May	Nil		
June	05	Momentarily 04 Persisting-01	Bird menace -01, Reptile menace-01

Chingavanam – Cheriyanad sector

Month	No. of faults	Type of tripping	Cause of faults identified
July	Nil	--	--
Aug	Nil	--	--
Sept	04	Momentarily 03 Persisting 01	Bird menace -01 Lightning -02
Oct	09	Momentarily 08 Persisting 01	Bird menace -01 Lightning -08
Nov	05	Momentarily 05	Man electrocuted -01
Dec	04	Momentarily 04	Bird menace -01 Lightning surges -01 Loco entered dead section
Jan	02	Momentarily 02	-
Feb	Nil	--	--
March	06	Momentarily 05 Persisting 01	Bird menace -03 Loco trouble -01
April	02	Momentarily 02	Lightning surges -01
May	04	Momentarily 04	Bird menace -01
June	02	Momentarily 01 Persisting 01	 Tree fallen on OHE -01

Chingavanam &Cheppad – Perinad sector

Month	No. of faults	Type of tripping	Cause of faults identified
July	02	Momentarily 02	Bird menace -01
Aug	05	Momentarily 03 Persisting 01	Bird menace -02 Loco trouble -01
Sept	06	Momentarily 05 Persisting 01	 Loco trouble -01
Oct	10	Momentarily 09 Persisting 01	Bird menace -03 Loco trouble -02 Tree fallen on OHE -01
Nov	05	Momentarily 05	Bird menace -01 Lightning surges -01
Dec	04	Momentarily 04	Foreign body on OHE -01 Lightning surges -01
Jan	01	Momentarily 01	
Feb	01	Momentarily 01	
March	03	Momentarily 03	
April	02	Momentarily 02	
May	03	Momentarily 03	Lightning surges -02
June	03	Momentarily 03	Bird menace -01

Perinad – Paravur sector

Month	No. of faults	Type of tripping	Cause of faults identified
July	02	Momentarily 02	
Aug	02	Momentarily 01 Persisting 01	 Loco trouble -01
Sept	05	Momentarily 03 Persisting 01	Lightning surges -01 Loco trouble -01
Oct	02	Momentarily 02	Bird menace -01
Nov	01	Momentarily 01	
Dec	Nil	--	--
Jan	04	Momentarily 03	Bird menace-01

		Persisting 01	Man electrocuted -01
Feb	04	Momentarily 04	Bird menace -01
March	02	Momentarily 02	Bird menace -01
April	01	Momentarily 01	Loco trouble -01
May	03	Momentarily 01 Persisting 01	 Insulator flashed -01
June	03	Momentarily 02 Persisting 01	Loco trouble -01 Tree fallen on OHE -01

Paravur – Kazhakkuttam sector

Month	No. of faults	Type of tripping	Cause of faults identified
July	02	Momentarily 01 Persisting 01	 Foreign body on OHE -01
Aug	02	Momentarily 02	Toddy cat menace -01
Sept	04	Momentarily 03 Persisting 01	Bird menace -01 Lightning surges -01
Oct	05	Momentarily 05	Ltng-1
Nov	03	Momentarily 03	Ltng-01
Dec	03	Momentarily 03	Bird menace-01
Jan	05	Momentarily 03 Persisting 01	Bird menace -01 Foreign body on OHE -01
Feb	05	Momentarily 05	
March	03	Momentarily 03	
April	02	Momentarily 02	Bird menace -01
May	03	Momentarily 03	
June	01	Persisting 01	Tree fallen on OHE -01
July	02	Momentarily 01 Persisting 01	 Tree fallen on OHE -01

Kazhakkuttam – Balaramapuram sector

Month	No. of faults	Type of tripping	Cause of faults identified
July	01	Momentarily 01	
Aug	04	Momentarily 04	Loco trouble -01
Sept	02	Momentarily 02	Bird menace -01 Rat menace -01
Oct	05	Momentarily 05	Bird menace -02
Nov	02	Momentarily 01 Persisting 01	 Loco trouble - 01
Dec	07	Momentarily 07	Lightning surges -03
Jan	05	Momentarily 05	
Feb	04	Momentarily 04	Bird menace -01
March	06	Momentarily 05, Persisting 01	Bird menace -03 Bird flashed insulator -01
April	08	Momentarily 07	Bird menace -03 Lightning surges -02
May	08	Momentarily 08	Bird menace -05
June	05	Momentarily 04 Persisting 01	Bird menace -01, Tree fallen on OHE -03

Balaramapuram- Eraniel sector

Month	No. of faults	Type of tripping	Cause of faults identified
July	Nil	--	--
Aug	03	Momentarily 02 Persisting 01	 Oil tanker lid touched 01
Sept	01	Momentarily 01	
Oct	01	Momentarily 01	
Nov	Nil	--	--
Dec	Nil	--	--
Jan	04	Momentarily 03 Persisting 01	 Insulator flashed -01
Feb	01	Persisting 01	Insulator flashed -01

March	02	Momentarily 02	
April	01	Momentarily 01	
May	02	Momentarily 01 Persisting 01	 Lightning Arrestor failed
June	01	Persisting 01	Tree fallen on OHE -01

Eraniel - Thovala sector

Month	No. of faults	Type of tripping	Cause of faults identified
July	01	Momentarily 01	Cable fallen on OHE -01
Aug	Nil	--	--
Sept	02	Momentarily 02	Lightning surges -01
Oct	01	Momentarily 01	Lightning surges -01
Nov	Nil	--	--
Dec	01	Momentarily 01	
Jan	02	Momentarily 02	
Feb	04	Momentarily 04	Bird menace -01
March	05	Momentarily 05	Bird menace -01
April	02	Momentarily 02	
May	04	Momentarily 04	Bird menace -01
June	Nil	--	--

Thovala – Nanguneri sector

Month	No. of faults	Type of tripping	Cause of faults identified
June	Nil		
July	Nil		
Aug	01	Persisting 01	Loco trouble -01
Sept	01	Persisting 01	Lightning arrester failed
Oct	02	Momentarily 02	Lightning surges -02
Nov	Nil	--	--
Dec	Nil	--	--
Jan	Nil	--	--
Feb	Nil	--	--

March	Nil	--	--
April	Nil	--	--
May	02	Momentarily 02	Lightning surges -02
June	Nil	--	--

Nanguneri – Tirunelveli (Meleppalayam) sector

Month	No. of faults	Type of tripping	Cause of faults identified
July	Nil	--	--
Aug	02	Momentarily 02	
Sept	12	Momentarily 09 Persisting 01	Bird menace-02 Man electrocuted -01
Oct	08	Momentarily 08	Bird menace -02 Lightning surges -01
Nov	10	Momentarily 07 Persisting 01	Bird menace -02 Lightning arrester failed
Dec	03	Momentarily 02 Persisting 01	Bird menace -01 Tree fallen on OHE
Jan	02	Momentarily 01 Persisting 01	Bird menace-01 Bird bypassed insulator
Feb	02	Momentarily 02	Bird menace -01
March	03	Momentarily 03	Bird menace -01
April	03	Momentarily 03	Bird menace -02
May	08	Momentarily 07, Persisting 01	Bird menace-01 Bird bypassed insulator
June	02	Momentarily 02	

APPENDIX. 4

NATURALLY OCCURRED PERSISTING EARTH FAULT ON OHE IN THE SURVEY REGION

Shoranur – Trissur section

Name of the Section where earth fault on OHE occurred : Shoranur - Trissur			
Date of fault occurred	Tripping distance from indicated relay, in km	Actual fault distance, in km	Topography of the section where railway track is laid
31/07/15	10	04	Almost plane land
10/08/16	35	29	Almost plane land
05/09/16	05	01	Almost plane land
05/10/16	20	16	Almost plane land
03/12/16	05	01	Almost plane land
27/01/16	11	16	Earth cuttings around 1 km length is available just before the fault occurred point
03/02/16	05	01	Almost plane land
10/02/16	03	00	Almost plane land
18/02/16	33	25	Almost plane land
26/02/16	19	12	Almost plane land
10/03/16	05	01	Almost plane land
11/03/16	06	04	Almost plane land
21/04/16	24	18	Almost plane land
02/05/16	18	12	Almost plane land
24/05/16	17	11	Almost plane land

Trissur - Chalakkudi section

Name of the Section where earth fault on OHE occurred : Trissur - Chalakkudi			
Date of fault occurred	Tripping distance from indicated relay, in km	Actual fault distance, in km	Topography of the section where railway track is laid

12/08/15	31	30	Almost plane land
01/12/15	00	00	Almost plane land
17/03/16	04	03	Almost plane land
18/03/16	64	56	Almost plane land

Chalakkudi – Alway section

Name of the Section where earth fault on OHE occurred : Calakkudi - Alway			
Date of fault occurred	Tripping distance from indicated relay, in km	Actual fault distance, In km	Topography of the section where railway track is laid
17/09/15	12	13	Almost plane land
30/09/15	02	02	Almost plane land
21/10/15	11	15	Almost plane land
25/10/15	11	15	Almost plane land
16/02/16	14	16	Almost plane land
05/04/16	13	15	Almost plane land
21/05/16	11	15	Almost plane land
11/07/16	01	02	Almost plane land

Alway - Ernakulam section

Name of the Section where earth fault on OHE occurred : Alway – Ernakulam			
Date of fault occurred	Tripping distance from indicated relay, in km	Actual fault distance, in km	Topography of the section where railway track is laid
31/07/15	11	09	Almost plane land
15/08/15	04	03	Almost plane land
09/09/15	03	04	Almost plane land
18/09/15	03	04	Almost plane land
25/09/15	02	03	Almost plane land
01/11/15	04	05	Almost plane land
02/11/15	02	02	Almost plane land

16/11/15	10	09	Almost plane land
23/11/15	09	09	Almost plane land
29/11/15	03	03	Almost plane land
04/12/15	10	10	Almost plane land
21/12/15	04	04	Almost plane land
30/12/15	03	03	Almost plane land
24/01/16	03	03	Almost plane land
03/02/16	03	03	Almost plane land
09/02/16	04	04	Almost plane land
20/02/16	04	03	Almost plane land
14/04/16	03	03	Almost plane land
25/06/16	03	04	Almost plane land
08/07/16	03	03	Almost plane land

Ernakulam – Sherthala section

Name of the Section where earth fault on OHE occurred : Ernakulam - Sherthala			
Date of fault occurred	Tripping distance from indicated relay, in km	Actual fault distance, in km	Topography of the section where railway track is laid
01/07/16	30	27	Almost plane land

Sherthala – Punnapra section

Name of the Section where earth fault on OHE occurred : Sherthala - Punnapra			
Date of fault occurred	Tripping distance from indicated relay, in km	Actual fault distance, in km	Topography of the section where railway track is laid
28/09/15	03 km	02 km	Almost plane land
05/11/15	09 km	07 km	Almost plane land
07/11/15	09 km	08 km	Almost plane land
21/03/16	09 km	08 km	Almost plane land

Punnapra - Cheppad section

Name of the Section where earth fault on OHE occurred : Punnapra - Cheppaad			
Date of fault occurred	Tripping distance from indicated relay, in km	Actual fault distance, in km	Topography of the section where railway track is laid
26/12/15	02 km	01 km	Almost plane land
09/02/16	03 km	03 km	Almost plane land
02/05/16	13 km	11 km	Almost plane land
02/06/16	06 km	05 km	Almost plane land

Eranakulam – VaikkomRoad section

Name of the Section where earth fault on OHE occurred : Eranakulam – Vaikkom Road			
Date of fault occurred	Tripping distance from indicated relay, in km	Actual fault distance, in km	Topography of the section where railway track is laid
13/09/15	04	02	Almost plane land
29/10/15	04	03	Almost plane land
03/02/16	10	09	Almost plane land
16/04/16	04	04	Almost plane land

Vaikkom Road - Chingavanam section

Name of the Section where earth fault on OHE occurred : Vaikkom Road - Chingavanam			
Date of fault occurred	Tripping distance from indicated relay, in km	Actual fault distance, in km	Topography of the section where railway track is laid
07/07/15	10 km	08 km	Almost plane land
2/11/15	11 km	09 km	Almost plane land
22/12/15	10 km	08 km	Almost plane land

19/02/16	32 km	26 km	Almost plane land
18/04/16	08 km	07 km	Almost plane land
12/06/16	09 km	07 km	Almost plane land
24/06/16	09 km	07 km	Almost plane land

Chingavanam – Cheriyanadu section

Name of the Section where earth fault on OHE occurred : Chingavanam - Cheriyanadu			
Date of fault occurred	Tripping distance from indicated relay, in km	Actual fault distance, in km	Topography of the section where railway track is laid
10/09/15	31 km	27 km	Almost plane land
21/10/15	23 km	22 km	Almost plane land
22/10/15	16 km	14 km	Almost plane land
22/10/15	11 km	08 km	Almost plane land
18/11/15	03 km	02 km	Almost plane land
05/12/15	23 km	18 km	Almost plane land
08/12/15	31 km	28 km	Almost plane land
18/03/16	30 km	27 km	Almost plane land
29/05/16	00 km	00 km	Almost plane land
22/06/16	03 km	03 km	Almost plane land

Cheriyanadu&Cheppad - Perinad section

Name of the Section where earth fault on OHE occurred : Cheriyanadu&Cheppad - Perinad			
Date of fault occurred	Tripping distance from indicated relay, in km	Actual fault distance, In km	Topography of the section where railway track is laid
06/07/15	16	13	Almost plane land
21/08/15	44	40	Almost plane land
04/10/15	34	32	Almost plane land
06/10/15	20	18	Almost plane land

09/10/15	22	20	Almost plane land
25/11/15	39	37	Almost plane land
09/12/15	40	37	Almost plane land
27/05/16	26	29	Almost plane land

Perinad – Parvur section

Name of the Section where earth fault on OHE occurred : Perinadu - Paravur			
Date of fault occurred	Tripping distance from indicated relay, in km	Actual fault distance, in km	Topography of the section where railway track is laid
02/10/15	10	10	Almost plane land
14/01/16	10	10	Almost plane land
22/01/16	10	10	Almost plane land
29/02/16	10	10	Almost plane land
05/03/16	10	10	Almost plane land
21/04/16	10	10	Almost plane land
18/05/16	09	09	Almost plane land
07/06/16	10	10	Almost plane land
19/06/16	08	09	Almost plane land

Parvur – Kazhakkuttam section

Name of the Section where earth fault on OHE occurred : Paravur - Kazhakkuttam			
Date of fault occurred	Tripping distance from indicated relay, in km	Actual fault distance, in km	Topography of the section where railway track is laid
18/08/15	08	08	Almost plane land
12/09/15	34	38	Almost plane land
01/12/15	06	02	Almost plane land
23/04/16	21	19	Almost plane land

02/06/16	10	04	Almost plane land

Kazhakkuttam – Balaramapuram section

Name of the Section where earth fault on OHE occurred : Kazakkuttam - Balaramapuram			
Date of fault occurred	Tripping distance from indicated relay, in km	Actual fault distance, in km	Topography of the section where railway track is laid
06/08/15	14	14	Almost plane land
14/09/15	15	14	Almost plane land
16/09/15	01	01	Almost plane land
28/10/15	12	10	Almost plane land
28/10/15	04	02	Almost plane land
25/02/16	15	14	Almost plane land
11/03/16	11	08	Almost plane land
13/03/16	01	01	Almost plane land
19/03/16	01	01	Almost plane land
01/04/16	14	14	Almost plane land
01/04/16	17	15	Almost plane land
05/05/16	08	07	Almost plane land
18/05/16	15	14	Almost plane land
24/05/16	13	06	Almost plane land
17/06/16	41	45	A tunnel of 200 long is available just before the faulty point

Balaramapuram – Eraniel section

Name of the Section where earth fault on OHE occurred : Balaramapuram - Eraniel			
Date of fault occurred	Tripping distance from indicated relay, in km	Actual fault distance, in km	Topography of the section where railway tack is laid
16/06/16	20	22	A tunnel of 60 long

Eraniel – Thovala section

Name of the Section where earth fault on OHE occurred : Eraniel – Thovala			
Date of fault occurred	Tripping distance from indicated relay, in km	Actual fault distance, in km	Topography of the section where railway track is laid
02/07/15	21	18	Almost plane land
06/02/16	22	19	Almost plane land
14/02/16	22	19	Almost plane land
07/03/16	22	19	Almost plane land
23/05/16	22	19	Almost plane land

Thovala – Nanguneri section

Name of the Section where earth fault on OHE occurred : Thovala - Nanguneri			
Date of fault occurred	Tripping distance from indicated relay, in km	Actual fault distance, in km	Topography of the section where railway tack is laid
13/10/15	21 km	14 km	Almost plane land

Nanguneri – Tirunelveli section

Name of the Section where earth fault on OHE occurred : Nanguneri - Tirunelveli			
Date of fault occurred	Tripping distance from indicated relay, in km	Actual fault distance, in km	Topography of the section where railway tack is laid
07/09/15	60 km	51 km	Almost plane land
09/09/15	36 km	27 km	Almost plane land
01/10/15	27 km	25 km	Almost plane land
12/10/15	58 km	48 km	Almost plane land
14/10/15	44 km	33 km	Almost plane land
20/02/16	36 km	27 km	Almost plane land

APPENDIX.5

PARASITE CAPACITANCES MEASURED FROM THE EXPERIMENT CONDUCTED ON TABLE TOP MODEL OF OHE OF LENGTH 1.0 M, FOR VARIOUS HEIGHTS FROM THE GROUND (RAIL LEVEL)

Height of OHE from ground, in m	Parasite capacitance measured ,in pF/m						Average/ consistent value obtained in pF/m
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	
0.10	72.831	72.830	72.830	72.832	72.382	72.380	72.381
0.11	72.480	72.470	72.481	72.480	72.481	72.490	72.481
0.12	72.135	72.134	72.136	72.138	72.140	72.138	72.138
0.13	71.781	71.782	71.782	71.781	71.781	71.782	71.780
0.14	71.434	71.435	71.433	71.343	71.434	71.433	71.434
0.15	71.089	71.091	71.090	71.088	71.089	71.088	71.089
0.16	70.744	70.743	70.743	70.745	70.745	70.743	70.744
0.17	70.402	70.401	70.402	70.402	70.401	70.403	70.402
0.18	70.061	70.062	70.061	70.060	70.059	70.061	70.061
0.19	69.721	69.721	69.720	69.722	69.722	69.721	69.721
0.20	69.382	69.381	69.381	69.382	69.382	69.380	69.381

APPENDIX.6

PARASITE CAPACITANCES MEASURED FROM THE EXPERIMENT CONDUCTED ON SIMILITUDE MODEL OF OHE OF LENGTH 50 M, FOR VARIOUS HEIGHTS FROM THE GROUND

Height of contact wire of OHE from rail level in m	Parasite capacitance of 50 m long OHE, in nF						
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Mean of six trials
3.00	0.991	0.990	0.991	0.989	0.989	0.990	0.990
3.25	0.903	0.903	0.901	0.900	0.901	0.901	0.902
3.50	0.861	0.861	0.860	0.860	0.859	0.860	0.860
3.75	0.831	0.832	0.833	0.831	0.831	0,831	0.831
4.00	0.810	0.808	0.809	0.810	0.809	0.808	0.809
4.25	0.788	0.786	0.785	0.786	0.785	0.787	0.786
4.50	0.766	0.768	0.768	0.767	0.768	0.769	0.768
4.75	0.755	0.754	0.754	0.755	0.754	0.754	0.754
5.00	0.738	0.739	0.739	0.738	0.739	0.739	0.739
5.25	0.726	0.727	0.727	0.727	0.726	0.727	0.727
5.50	0.717	0.718	0.718	0.718	0.718	0.717	0.718

APPENDIX. 7

PARASITE CAPACITANCE BETWEEN OHE AND EARTH AT CUTTINGS OF SLOPE 30^0, FOR VARIOUS STANDARD BASE WIDTHS

Base width of earth cutting, in m	Parasite capacitance of OHE model of 50 m measured at earth cuttings slope 30^0 for its various base widths, in nF							
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Mean	For 1000 m
6.16	0.731	0.731	0.732	0.732	0.732	0.731	0.7315	14.63
6.72	0.731	0.731	0.732	0.732	0.731	0.732	0.7315	14.63
7.28	0.727	0.727	0.728	0.728	0.727	0.728	0.7275	14.55
7.84	0.726	0.726	0.727	0.727	0.726	0.727	0.7265	14.53
8.40	0.725	0.726	0.725	0.725	0.726	0.726	0.7255	14.51
8.96	0.723	0.725	0.724	0.724	0.724	0.726	0.725	14.50

APPENDIX. 8

PARASITE CAPACITANCE BETWEEN OHE AND EARTH AT CUTTINGS OF SLOPE 45^0, FOR VARIOUS STANDARD BASE WIDTHS

Base width of earth cutting, in m	Parasite capacitance of OHE model of 50 m measured at earth cuttings slope 45^0 for its various base widths, in nF							
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Mean	For 1000 m
6.16	0.741	0.742	0.742	0.742	0.741	0.741	0.7415	14.83
6.72	0.7385	0.7385	0.7385	0.7385	0.7385	0.7385	0.7385	14.77
7.28	0.737	0.736	0.736	0.737	0.738	0.738	0.737	14.74
7.84	0.734	0.736	0.735	0.734	0.735	0.736	0.735	14.70
8.40	0.732	0.734	0.734	0.733	0.734	0.735	0.734	14.65
8.96	0.728	0.730	0.729	0.730	0.731	0.731	0.730	14.60

APPENDIX.9

PARASITE CAPACITANCE BETWEEN OHE AND EARTH AT CUTTINGS OF SLOPE 76^0, FOR VARIOUS STANDARD BASE WIDTHS

Base width of earth cutting, in m	Parasite capacitance of OHE model of 50 m measured at earth cuttings slope 76^0 for its various base widths, in nF							
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Mean	For 1000 m
6.16	0.776	0.777	0.778	0.779	0.779	0.778	0.778	15.56
6.72	0.772	0.772	0.773	0.773	0.772	0.773	0.7725	15.45
7.28	0.765	0.766	0.767	0.768	0.767	0.767	0.767	15.34
7.84	0.761	0.761	0.761	0.762	0.762	0.762	0.7615	15.23
8.40	0.754	0.755	0.756	0.755	0.754	0.756	0.755	15.10
8.96	0.747	0.748	0.748	0.747	0.747	0.748	0.7475	14.95

APPENDIX.10

PARASITE CAPACITANCES MEASURED FROM THE EXPERIMENT CONDUCTED ON SIMILITUDE MODEL OF OHE OF LENGTH 50 M, AT EARTH CUTTINGS WITH DIFFERENT HEIGHTS AT SLOPE 30^0

Height of earth cutting, in m	Capacitance of model OHE of 50 m length at earth cutting of slope 30^0							
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Mean, in nF	For 1000 m
5.60	0.721	0.719	0.719	0.720	0.721	0.720	0.720	14.40
6.16	0.722	0.723	0.724	0.723	0.725	0.725	0.724	14.48
6.72	0.729	0.730	0.729	0.729	0.730	0.728	0.729	14.58
7.28	0.731	0.733	0.734	0.733	0.732	0.733	0.733	14.66
7.84	0.734	0.734	0.735	0.736	0.735	0.735	0.735	14.70
8.40	0.737	0.737	0.738	0.739	0.738	0.739	0.738	14.76

APPENDIX.11

PARASITE CAPACITANCES MEASURED FROM THE EXPERIMENT CONDUCTED ON SIMILITUDE MODEL OF OHE OF LENGTH 50 M, AT EARTH CUTTINGS AT SLOPE 45^0

Height of earth cutting, in m	Capacitance of model OHE of 50 m length at earth cutting of slope 45^0							
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Mean, in nF	For 1000 m
5.60	0.720	0.721	0.721	0.722	0.721	0.721	0.721	14.42
6.16	0.724	0.726	0.726	0.725	0.726	0.727	0.726	14.52
6.72	0.734	0.733	0.734	0.735	0.734	0.734	0.734	14.68
7.28	0.738	0.740	0.742	0.739	0.741	0.741	0.740	14.80
7.84	0.748	0.749	0.749	0.748	0.749	0.749	0.749	14.85
8.40	0.746	0.747	0.748	0.748	0.748	0.748	0.748	14.96
8.96	0.750	0.750	0.751	0.751	0.751	0.752	0.751	15.02
9.52	0.754	0.754	0.754	0.754	0.754	0.754	0.754	15.08
10.08	0.755	0.756	0.756	0.756	0.755	0.756	0.756	15.12

APPENDIX.12

PARASITE CAPACITANCES MEASURED FROM THE EXPERIMENT CONDUCTED ON SIMILITUDE MODEL OF OHE OF LENGTH 50 M, AT EARTH CUTTINGS AT SLOPE 76^0

Height of earth cutting, in m	Capacitance of model OHE of 50 m length at earth cutting of slope 76^0, in nF							
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Mean, in nF	For 1000 m
5.60	0.725	0.726	0.727	0.727	0.728	0.727	0.727	14.54
6.16	0.741	0.742	0.742	0.742	0.743	0.743	0.742	14.84
6.72	0.760	0.761	0.760	0.761	0.761	0.762	0.761	15.22
7.28	0.7764	0.7764	0.7765	0.7765	0.7766	0.7766	0.7765	15.53
7.84	0.787	0.786	0.787	0.787	0.787	0.788	0.787	15.74
8.40	0.794	0.795	0.795	0.796	0.795	0.795	0.795	15.90
8.96	0.801	0.801	0.802	0.801	0.802	0.804	0.802	16.04
9.52	0.806	0.807	0.806	0.807	0.807	0.808	0.807	16.14
10.08	0.810	0.811	0.811	0.811	0.812	0.812	0.811	16.22
10.64	0.812	0.813	0.814	0.814	0.815	0.815	0.814	16.28
11.20	0.815	0.816	0.816	0.815	0.816	0.817	0.816	16.32
11.76	0.817	0.818	0.818	0.818	0.817	0.818	0.818	16.36
12.32	0.818	0.818	0.819	0.819	0.820	0.819	0.819	16.38
12.88	0.819	0.819	0.820	0.820	0.821	0.820	0.820	16.40
13.44	0.8205	0.8204	0.8205	0.8205	0.8205	0.8206	0.8205	16.41
14.00	0.8205	0.8205	0.8205	0.8205	0.8205	0.8207	0.8205	16.41

APPENDIX.13

PARASITE CAPACITANCES MEASURED FROM THE EXPERIMENT CONDUCTED ON SIMILITUDE MODEL OF OHE OF LENGTH 50 M INSIDE A RAILWAY TUNNEL HAVING STANDARD DIMENSIONS

Ht. of OHE in m	Ht. of top wire, in m	Capacitance (Cp) of 50 M long conventional OHE in nF, with fixed dip 0.3 m							For 1000 m long OHE, in nF
		Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Mean of all the trials	
0.50	0.80	1.90	1.905	1.90	1.905	1.894	1.91	1.905	38.1
0.75	1.05	1.755	1.76	1.755	1.758	1.756	1.758	1.757	35.94
1.00	1.30	1.705	1.71	1.71	1.71	1.705	1.71	1.71	34.2
1.25	1.55	1.656	1.568	1.659	1.702	1.703	1.7	1.659	33.18
1.50	1.80	1.59	1.595	1.60	1.595	1.59	1.60	1.595	31.9
1.75	2.05	1.56	1.565	1.567	1.567	1.563	1.568	1.565	31.3
2.00	2.30	1.53	1.525	1.525	1.525	1.526	1.53	1.525	30.5
2.25	2.55	1.515	1.518	1.517	1.516	1.519	1.516	1.517	30.34
2.50	2.80	1.50	1.495	1.49	1.505	1.50	1.49	1.495	29.9
2.75	3.05	1.511	1.513	1.512	1.513	1.514	1.513	1.513	30.26
3.00	3.30	1.535	1.53	1.525	1.53	1.53	1.53	1.53	30.6
3.25	3.55	1.55	1.554	1.553	1.555	1.554	1.552	1.553	31.06
3.50	3.80	1.60	1.605	1.605	1.60	1.61	1.605	1.605	32.1
3.75	4.05	1.635	1.64	1.636	1.639	1.639	1.635	1.638	32.76
4.00	4.30	1.70	1.705	1.705	1.70	1.70	1.705	1.705	34.1
4.25	4.55	1.766	1.768	1.769	1.768	1.769	1.768	1.768	35.36
4.50	4.80	1.865	1.86	1.86	1.855	1.855	1.86	1.86	37.2
4.75	5.05	1.94	1.945	1.943	1.942	1.945	1.942	1.943	38.86
5.00	5.30	2.055	2.06	2.055	2.055	2.06	2.065	2.055	41.1
5.25	5.55	2.161	2.163	2.163	2.164	2.164	2.165	2.163	43.25
5.50	5.80	2.265	2.27	2.27	2.27	2.265	2.265	2.271	45.42