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Power Electronic Transformer based IGBT Converters for Electric Locomotive Applications

Sachin Gee Paul , CS Ravichandran

Abstract**:** ***Electric locomotives up gradation is one of fastest growing technology on railway research. Modern locomotive traction drives operate for high speed rail networks. This paper proposes locomotive drives directly from the mains without line frequency locomotive transformer. Power electronic transformers (PETs) offer the advantage of the reduction in size and weight compared to conventional line frequency transformers. In this article discussed about high power converter using IGBT with high-frequency transformer for electric locomotives is utilized for the power converter side. The catenary feeding front end of the locomotive is connected directly to IGBT based cascade H bridge converter and conventional IGBT based three phase inverter act as load end converter for driving induction motor. The MATLAB simulation results of PET based high frequency transformer with IGBT power converter integrated with traction inverter has justified .***

Keywords **:** ***Line Frequency Transformer (LFT), Insulated Gate Bipolar Transistors IGBT, Power Electronic Transformer (PET), Voltage Source Inverter (VSI).***

I. INTRODUCTION

Traction engineering development, especially in the area of electric locomotives is the core areas for research for railways. Electric locomotive now turned railway network to one of the promising transportation channel. For the passengers we should ensure the transportation with greater convenience in locomotives. Moreover, we should consider with a high efficient electric locomotive unit with greater energy efficiency on the system as well as on grids. Power electronic transformers (PETs) is the combination of several power converter configuration with high frequency transformer. Because of this configuration it will reduce the weight and volume of power cubicle when compare to conventional line frequency transformer configuration[1].The main difficult of conventional electric locomotives is riding speed is low .This issue can be alter and improve by use of PETs based power converters topology's there by riding speed of locomotive is substantially improved. Many dc to dc converters types are discussed on previous papers.

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The galvanic isolation based power converters are substantial role in PET based converters. The several configuration of converters in series, parallel and series-parallel with transformer arrangement is analyzed in previous literature papers. The voltage reduction to suitable level for converters is the only purpose of LFT. Since LFTs are bulky and heavy due to low operating frequency even with its high efficiency but its overall volume will increase tractive effort. Front end locomotive transformer or LFT is the major section of an electric locomotive . This Line frequency transformers (LFTs) in railway vehicles are molded to operate for minimum power density (0.25–0.35 kVA/kg) with an efficiency around 94% for high voltage overhead systems. Railway consider the size, weight, and efficiency constraints in an optimized fashion with traction equipment [9]. The better use of new insulation materials, synthetic ester oil as dielectric, design of windings, and coolants may not suitable to fully address the issues. The overhead equipment embraces catenary wire of a 65 sq. mm cadmium copper and a hard drawn grooved copper contact wire of 107 sq. mm size suspended from the catenary by 5 mm diameter copper dropper wire spaced 9 meters apart. The catenary wire comprises 19 strands of cadmium copper, each strand of 2.10 mm diameter, with an overall diameter of 10.5 mm having about 80% conductivity. The contact wire is a solid hard drawn grooved electrolytic copper of 12.24 mm diameter and cross-sectional area is about 107 sq. mm. Total current carrying capacity 600A carrying each line .Since because of high current utilized for locomotive, the front end converters also should be with IGBT switches Power electronic revolution will adopt the recent power switches such as Insulated Gate Bipolar Transistors (IGBT) in 3.3 kV, 4.5 kV, and 6.5 kV range and Integrated Gate-Commutated Thyristors (IGCTs) in 4.5 kV, 5.5 kV range , utilized for the designs of high power converters platform and the broad introduction of multilevel topologies have risen to a substantial increase in the market share of PWM controlled voltage source converters (VSC). Since because of huge tractive load it is very essential to meet high load current flowing through the power switches. Thus IGBT holds the key role in fulfilling the demands because of the unique characteristics. In many review papers, they focused on individual components, such as power devices, motors, and transformers. Specially designed rolling stock and tracks is needed to achieve greater speed for high speed rail concepts. In Future, new lines with running speed above 350 kilometers per hour widely which uplift the conventional locomotives in existing lines run with a maximum of 130 kilometers per hour.

Direct conversion of line voltage to suitable traction voltage without using any transformer with converter inverter configuration is also discussed in papers ,thus reduces volume mass and cost of locomotive unit [2-5]. The Figure 1 shows the structure diagram of the transformer less drive system. The input initial stage consists of a cascaded H bridge converter with four series-connected drives. The main drawback regarding direct transformer less operation is insulation and protection concept, if any failure occurs in any part of the module it will affect the entire unit So isolation of the power stage is important for the case of locomotive operation.

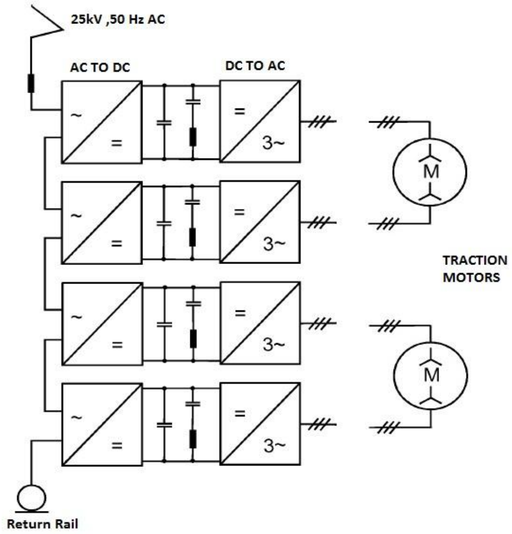

Fig. 1. Structure of transformer less traction drive

In this paper , PET based high power converter configuration used for driving traction motors for electric locomotives .In section II discuss about details descriptions of block diagrammatic representation of PET based converters for electric locomotives is addressed. More over the importance of IGBT power switches and the comparison with other power switches has also discussed in this section. The section III discuss about various types traction inverters and configuration of traction motors with axle has also addressed.The section IV and section V discusses about various simulation results obtained from MATLAB SIMULINK platform and its conculsion .

II.CONFIGURATION OF POWER ELECTRONIC TRANSFORMER IN LOCOMOTIVES

Presently electric locomotive plays a substantial role in rail transportation. A lot of researchers doing in the field of locomotives for future high-speed rail system. In fully electric powered locomotive no internal combustion engines are connected to the axle, but only electric motors are available to drive the traction load. Figure 2 shows the basic block diagram of an LFT based electric locomotive.

A. Conventional Electric Locomotives

In conventional rail networks system, overhead equipment-pantograph, mounted on the locomotive collect high voltage single phase 25kV,50 Hz from the grid . Then locomotive transformer or Line Frequency Transformer[LFT] step downs to suitable voltage for the power rail of converter bridge. Since locomotive transformer operates with 50 Hz supply , the dimension and size is so heavy. The axle of the locomotive is coupled with several set of traction motors .Due to easy maintenances and performance cage induction motors are preferred for traction purposes.

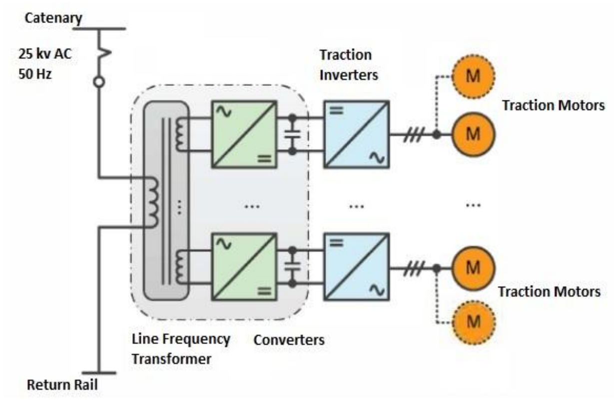

Fig. 2. LFT based electric locomotive.

B. Power electronic transformer based traction drive

In the conventional system locomotive transformer or LFT itself having great volume and mass .This is one of the reason for weight contributors on electric locomotives . This issue is the main reason of blocking the development of high speed rail concepts with this conventional electric locomotives. The fast growing technology on power semiconductor devices and other control strategies for soft switching materials, will assure Power Electronic Transformer (PET) based locomotive systems become substantial importance for high-speed rail networks and in addition to that it also ensure provides greater efficiency and higher power density [1]. Figure 3 shows the functional diagram of proposed locomotive power drive system

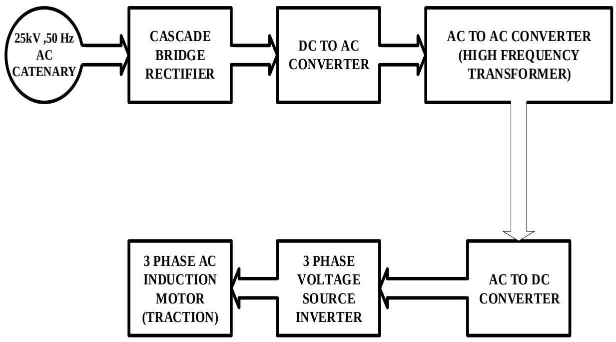

Fig. 3. Locomotive power drive system

Overhead equipment on the locomotive receive power from the grid as 25kV single phase a.c. Since it magnitude is very high ,it should reduce the amplitude by cascade bridging using rectifier .The voltage stress on each device on the converter is reduced due to this cascade configuration. After the rectification from a.c it directly fed to dc to dc converter with high frequency transformer .This high frequency transformer further reduce the voltage to suitable value load voltage and finally fed to traction inverter which drives traction motors fixed on the axle of the locomotives. This is the core concept of power electronic transformer based system.

The following features shows some unique behaviour of PET-locomotive drives[6]:

1. Locomotive transformer operates with high frequency ,there by its mass volume is considerably reduced.
2. The front-end converters of locomotive is suitable for holding high voltage and inrush current by using high power switching devices like IGBT .
3. For PET based converters ,several switching devices and a high power frequency transformer are used because of this reason the terminal voltage is of pulsed nature not like sinusoidal..

C. Direct Coupling to Overhead Equipment

The primary ultimate objective task for PET driven locomotives is direct interconnection of the front end converter of locomotive to overhead line [3]. For conventional locomotives line frequency transformer or locomotive transformer is located at the front cubicle of the engine room of locomotive. The elimination of this locomotive transformer at the front cubicle of locomotive is the ultimate difference when compare to conventional one . The absence of locomotive transformer can be overcome by interconnecting with different h bridge converter cell in such fashion that cascade to one after one [4].Thus high voltage grid voltage can split into different bridges in a cascade fashion thus voltage reduction occur one each bridge .More over voltage stress on each device is also reduced. . [7]. Figure 4 shows the cascade connection of front end H bridge converter of the locomotive. The decoupling inductance connected between the line-voltage and the converter voltage is equal to the sum of the partial inductances on each cell[8]. The global voltage-drop depending on the line current is based on this inductance. In all cells of cascade connection, the line current is of identical. The major challenges on PET Front end converter configuration with High-frequency transformers are as follows:

1. Since front-end converters are connected directly from high voltage catenary, balancing of voltage distribution in each cell is complex.
2. The power switches used in front end should be capable of high dv/ dt required.
3. Voltage balancing on the load side is so critical. Speed control of motor play a significant role, if any variation in voltage on load side it will vary the speed of each motor, thereby it's a chance of derailment of the locomotive.
4. Design of high-frequency transformer for high voltage is complex to sustain the load.

The conversion of high voltage from over head equipment(OHE) to load system is the ultimate challenge . The recent research are going with power drives to overcome this challenge[7]. Since the high voltage high current is utilized for heavy loaded rolling stock, the introduction IGBTs have a significant role among various high power switching devices. The Figure 5 shows specification details with voltage and current rating of various power semiconductor devices used recently. The researchers are more focused on the development and design of IGBT working with greater voltage stress. Today there are various types of IGBT are available in the market with a high power rating in both voltage and current.

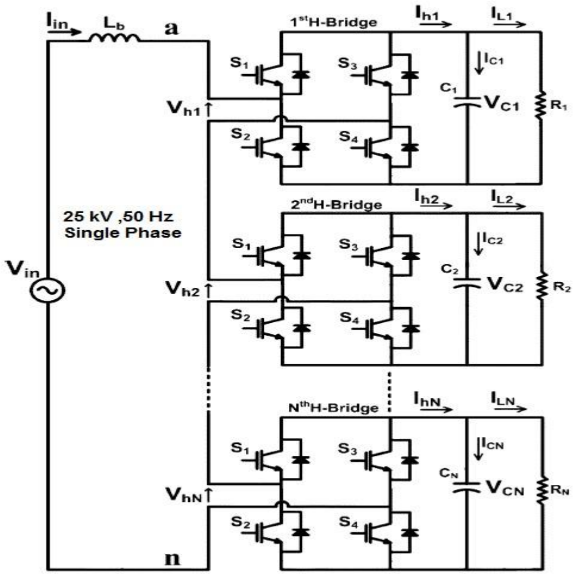

Fig. 4. Cascade front end H bridge converter

The new power switch like 6500 V IGBTs for currents of 200A, 400A, and 600A. All high power IGBTs designed with parallel chips which are covered by a thin aluminum metallization. By using ultrasonic soldering technique connection between IGBT and diodes with aluminum wires is realized[7]. The vertically optimized IGBT designs enhance a great role for improvement of the plasma distribution and reduction on size of wafer on IGBT which ensure significantly reduced switching losses and on-state voltages. Based on junction temperature , the IGBT is able to limit its maximum collector current and the gate-emitter voltage. These unique characteristics enhance the operation of front end converter as well as on dc to dc converter of power electronic transformer.

D. Inrush Current Reduction during switching

During turn-on The instantaneous high current taken by a power supply during turn on time or switching time of electrical equipment which results in inrush current. The capacitors and inductors are charged during this high current flow due to inrush . This transient current is also called as the switch–on the surge, or the input surges current. At the time of turn on process the capacitors offers low impedance which results the flow of high currents into the circuit.

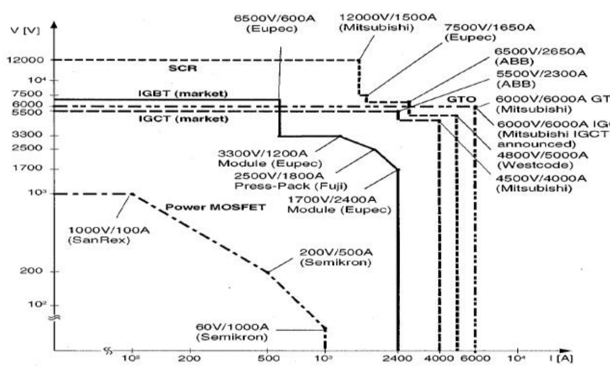

Fig. 5. Rating specification of various Power devices

The intensity of inrush currents can consider as 20 times greater than when compare to normal steady-state currents. Even though its duration is about 10ms it takes between 30 and 40 cycles for the current to return to the normal operating value. If not controlled these inrush current can damage significant effect on electrical apparatus. High inrush currents indicate more stress on power semiconductor devices and hence lower reliability. The inrush current is normally mentioned in terms of average of a half cycle or peak. Figure 6 shows the waveform of current when the power is switched on. The current begins to flow in such a fashion that its the initial current reaches the peak current value within a short moment , its magnitude is larger than the steady-state current value. Thus by the current value gradually decreases until it normalizes at the steady-state current. The portion during which a large current flows before reaching the steady-state current is the inrush current.

There are two key major problems associated with inrush current. The first is exceeding the maximum rating for the traces and components on a PCB. All connectors and terminal blocks have under a specific current rating which, when it above a certain limit, it could cause damage to these parts. Generally, all PCB traces are designed with a certain rating in terms of current capability in mind, for that apply traces to thicker in PCB and more durable connectors The second problem addressed is when a capacitive load switches put to an already stable voltage rail. If the power supply has not stabilized the amount of inrush current needed to charge that capacitor, then the voltage on that rail will be down. If the voltage regulator is not properly to supply enough current at turn-on, the voltage rail could completely lead to system failure. Since power electronic transformer having different types of converter configuration, with more switching devices. The rise of inrush current is reduced by gradually raising the rise time of voltage on the load capacitance and slow down the rate capacitors charge.

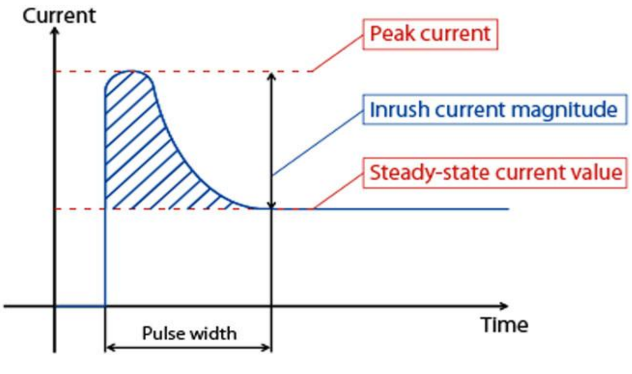

Fig. 6. Representation of Inrush current waveform

Most of the recent power semiconductors are using intelligent power device it can be capable of a high value of voltage and rise of current. The other methods like integrated soft-start switch in dc to dc converters, discrete implementation, and integrated load switch are also used in the field of reduction of inrush current in power semiconductor devices. By all these feature, the rise time can be increased, thus by reducing the inrush current in the circuit can be achieved in the PET circuits. Table 1shows Comparison of various power devices like MOSFET,BJT with IGBT.

Table 1 IGBT Comparison with other power devices

COMPARASION CHART OF IGBT

	Power BIPOLAR	*Power MOSFET*	*IGBT*
Voltage	High <1kV	High <1kV	Extra high >1kV
Current	High <500A	High>500A	High >500A
Input impedance	Low	High	High
Output impedance	Low	Medium	Low
Switching speed	Slow	Fast	Medium
Cost	Low	Medium	High

E. Topology Description for High-frequency transformer

In many of the electrical standards primarily focusing on safety, for that isolated converter play a significant role. In addition to personal safety, separation of load side voltage from high voltage supply also holds key importance. The fine voltage matching is also needed in many applications as it helps in designing and optimizing the voltage rating of different stages in the system. This structure consists of two high-frequency switching DC-AC and AC –DC converter with a high-frequency transformer as shown in Figure 7

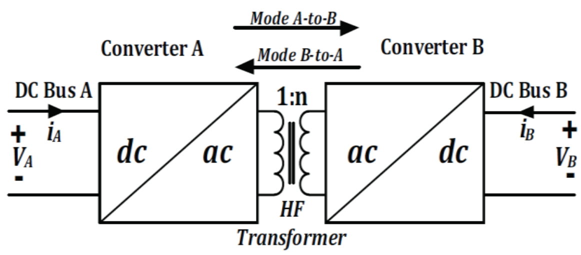

Fig.7. Galvanic isolation using a high-frequency transformer

The operating principles of high-frequency transformers is exactly same as of standard conventional transformers. The only difference in the operating frequency aspect only, they operate at much higher frequencies than in 50 Hz or 60 Hz operating transformers. The main benefits for operating at a higher frequency, the first one is the reduction of the size of the transformer. Since because of smaller size, less copper wire is used, thus reducing the losses and helping to achieve transformer high efficiently. In addition, the core is typically made with ferrite, a wide variety of geometries are available. However, the major advantage brought about by light weight, small size, and higher power density, which meet a number of challenges. Minimizing the common problems such as skin and proximity effects are also considered during the design stage of the high-frequency transformer.

III.TRACTION INVERTER FOR LOCOMOTIVES

A. Configuration for Traction Motors

High starting torque is the unique feature for traction motors.

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Earlier dc series motors are normally used for locomotives but due to easy operational and maintenances, cage induction motors with better performance characteristics are prefered recently. In thecase of ac motors,when the motor rises speed , the frequency of supply also rises in manner such it maintains net slip frequency, above the motors rotational frequency.Thus we can control the speed by using some Variable frequency Drives (VFD)drives. In the case of dc series motor drives, the commutator acts as a mechanical inverter also its need for regular maintenance, its susceptibility to water ingress and flashover. In addition to the commutator maintenance, the other accessories like contactors/camshaft also require maintenance regularly and the overall cost of the dc drive system is also high . Because of all these reasons squirrel cage induction motors are most preferable motor drives for locomotive application .The advantages of using induction motor for traction application as listed below:-

1. Better compact size for induction motors ,thereby easy to fix on the bogies and overall weigh is reduced.
2. The availability of induction motors are more, there by its cost of manufacturing is cheap.
3. The frame size of the machine is reduced due to the higher rotational speed.
4. The absence of commutator improves the induction machine can operate at any working condition.

B. Types of Inverter for Traction load

Based on the a.c. controlled parameter, voltage source inverter has the unique feature than current source inverter. For propulsion application voltage source inverter(VSI) has a significant role. Generally for high power drives , two major types of VSIs are commonly used force commutated thyristor type and GTO type VSI as shown in Figure 8. In thyristor (IGBT)based VSI have regulated dc from front end dc choppers. There by it can permit to control large variation of voltage with certain range. The GTO VSI is another type however the various researches are going on for high voltage switches to meet with reduction of losses [10].

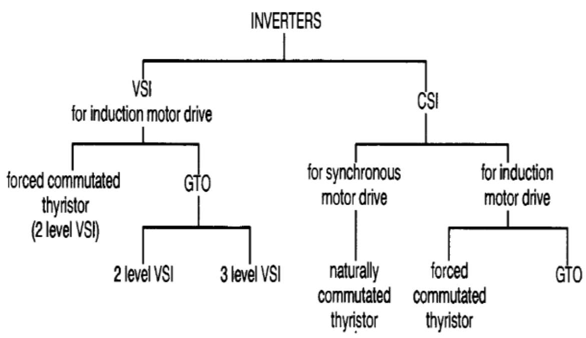

Fig. 8. Types of Traction Inverters

IV. RESULTS

Simulation results from MATLAB for Power electronic transformer based dc to dc converter for electric locomotives was carried out with input voltage parameter of 25 kV is simulated. The frequency range on PET transformer as 1500Hz is used. The high voltage from OHE is converted to suitable load voltage using locomotive power converters and the results with certain parameters are discussed. The simulation result of load voltage of traction motor as shown in Figure 10. The dc to dc converter is coupled to traction load inverter . So the output voltage of traction load inverter as 2000V is obtained from the simulation output.

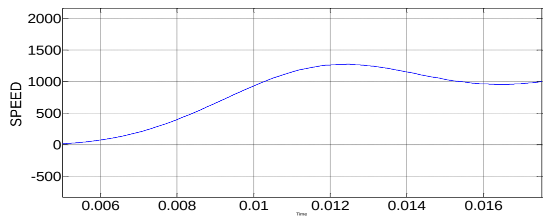

Fig.9. Traction Motor Speed

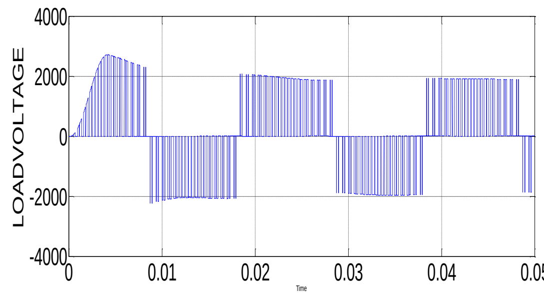

Fig. 10.Load voltage of traction inverter

This traction load voltage is vary based on power configuration and design scheme of each locomotive .Modern locomotive traction motors are capable to operate above 1500 V . The speed of traction motor units simulation result as obtained in Figure 9. In this paper high voltage dc to dc converters is fulfilled by using high frequency transformer. The result of high frequency transformer output as shown on Figure 11. Due to several switching devices are operated ,first order filter is attached between traction inverter and load for the reduction of harmonics generation .

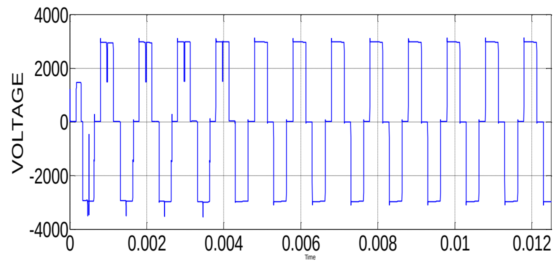

Fig. 11.High frequency voltage of transformer

V. CONCULSION

In this paper, IGBT based power electronic transformer based converter drives used for electric locomotives is proposed. By shifting the locomotive transformer arrangement to middle end of the locomotive power drive converters unit with increasing the operating frequency of the transformer .There by reduction in mass volume of transformer is achieved .By using power electronic transformer for locomotive power drive converter has simulated with MATLAB SIMULINK platform .

The operation of traction motor as cage induction motors connected on the axle of locomotive has also discussed. The proposed paper has great scope for real time research progress for the development of high speed rail network locomotive systems.

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