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Effect of Unaccounted Parameters on Reactive Power Compensation in Indian Electric Traction Line

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ABSTRACT The quest for electrification of railway tracks is very high at developing countries, with a very high ratio of population per kilometre length of railway track. India has electrified almost 50% of its track length and aiming 3000 km track electrification every year. Presently in Indian traction system, all the fault locating methods and power factor correction methods for AC high voltage line are based on the conventional model of railway Overhead Equipment (OHE). The conventional OHE model does not include the effect of self-generated reactive power at the geographically challenged area. This paper explains, how the variations in parasite capacitance of OHE adversely affect the prevailing conventional power factor improving methods; after monitoring the active power, apparent power, leading reactive power injected to improve the power factor of AC high voltage traction system for one calendar year, at two different Traction Sub Stations (TSS). Further simulation of 61 km track with actual mixed geographical terrain to validate the experimental results and to develop a new power factor correction algorithm has been done. The proposed algorithm has been implemented on one TSS of Southern Indian Railways division, and it turns out in reducing penalty around 2.5 million Indian rupees per year, paid by sampling region TSS.

INDEX TERMS Electric variables, over-head equipment, parasitic capacitance, railway engineering, reactive power control, traction power supplies.

I. INTRODUCTION

The 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 the lesser duration of time, with lesser risks [1]. A comparative study made on the energy-efficient operation of various types of tractions used in railways (Table -1) brought to light that the high voltage Alternating Current (AC) electric traction is the best system of traction for railways [2].

The figures on the cost effectiveness of Diesel Traction and Electrical Traction of Indian railways organization [3], which is indicated in Table 2 to substantiate it. Moreover, to achieve the UN SGDs goal [1], Indian Railways has implemented the world's first solar power plant to directly power overhead equipment. Besides, Ministry of Railways announced to become green railways by 2030 [2]. To empower the whole railway network from solar PV power will face many challenges due to the intermittent nature of solar PV output. However, the proper combination of energy storage units and renewable energy sources (RES) can curb the uncertain nature of RES in railway electrification [3]–[5].

Railway network is the integral form of many interdependent functional subnetworks. 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 maintain power quality, 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.

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

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TABLE 1. Comparisons on efficiencies of various types of traction.

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

TABLE 2. Diesel-electric power vs electric traction power.

S.No.	Parameter	Diesel-Electric power	Electric traction power
1	Percentage consumption of energy	42.56 %	57.36 %
2	Percentage sharing of traffic load	39.08 %	61.10 %
3	Percentage sharing in energy cost	55.257%	44.143%
4	Cost	@ Rs. 40/- litter of High Speed Diesel, HSD	cost of energy @ Rs. 6.0/kWh

reliability in the electric traction system. Those types of system are integrated with several basic functional modules. One such module shall usually cater more than 300 kilometres length of the electrified rail route. 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 on electric traction lines. 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.

A. INCOMING POWER SUPPLY ARRANGEMENTS TO THE RAILWAY ELECTRIC TRACTION SYSTEM

The incoming supply to the TSS will be from the locally available three-phase power grid of power generation/distribution companies, whose voltage shall typically be 66 kV, 110kV, 132kV, 220kV or 400 kV. The interspacing of high voltage AC TSSs shall vary in between 50km to 80 km. Standard designed TSS usually needs to feed with two phases. Hence the asymmetry in loading due to the TSS is likely to occur on the Extra High Voltage (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 TSS 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 [4].

B. GENERAL LAYOUT OF INDIAN TSS

TSS (Fig.1) 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 a single phase. Hence it is evident 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 regular working tap. The primary windings are tailor-made in accordance with the available grid voltage at the incoming side. There are two such parallel standby arrangements (bays) available at most of the TSSs with equipment for proper coupling of bays. TSS is designed to work on single phases; hence outgoing is single phase 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, Over Head Equipment (OHE), the electric locomotives and the return path of traction current, which is theoretically, will be the rails (Fig. 2).

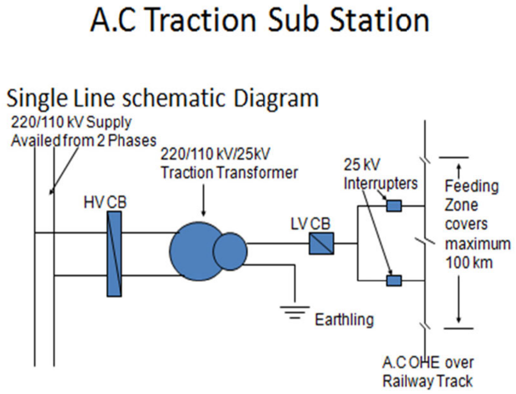

FIGURE 1. Single line schematic diagram of an EHV/25 kV AC TSS.

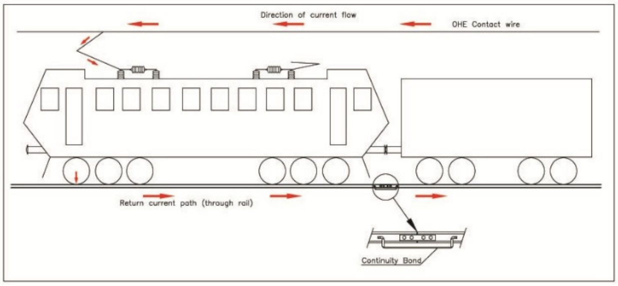

FIGURE 2. Flow of railway traction current.

C. ISSUES IN ELECTRIC TRACTION SYSTEM

The electric traction load is highly dynamic in nature which results in various technical problems such as distortion in voltage, the current waveform of the power supply and miscalculation of the power quality indices.

The most common power quality issues faced in traction are reactive power, harmonics, fluctuation in current and voltage [5]. The major challenge for traction system operators is to maintain the power factor close to 0.9 (lag/lead) [6]. Therefore, power factor correction plays a significant role, because not only the traction system will face energy loss due to low power factor, it has to pay a huge penalty to the utilities for not maintaining the power factor within limits [7]. Therefore, accuracy in power factor evaluation and its impact on traction system is vital. In the current scenario, the power factor problem has been divided into two areas, design or development of compensation devices and analysis of power factor behaviour [8], [9].

Static VAR, Static power conditioner, active and hybrid power quality conditioner all are compensation devices [1], [10]–[18]. The conventional set of the ac-dc thyristor is used in single-phase, 25 kV electrified traction system locomotives, it draws rich harmonic current content and low displacement power factor. This current rich in harmonic degrade the supply quality [19]. To mitigate the problem, hybrid power quality conditioner is used. Actually, along the feeder line, a notable amount of reactive voltage drop has seen, and the circulated harmonic rich current resulted in a distorted waveform of the supply voltage. As per IEC standard 349, 19 kV is the minimum pantograph voltage must be maintained [20]. Therefore, various implementations were done by researches; one of them is to terminate the feeder with a low impedance [19]. Research Designs & Standards Organisation (RSDO) from Ministry of Railways, India has provided guidelines for the calculation of dynamic reactive power compensation. Previously for lagging MVAR compensation, a fixed capacitor incorporated with 13 percent detuned reactors were used. Moreover, this method used in traction has various limitations that during low load condition, high voltage transients of 1.4 to 2 times of the system voltage (approx.) are produced due to capacitor switching in the system [20]. However, most of the Indian railway zonal, specifically having geographically mixed terrain route, end up with poor power factor. Moreover, wrong calculation of a capacitor to be switch in can create high voltage in the system during light load or no-load condition. This rise in voltage due to capacitor bank can be measured by Eq. 1.

$$\%\Delta V = \frac{KVAR_{cap} * Z_{tx}(\%)}{kVA_{tx}} \tag{1}$$

where $\%\Delta V$ = percent voltage rise; $KVAR_{cap}$ = capacitor bank rating; Z_{tx} = traction transformer impedance; kVA_{tx} = traction transformer rating.

This condition also increases the losses in the transformer winding on account of leading reactive current. The dynamic power factor correction unit (DFCU), thought to be a promising solution to maintain PF at 0.9 or above. In recent times, very few DFCU were implemented in Indian Railways (IR), but results were not satisfactory as it thought to be, due to the highly non-linear dynamic nature of traction load. This situation created very frequent switching of capacitor banks, hence increases the harmonics in the system and also waste a significant amount of energy in the switching process. Therefore, the performance of DFCU in IR is not catching up the expectations on account of capital investment, incurred losses in the system, maintenance and system output.

The presented study found that the parasite capacitance generated at different topographical location en-routed alongside OHE is creating leading electrical energy in the system. Therefrom, this paper presents, the identified route cause and paves the way for zonal railways to implement static power factor correction method over dynamic power factor compensation equipment. This paper proposes an algorithm to decide the correct capacity for static compensation to be switched for a specific TSS.

Moreover, present-day research in electric loco is, to provide the synchronous motor for traction purpose. Such traction motors available in 3 phase locomotives shall work on Variable voltage variable Frequency (VvvF) technology [21]. Hence, it is easier to reach the unity power factor within locomotives itself while on the run, just by controlling the excitation of rotor windings. Therefore, electrical traction utility needs to be focused on maintaining unity power factor of traction line only (OHE). However, leading leakage current will be present, if the parasitic capacitance is dominant in the traction line. Hence, ones the locomotives are changed to unity power factor loads by themselves [21], the additional leading reactive power to be pumped with static capacitors will be limited for other lagging loads like signalling power drawn from traction line. In such a situation, if the parasitic capacitance of traction can be calculated more or less accurately, the remaining leading reactive power to be injected using static capacitors can be precisely calculated. The presented study will also help in reducing over compensation during no traction load time for future IR system consisting of the 3-phase locomotive with VvvF technology.

The presented paper articulated in 8 sections. Section 1 states the problem faced by the Railway organization for PF compensations and also presents the general architecture of Indian traction system. Sections 2 depicts the shortfall of the conventional model of OHE and its economic burden on Indian railways. The prevailing method of PF correction in traction system is presented in section 3 and the limitation of DFCU. Section 4 formulates the role of parasite capacitance in the wrong compensation calculation. Section 4 also presents the modified model of OHE to curb the need of DFCU unit and to calculate precise compensation required to achieve 0.9 PF. Section 5 presents the simulation of the sampling region's 61 Km long OHE with mixed terrain feature, used to conducted experiments. Section 6 develops the modified algorithm for Indian Railways for precise PF correction based on new OHE model. Section 7 discusses the prominent solution

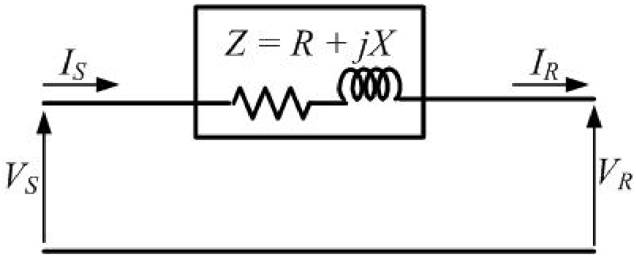

FIGURE 3. Model of 25 kV AC Electric traction line.

to cater to the technical & economic limitation of DFCU in electric traction system. Conclusion of the conducted study and subsequent findings has been made in section 8.

II. PREVAILING MODEL OF OHE AND ITS SHORTFALL

The generalized model of high voltage electric traction line is shown in figure 3. Albeit, 25 kV electric traction line has no similarity with the power transmission line; its parameter modelling has been done with reference to a short transmission line model [3], [22]. EHV lines those have length 100 km or less, and a working voltage of 110 kV or below are classified as short transmission lines.

Effect of shunt admittance exits in between power line and earth is conveniently neglected in the 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. Whereas proximity of AC traction line includes plane ground, earth cuttings and tunnels and OHE drew closer to earth surface at those topographical areas [1], [2] as shown in figure 4. Due to the equipotential characteristic of the earth surface, the capacitance of any high voltage AC power line varies inversely with its distance from the earth/earthed surface. The effect of the capacitance of AC traction lines will be many times higher [23]; hence conventional model of OHE leads to a false calculation for fault calculation and power quality control.

A. UNSATISFACTORY FISCAL FEATURES OF OHE

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 the 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 [24], where the Railways organization was penalized around 9.9 million Indian Rupees (INR) by the one electric supply company, up to March 2014 for drawing excessive reactive power by the electric traction system (Table 3), 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 only for drawing excessive reactive power by 60 km long 25 kV OHE with mixed topographical terrain. Usually, electric supply companies consider the difference between those two figures to calculate the reactive power drawn by the consumers, and to impose a 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 an unpredictable manner is very common in electric railway traction.

It is learned [3], [25] that the lagging reactive power in electric traction is 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 table 3 that in the month of May 2012, the power factor was as low as 0.43. It has come to light that fixed capacitors were put in continuous service at that particular TSS for seven days on a trial basis in May 2012 for power factor improvement. However, instead of improving the 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 the electric traction load varies between 0.65 to 0.8 lag. However, 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.

Hence it is conceived that the irregular variations in the capacitance of OHE play a crucial role in determining the generation of leading reactive power, at areas where earth potential surfaces like earth cuttings, tunnels etc., are available at the proximity of it.

III. PREVAILING METHOD OF POWER FACTOR CORRECTION IN INDIAN TRACTION SYSTEM

The conventional method of power factor improvement is the 'injection of leading reactive power (kVAR lead) using static capacitors on a monthly average basis, connected in parallel to the load, at TSS as shown in figure 1 [26], [27]. The kVAR lead is determined by measuring one-month lagging reactive power caused by the railway traction load of any particular TSS [3], and railways prefer the power factor near to unity (Fig. 5). It pumps fixed leading reactive power to the system on every second and still widely in use in almost all power systems. It is highly economical in a power system where similar shaped load curve (Fig. 7) is possible to plot on every day [28]. Almost all major power distribution systems have such load curves.


(a) (b) (c)

FIGURE 4. OHE at (a) plane ground (b) tunnel (c) earth cuttings.

TABLE 3. 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			

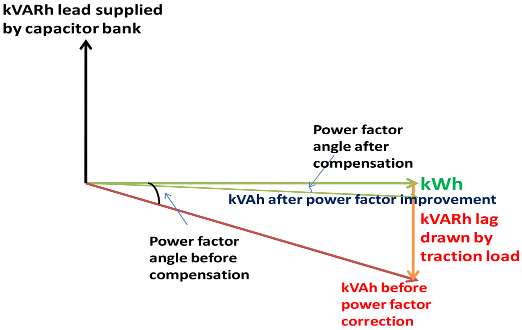

FIGURE 5. Illustration of power factor correction on a 'periodic average' basis.

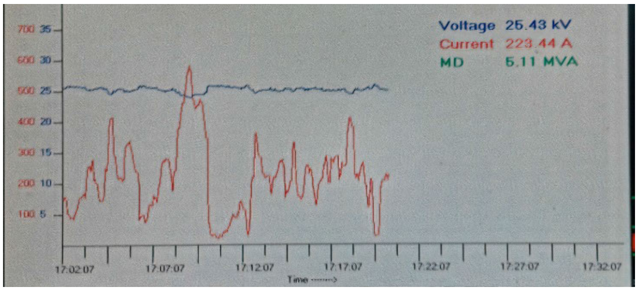

FIGURE 6. Load curve of 20 minutes duration of a railway traction line.

Whereas, dynamic power factor correctional system is one, which is used in a power system where the load variation is abrupt uncertain on every moment. Dynamic power factor correctional system [26], [29], contains small units of capacitors in large numbers with individual switching arrangements. Reactive coils will also be available in such arrangements to feed lagging reactive power whenever the power factor in the system is leading. Switching operations of each capacitor units & reactors will be on a real time basis. The power factor of every second will be measured, and the switching operation of capacitors and reactors will be controlled by microprocessors to achieve near unity power factor at any point in time. This system is used in a power system where the regular-shaped load curve will not be available, and the cost of such a dynamic system shall be ten times to that of fixed capacitor arrangements. Figure 6, shows the on-line load curve for 20 minutes' duration taken from one of the 'best

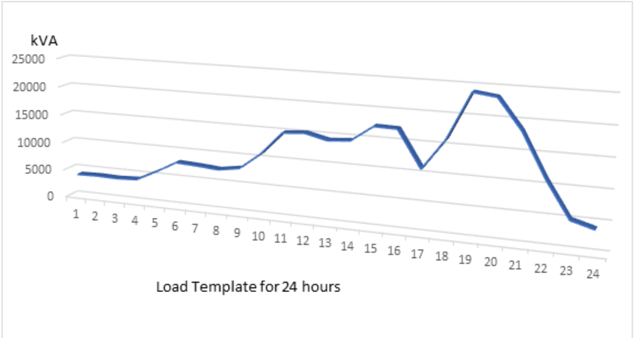

FIGURE 7. Load curve for 24 hours of the grid substation.

power factor compensated' TSS in Railways and figure 7, shows the load pattern for 24 hours of the grid substation where the electric traction power line is connected.

From figure 6, it is evident that the load curve of a traction substation variation is sudden as well as uncertain. This is so happened because of the unique speed control skills of each loco pilots, and the gradient of track. Moreover, we can't precisely predict that how many trains will be available within the feeding zone of a TSS in any time slots, since minor delay in running of trains by few minutes (sometimes too large also) on every day is possible.

So, if the dynamic power factor correction method is used, the switching operations (by many hundreds of micro switches within the system) of capacitors will be too fast. However, once the capacitor is switched off, it must be given a delay in next switching on operation, else, the capacitors would get damaged very soon [30]. It implicates that the failure rate of such a dynamic system will be very high when get introduce in electric traction field and shall be a costlier affair to maintain it in electric traction field. Besides, a significant amount of energy is required for its operation as switching operations are energy-intensive.

Such a system is suitable for a power system with more or less gradual changes in the load, as shown in figure 7. Hence the trend of establishing dynamic power factor correction system is not attractive nowadays in electric traction field. However, correcting capacitor banks of 'fixed leading reactive power' to a power distribution system for the power factor correction in the system is not advisable in light of latest norms stipulated by Central Electricity Authority of India (CEA) [31], [32]. Nevertheless, at the same time, this situation leads to the under-compensation of 'lagging reactive power' at TSS due to the highly fluctuating nature of traction load, resulting in low power factor.

IV. MODELLING THE EFFECT OF PARASITE CAPACITANCE IN POWER FACTOR (PF) COMPENSATION FOR TRACTION LINE

In general, the static capacitors are permanently connected to the traction system for PF compensation. However, the traction load, and hence the lagging reactive power, is generated randomly, as shown in figure 6. Eventually, the leading reactive power injected by the capacitor banks will dominate at some period, which is quite unpredictable due to the inherent randomly fluctuating nature of the traction load. In this juncture, if the leading reactive power generated in the OHE itself is considerably high (like it happens in long transmission line)[24], [33], the PF correction using static capacitors with pre-calculated leading reactive power result to adverse effect [32], [34]. To model, the effect of parasite capacitance for PF compensation, two different TSS, one which feeds traction supply to OHE laid above railway track at the plane area, and the other feed traction supply to OHE laid above the track at earth cuttings & tunnels have been chosen for observation. The observation has been done after monitoring the active power, apparent power, leading reactive power injected to improve the power factor of AC high voltage traction system duly presenting the monthly average of everyday readings recorded in the Time of the Day metering (TOD) meters for one calendar year, i.e. 2018.

TABLE 4. Data recorded at TSS, 25 kV AC traction power to OHE laid over railway track on level topographical area.

Month of Reading	Monthly Readings			
	*kWh	*kVAh	*kVARh	Power Factor
Jan 2018	100,000	104,328	31,076	0.959
Feb 2018	100,000	104,482	28,257	0.957
Mar 2018	100,000	103,814	31,535	0.963
Apr 2018	100,000	103,842	36,395	0.963
May 2018	100,000	103,997	34,179	0.962
Jun 2018	100,000	104,708	29,424	0.955
July 2018	100,000	104,090	31,319	0.961
Aug 2018	100,000	104,112	33,939	0.961
Sept 2018	100,000	104,883	32,080	0.953
Oct 2018	100,000	104,137	33,388	0.960
Nov 2018	100,000	104,340	32,176	0.958
Dec 2018	100,000	104,655	28,663	0.956

A. RELATION OF RATIO OF LEADING AND LAGGING REACTIVE POWER TO THE MONTHLY AVERAGE PF OF ELECTRIC TRACTION AT LEVEL AREA

Table 4 is the data recorded at TSS, which supply 25 kV AC traction power to OHE laid over railway track on level geographical area. It can notice from the readings that the higher the leading reactive power injected to the system, the higher (closer to unity) is the monthly average power factor obtained.

All the readings in table 4 are taken on a monthly basis, and all the energy vectors are transformed to 100,000 kWh/Month basis. Figure 8 is the graphical representation of the response in PF Vs Lead kVARh injected to a 25 kV, 50 Hz AC OHE railway traction system established on the level ground throughout.

B. RELATION OF RATIO OF LEADING AND LAGGING REACTIVE POWER AT TOPOGRAPHICALLY CHALLENGED AREA

Table 5 shows the data recorded at TSS, which supply 25 kV AC traction power to OHE laid over railway track at topographically challenged areas, like earth cuttings, tunnels, etc. It can be noticed from the readings that the higher the leading reactive power injected to the system, the lower

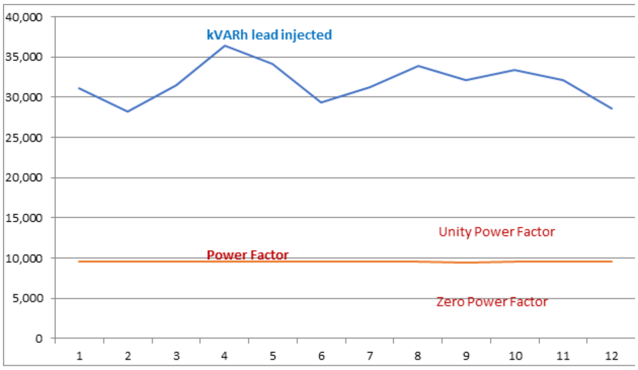

FIGURE 8. Graphical representation of power factor improvement in TSS at plane area.

TABLE 5. Data recorded at TSS, which supply 25 kV Ac traction power to OHE laid over railway track on topographically challenged area.

Month of Reading	Monthly Readings			
	*kWh	*kVAh	*kVARh	Power Factor
Jan 2018	100,000	122,850	22,775	0.814
Feb 2018	100,000	123,762	26,680	0.808
Mar 2018	100,000	121,066	20,441	0.826
Apr 2018	100,000	121,800	20,607	0.821
May 2018	100,000	121,848	21,059	0.821
Jun 2018	100,000	120,920	19,469	0.827
July 2018	100,000	115,598	6,215	0.865
Aug 2018	100,000	115,317	5,490	0.867
Sept 2018	100,000	114,550	4,160	0.873
Oct 2018	100,000	114,410	3,915	0.874
Nov 2018	100,000	114,800	4,996	0.871
Dec 2018	100,000	114,910	5,408	0.870

(deviates from unity) is the monthly average power factor obtained.

Figure 9 is the graphical representation of the response in PF Vs Lead kVARh injected on a 25 kV, 50 Hz AC OHE railway traction system established at geographically challenged areas; like earth cuttings, tunnels etc. (figure 4).

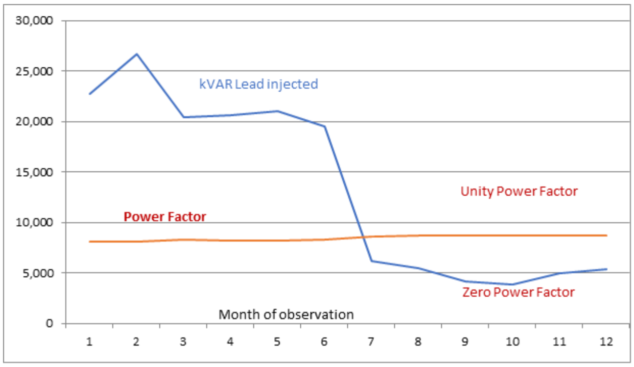

FIGURE 9. Graphical representation of power factor improvement in TSS at topographically challenged area.

TABLE 6. Comparison of the power factor with the ratio of leading reactive power and lagging reactive power at plane area.

Month of the Year	kVARh lag	kVARh lead	kVARh Lead / kVARh Lag	Power Factor
Jan 2018	512500	818600	1.5972	0.959
Feb 2018	584400	799400	1.3679	0.957
Mar 2018	513900	897100	1.7457	0.963
Apr 2018	463800	975700	2.1037	0.963
May 2018	470200	891900	1.8969	0.962
Jun 2018	547500	799400	1.4601	0.955
July 2018	463200	828600	1.7889	0.961
Aug 2018	439700	903800	2.0555	0.961
Sept 2018	446200	771800	1.7297	0.953
Oct 2018	420500	881400	2.0961	0.960
Nov 2018	436300	883000	2.0238	0.958
Dec 2018	488700	793700	1.6241	0.955

TABLE 7. Comparison of the power factor with the ratio of leading reactive power and lagging reactive power at geographically challenged area.

Month of the Year	kVARh lag	kVARh lead	kVARh Lead / kVARh Lag	Power Factor
Jan 2018	657000	217500	0.3311	0.814
Feb 2018	628000	233100	0.3712	0.808
Mar 2018	612500	171500	0.2800	0.826
Apr 2018	673500	197000	0.2925	0.821
May 2018	657500	196500	0.2989	0.821
Jun 2018	613000	168500	0.2749	0.827
July 2018	703500	60000	0.0853	0.865
Aug 2018	724000	60000	0.0829	0.877
Sept 2018	829500	48500	0.0585	0.874
Oct 2018	800500	45000	0.0562	0.873
Nov 2018	796000	61500	0.0773	0.866
Dec 2018	794500	65000	0.0867	0.876

C. COMPARISON OF THE PF, AND THE RATIO OF LEADING REACTIVE POWER AND LAGGING REACTIVE POWER OF TSS

The comparison of the PF with the ratio of leading reactive power and lagging reactive power of TSS which feed traction supply to OHE at plane area and at geographically challenged areas detailed hereunder.

1) OHE LAID AT PLANE AREAS

It is clear from the table 6 that the higher the value of the leading reactive power injected to 25 kV ac electric railway traction system with the help of static capacitor banks for power factor correction, the higher is the power factor obtained. This indicates that no leading reactive power is generated by self, due to the parasite capacitance of the OHE at the plane area.

2) OHE LAID AT TOPOGRAPHICALLY CHALLENGED AREAS

The comparison of the power factor with the ratio of leading reactive power and lagging reactive power of TSS which supply traction power to OHE at geographically challenged areas are given in table 7.

Table 7, clearly shows that the higher the value of the leading reactive power injected to 25 kV AC electric railway traction system with the help of static capacitor banks for power factor correction, the lower is the power factor obtained. It indicates that a considerable amount of leading reactive power is generated in the system with the parasite capacitance of the OHE at geographically challenged areas. Injection of leading reactive power to the traction system at those areas will deteriorate the power factor.

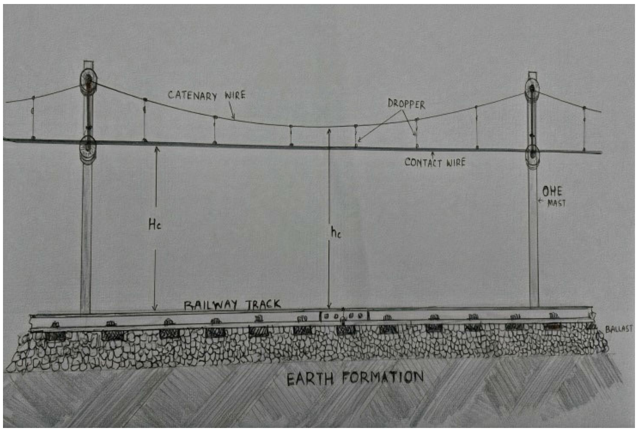

FIGURE 10. Over head equipment (OHE) of electric traction line.

D. MODIFIED MODEL OF OHE

The conventional model of OHE does not include the effect of shunt capacitance generated at earth cuttings and inside tunnels, as shown in figure 3. This leads to wrong calculation of kVAR to be injected in 25 kV traction line for power factor calculation. The OHE carry the single-phase, i.e. one conductor and one catenary wire, as shown in figure 10. The altitude of its bottom conductor (contact wire, Hc) varies in between 4.58 m to 5.8 m, whereas, the altitude of top conductor (catenary wire, hc) varies in between 4.78 m to 7.2 m from the ground (rail level) randomly in accordance with the presence of over line structures. The capacitance generated between any phase and earth can be calculated by using mirror image method (Eq. 2), but this leads to false value in case of OHE due to the unique characteristic and laying of OHE at earth cuttings & tunnels.

$$C = \frac{10^{-9}}{\left(18 * l_n\left(\frac{2H}{r}\right)\right)} F/m \tag{2}$$

where

H = height of conductor from earth,
r = radius of conductor

To model the effects of mixed terrain routed alongside OHE e.g. earth cuttings of various angles, the variation of OHE height at plane ground and tunnels; authors have conducted the experimental study for 36 months in the sampling region (Figure 12). Two separate studies have been conducted during those 36 months for urban and suburban traction system operating at 25 kV AC system.

In [23], authors have presented the modified OHE modelled as shown in figure 11 for 25 kV traction line by modelling the effect of parasite capacitance at level ground, earth cuttings with different base width & angles and inside countryside tunnels for suburban traction system. The entire length has been segregated in 100-meter length, and for each segment, the parasite capacitance has been formulated by using equations 3-7. The conducted study had the aim to pinpoint the exact fault location on OHE.

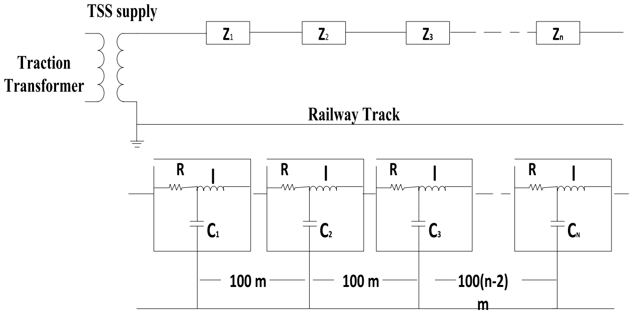

FIGURE 11. Modified OHE model with the inclusion of parasite capacitance.

For urban traction system of India, authors of [35], have developed a similar model where tunnel dimensions are different from countryside tunnel. The study and observation presented in the previous section prove that same effect (exclusion of capacitance in OHE model) is responsible for mismatch between injected kVAR from fixed capacitor banks and correct PF compensation. During 36 months exhaustive experiments and study have been conducted to model the parasite capacitance at the plane ground, earth cutting with 30^0, 45^0& 76^0 slopes and inside the tunnel, which is depicted in equation 3-7 respectively.

$$C_p = \frac{L}{3}10^{-12}\left(2.5H^2 - 27H + 115\right)F \tag{3}$$

$$C_{et} = 8 * 10^{-4}h^3 - 3.3 * 10^{-2}h^2 + 4.74 * 10^{-1}h + 12.668 \text{ nF/km} \tag{4}$$

$$C_{et} = 1.1 * 10^{-3}h^3 - 4.7 * 10^{-2}h^2 + 6.69 * 10^{-1}h + 11.844 \text{ nF/km} \tag{5}$$

$$C_{et} = 4.3 * 10^{-3}h^3 - 1.67 * 10^{-1}h^2 + 2.1723h + 6.831 \text{ nF/km} \tag{6}$$

$$C_t = 10^{-12}L_t\left(1.79H^2 - 9.1H + 41.75\right) \text{ F} \tag{7}$$

where,

C_p =	Parasite capacitance between OHE and earth at plane ground
C_{et} =	Parasite capacitance between OHE and earth at earth cuttings
C_t =	Parasite capacitance between OHE and earth inside tunnel
H =	Height of OHE from rail level in meter
h =	Height of earth cutting in meter
L_t =	Length of tunnel in meter

V. SIMULATED OHE WITH MIXED GEOGRAPHICAL FEATURE

In the previous sections, the importance of considering the effect of parasite capacitance into the modelling of OHE lines and thereby essentially including the same for power factor correction method has been discussed. To validate the proposed modification including the effect of parasite capacitance, a 61 km stretch of Indian Traction system (8.2059° N, 77.3159° - 8.2312° N, 77.5060° E - 8.4321° N, 77.0503° E)

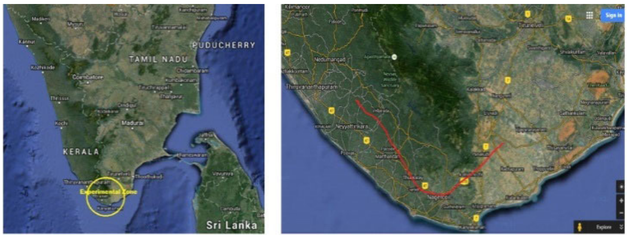

FIGURE 12. Experiment zone and highlighted OHE route in red.

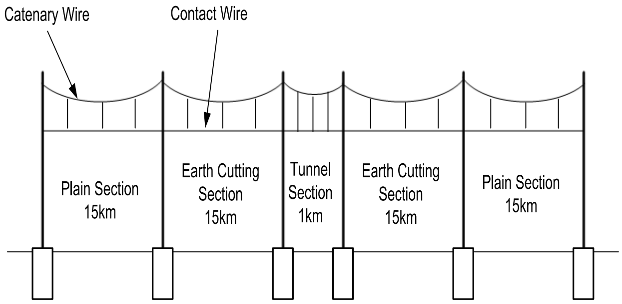

FIGURE 13. Various sections modelled in 61 km stretch of indian traction system.

TABLE 8. Specifications of catenary and contact OHE.

Conductor type	Catenary Wire	Contact Wire
Nominal Voltage	25 kV	25 kV
Nominal Current	0.45 kA	0.6 kA
Resistance	0.431 Ohms/km	0.461 Ohms/km
GMR	4.0887 mm	5.140085 mm
Outer Diameter	10.5 mm	12.24 mm

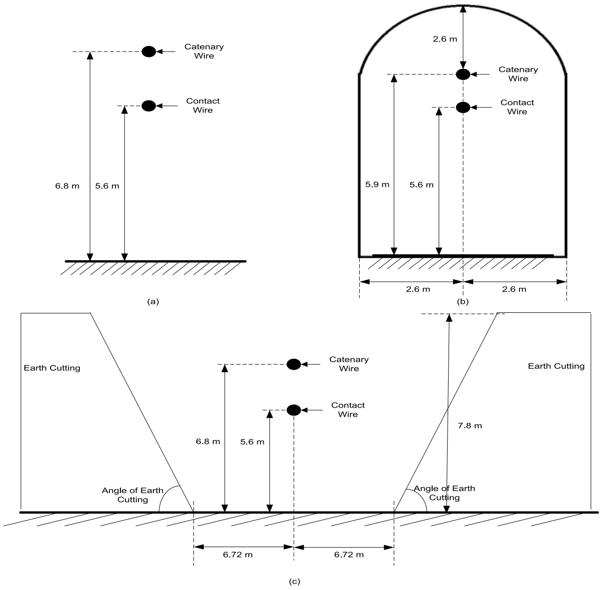

FIGURE 14. Physical dimensions of OHE in (a) Plain section (b) Tunnel section (c) Earth Cutting section.

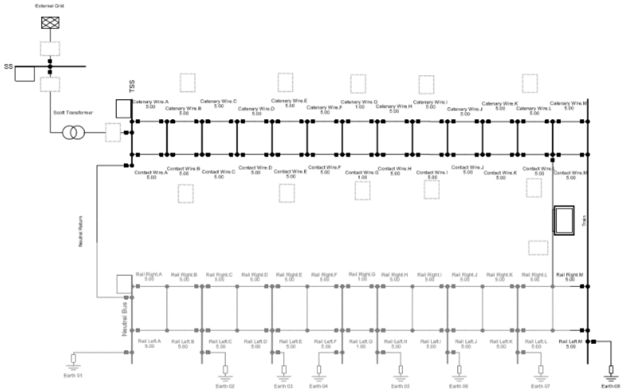

FIGURE 15. DigSILENTPowerFactory model of 61 km stretch of indian traction system.

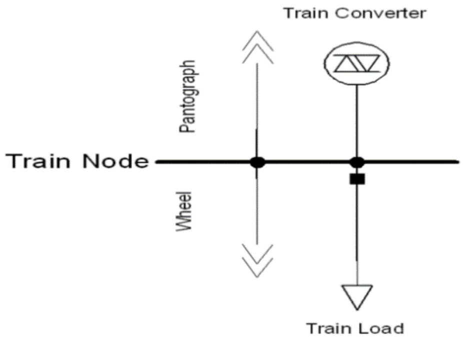

FIGURE 16. PowerFactory model of train.

consisting of plain, earth cutting and tunnel sections are modelled in DigSILENT PowerFactory [36]. The geographical map of the experimented stretch has highlighted in figure 12. This stretch consists of plain and earth cutting sections of 60 km each and a tunnel of 1 km as shown in figure 13.

The OHE catenary and contact conductor specifications used to build the model are shown in Table 8. The physical dimensions of OHE in plain, earth cutting and tunnel sections modelled are shown in figure 14 [37].

A. POWER FACTORY MODEL WITH A MIXED TOPOGRAPHICAL FEATURE

The plain and earth cutting sections mentioned in figure 13, is modelled at 5 km interval in DigSILENT PowerFactory, as shown in figure 15. This system consists of a three-phase external grid (power supply from distribution grid) which is converted into two phase 25 kV. Then a single-phase transformer of 21.6 MVA power output is connected to TSS, as shown in figure 15. From the two-phase supply, single-phase is utilized to power the traction line of the complete stretch. The catenary and contact wires are modelled as phase wires, and rail tracks are modelled as rail right and rail left which are modelled for the return path. The rail tracks (both right and left) are connected at every 5 km in this model and earthed at every 10 km. As the tunnel sections are earthed both at the start and end of the tunnel, the same is reflected in the model. The train is modelled with pantograph, wheels, converter and an AC load, as shown in figure 16. The train load is modelled with the combination of the converter and AC load to represent the effect of the converter (harmonic injection) on the grid and also to represent the power drawn from the grid. The real power and the

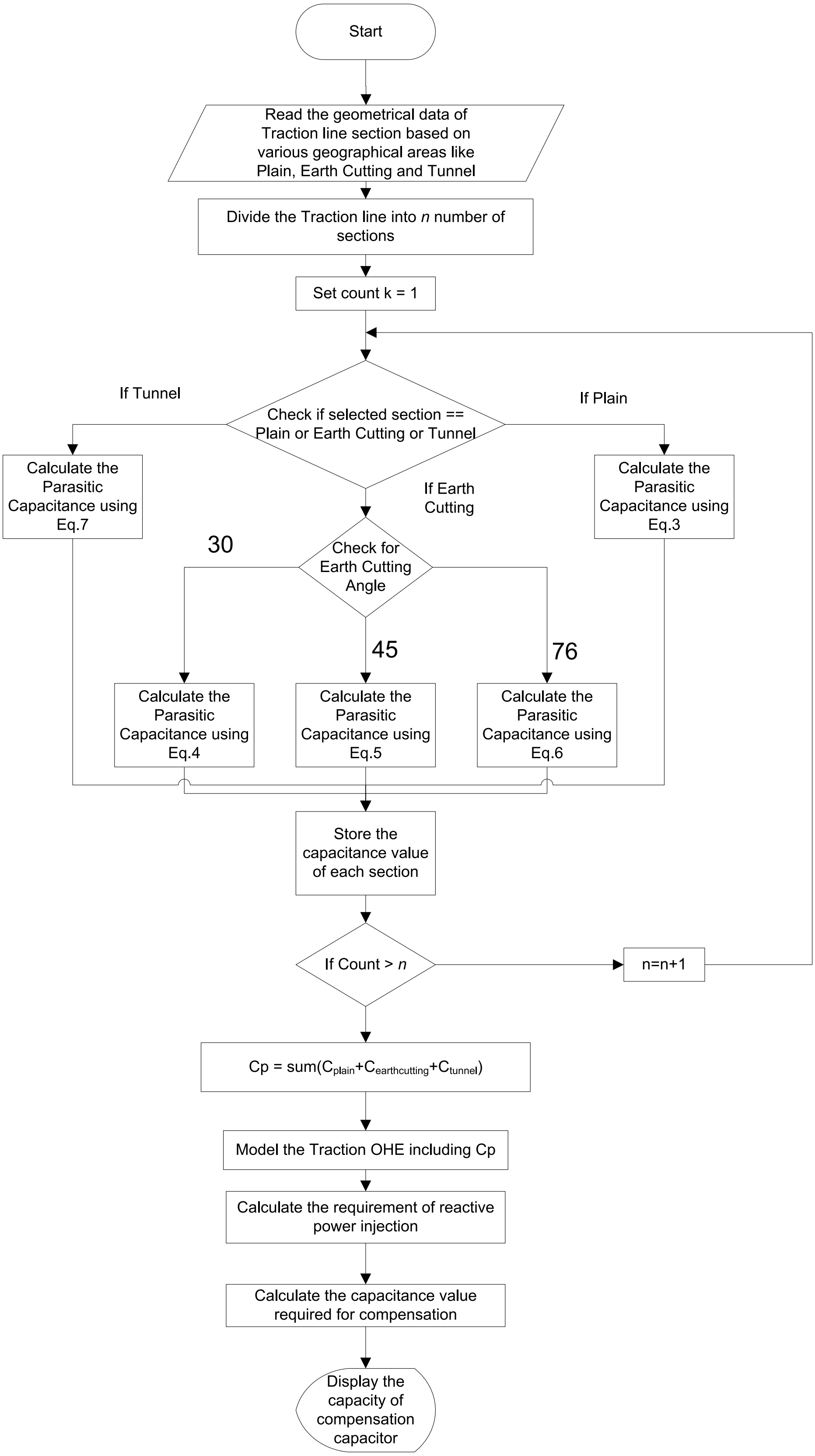

FIGURE 17. **Proposed algorithm of capacitance calculation for power factor correction.**

reactive power of the train load is 2.5 MW and 3.05 MVAR, respectively, with an operating power factor of 0.636 lagging.

The train load is dynamic in a traction line; however, to enhance the clarity of the effect of parasite capacitance in

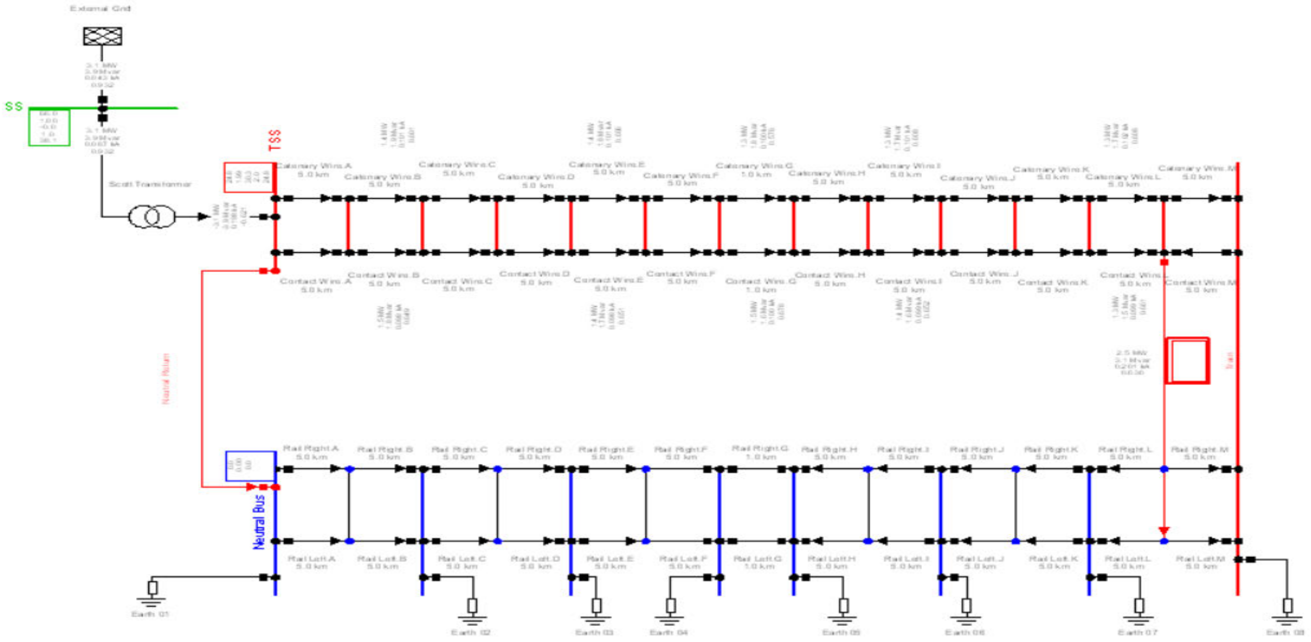

FIGURE 18. Load flow results of 61 km stretch of Indian Traction system.

power factor of the line, the train model is connected at the end of the stretch.

VI. PROPOSED ALGORITHM FOR POWER FACTOR CORRECTION

The effect of parasite capacitance on the power factor is significant (as mentioned in the results represented in previous sections). Therefore, an algorithm is proposed in this paper for the calculation of capacitance required for shunt compensation. The flowchart of the proposed algorithm is shown in figure 17. The steps followed in the proposed algorithm to calculate the shunt capacitance required for compensation is as follows:

Step 1: Read the geometrical data (e.g. distance of railway track in the plain area, earth cutting and tunnels) of the railway stretch section chosen for compensation.

Step 2: Read the dimensions of catenary and contact wire throughout the chosen stretch.

Step 3: Divide the selected stretch into n number of sections.

Step 4: Check for the plain, earth cutting and tunnel sections.

Step 4a: If the section is under plain, calculate the parasite capacitance using equation 2.

Step 4b: If the section is under earth cutting, check for the earth cutting angle.

Step i: if the earth cutting angle is 30 degrees, calculate the parasite capacitance using equation 3.

Step ii: if the earth cutting angle is 45 degrees, calculate the parasite capacitance using equation 4.

Step iii: if the earth cutting angle is 76 degrees, calculate the parasite capacitance using equation 5.

Step 4c: If the section is under the tunnel, calculate the parasite capacitance using equation 6.

TABLE 9. Power factor variation across various section of chosen indian traction system.

Section	Distance	Type	Power Factor
Section 1	15 km	Plain	0.649
Section 2	15 km	Earth Cutting	0.651
Section 3	1 km	Tunnel	0.678
Section 4	15 km	Earth Cutting	0.652
Section 5	15 km	Plain	0.661

Step 5: Add the capacitance of all the sections calculated using previous step 4.

Step 6: Model the OHE including the calculated parasite capacitance (from step 5)

Step 7: Calculate the required amount of reactive power injection for the developed model in step 6.

Step 8: Calculate the required capacitance for power factor compensation.

VII. RESULT AND DISCUSSION

In order to verify the effect of parasite capacitance, load flow studies are performed with the developed model. The results obtained from the load flow studies are shown in figure 18. The power factor obtained from load flow at various sections is mentioned in Table 9. It is evident from the results shown in Table 9, and there is a significant improvement in the power factor with respect to the section type (without including any compensation devices). The calculation of shunt capacitance by any simulation software is done by using the mirror image method (Eq.2). The presented simulation results (table 9) are also based on the mirror image method. In contrast, the actual parasite capacitance value of OHE on different terrains are many times higher [23] and hence power factor. Table 10 presents the actual parasite capacitance value of OHE with height 5.6 meters and radius 0.0124 meters, measured at the experimental zone with calibrated LCR meter and

TABLE 10. Variation in parasite capacitance calculation.

S.No.	OHE topographical feature	Parasite capacitance value measured from LCR meter	Parasite capacitance value calculated using mirror image method (Eq.1)	Offset from actual value	Parasite capacitance calculated using developed empirical formula (Eq.2, 5, 6)	Offset from actual value
1.	At level ground	14.4304 nF/km	8.1627 nF/km	-43.43%	14.1606 nF/km	-1.86%
2.	At earth cuttings of 760 and 7.8m height-	15.53 nf/km	8.1627 nF/km	-47.43%	15.68 nF/km	0.96%
3.	Inside tunnel	45.42 nF/km	9.1998 nF/km	-79.74%	45.84 nF/km	0.92%

TABLE 11. Validation of proposed algorithm for PF compensation.

S.No.	Month (2019)	Power Factor
1	January	0.891
2	February	0.899
3	March	0.896
4	April	0.903
5	May	0.896
6	June	0.900
7	July	0.894
8	August	0.899
9	September	0.905
10	October	0.905
11	November	0.894
12	December	0.900

capacitance value calculated by using mirror image method (Eq.2) & developed empirical formulas (Eq. 3-7).

Therefore, it is essential to consider the effect of parasite capacitance for the calculations of power factor improvement, essentially if a static capacitor setup is used for compensation. Now, with the quantification of the parasitic capacitance of it, the reactive leading power to be injected can be recalculate for the traction lines. Duly considering the effect of parasitic capacitance on increasing the leading reactive power, and to achieve the power factor closer to 0.9, just by adjusting the timing of switching only on the fixed capacitor bank. Employing of expensive dynamic power factor compensating system to achieve higher power factor is avoided. It helps in saving millions of Indian rupees every year. The proposed algorithm has been implemented for the same experimental zone TSS. Table 11 given below validates the proposed algorithm, which shows the power factor of the same traction lines for the last one year. The proposed algorithm and subsequently validated result is also helps IR to achieve the "responsible consumption and production" goal out of 17 UN SDGs goal [1].

VIII. CONCLUSION

The quantification of the parasitic capacitance of 25 kV, 50 Hz electric traction wires, which was creating unpredicted nuisances to railway electric traction system at the geographically challenged area has been presented after conducting exhaustive monitoring & study on one TSS of IR. It has been formulated that, self-generated reactive power was the prime hurdle in maintaining power factor of traction lines at 0.9 minimum. One full calendar year readings gave reliable high-level information about the interrelationship energy vectors with the line parameters of 25 kV AC electric traction systems established at distinct geographical areas. As such, the readings obtained from two different TSS in the research areas, and their comparison are found useful in drawing meaningful inference on the adverse effect of the self-generated leading reactive power in OHE under the influence of its abnormal parasite capacitance at geographically challenged areas. An algorithm to calculate the shunt capacitor rating for power factor compensation for traction system has been presented. The validation of the proposed algorithm has been done after practical implementation for 12 months in the Southern region of IR organization. Therefore, validation & implementation of the proposed algorithm in IR has catered the need of employing expensive dynamic power factor compensating system to achieve higher power factor. The implementation of the new algorithm helps in saving millions of Indian rupees in every year for one TSS of Indian Railway organization. The paper findings will also helpful for future Indian traction system, employing VvvF technology locomotives. In which, power factor within locomotives can be maintained while on the run. Therefore, electrical traction utility needs to be focused on maintaining unity power factor of traction line only (OHE). Indian Railway is aiming the dependency on Green Energy by 2030 using solar PV power. Therefore, the proposed methodology will be a substantial financial benefit as far as power quality issue is a concern.

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