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# A High Reliable Drive System For Electric Freight Locomotives Of Indian Railways

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**Abstract**

The Electric Freight Locomotives are six Axle Locomotives with all Axles powered by Traction Motors. These Locomotives should be highly reliable and robust in operation with high Starting Effort. For a Freight Locomotive, the trailing Load is a heavy Load. The Locomotive has to produce constant Torque for it to be able to haul the Load even at Gradients. When the six Traction Motors are powered by Three Inverters, the load on the Inverters will reduce and in case of Locomotive on no Load, Two Motors can also be switched off, saving Power. A new Drive System is proposed in this paper with Six Traction Motors powered by Three Inverters for a high reliable operation and better division of required Tractive Effort among the Driving Axles.

**Key Words:** Efficiency, Freight Locomotives, Squirrel Cage Induction Motors, Speed, Tractive Effort.

## 1. INTODUCTION

The Freight Locomotives are normally heavier as compared to their Passenger counterparts as they are expected to haul heavy Loads and hence they will have lower Gear Ratios, higher Tractive Effort but the Speed of these Locomotives is compromised. Three-Phase Alternating Current Locomotives of Indian Railways of the Class WAG-9 use Squirrel Cage Induction Motor as Traction Motors. Three Motors are connected in parallel in a Bogie. These Motors are fed by a set of three 2-pulse Bridge Inverters where fundamentals are shifted by a phase difference of 120˚ [1]. The Input Converter is a 4-pulse Bridge Rectifier. The input voltage to the Rectifier is 4kV, 50Hz, 1-phase AC stepped down by the 25kV/4kV Transformer where 25kV, 50Hz AC Voltage collected by the Pantograph. The Main Converter, Motor Inverter and auxiliary Converters use Gate Turn-Off Thyristors as switches. The Insulated Gate Bipolar Transistors have many inherent advantages over the Gate Turn-Off Thyristors for high power applications and hence the proposed Drive System will use IGBTs as switching Devices in Rectifiers and Inverters.

## 2. DESCRIPTION OF THE EXISTING POWER CIRCUIT

The Locomotives of the type WAG-9 (Broad Gauge AC Goods type) make use of the Three-phase drive technology with Gate Turn-Off thyristors and are controlled by microprocessors [1]. The primary winding of the main transformer is fed from the Overhead Equipment through Pantograph and is 25kV, single phase, 50Hz supply. This transformer is a specially built high impedance transformer. A primary voltage transformer is provided at the primary of the main transformer to continuously measure the Voltage supplied by the Catenary. The signals from this transformer are picked up by the control circuit and in case of abnormality in the Catenary Voltage, the Vacuum Circuit Breaker trips to protect the equipments. There are four identical traction windings and one auxiliary winding on the secondary side of the main transformer. The Line Converter consists of two sets of pulse controlled single phase Full-Bridge rectifiers. These are self commutated four quadrant converters. The stepped down Voltage is converted to DC by these Rectifiers connected to the secondary of the main transformer. The DC Link Voltage is maintained at a value by the Power Converter depending on the Power, direction of flow of energy and line Voltage.

The Motor Converter is connected to the Line Converter via the DC Link. The DC Link also serves the purpose of smoothening out the harmonics in the DC Voltage generated by the Line Converter. It compensates both periodic and non-periodic power differences between the motor side and the line side. Such power differences occur when there is low frequency pulsations caused by the single phase circuit of the Line converter, due to pantograph bounce or due to wheel spin. These power differences are minimised after a certain delay in the circuit as the recovery cannot be instantaneous. The periodic pulsations may occur because the fundamental power of the three phase system (Motor side) is constant but the fundamental power on the single phase system pulsates at double the line frequency. The DC Link is fed pulsating current from the Line converter at double the line frequency whereas motor converter draws pure DC current. The DC Resonant filter serves to filter out the currents at double the line frequency. A DC Link Capacitor is used to cater to the non-periodic disturbances. It is rated in such a way that the DC Link Voltage remains constant under all operating conditions. This Capacitor also serves the purpose of filtering out the harmonic currents produced both by Motor Converter and Line Converter.

The Motor Inverter consists of the three-phase bridge connected to the DC Link. On the AC side the three-phase bridge is connected to traction motors. Each of the three pairs of arms generates an AC Voltage consisting of square pulses of constant amplitude from the DC Link. These three Voltages are displaced by 120˚ from each other. The Torque and Speed of the Traction Motors are varied by varying both frequency and amplitude of the Voltages. In Motoring mode, the fundamental frequency of the motor terminal voltage is higher than the frequency corresponding to motor speed thus generating a positive slip and hence a positive torque. In Braking mode of operation, the fundamental frequency of the motor terminal voltage is lower than the frequency corresponding to the motor speed thus resulting in a negative slip and generating braking torque.

## 3. DRAWBACKS OF THE EXISTING POWER CIRCUIT

The existing design of Power Converters makes use of GTO as switching devices [1]. As seen in the properties of GTO, it requires bulky Snubber Circuits for both protection and turn-on/off. Its capability for working at momentary high voltage surges is limited. The Motor Converter is of single arm 2-pulse Bridge producing AC Voltage displaced by an angle of 120˚ with respect to the Motor terminals. Each of the 3-pairs of arms consists of two GTOs and two diodes connected in anti-parallel with respect to each other. The reliability of such a circuit is questionable for an application like Traction wherein any fault in one of the switches of the Inverter can result in un-balance of supply to the Traction bringing the traffic to a halt. Hence a more reliable three-phase Inverter would be needed to ensure 100% reliability in operation. In case of a six axle Locomotive with all Six Axles Powered, it would be more reliable to feed a pair of the Traction Motors from one three-phase Inverter as any failure of the switch would still ensure isolation of faulty Motor circuit and working of other Traction Motors. Another drawback with GTO is its intolerance towards high Voltage surges [2]. This can be expected in case of Pantograph bounce, Wheel spins. Hence, a device that is capable of tolerating high momentary surge Voltage without bulky protecting devices would be preferable. To overcome these drawbacks, one will need to use a different switch which is reliable in operation, can withstand momentary surges. Also to ensure 100% reliable operation, the Motor Inverter design would need a makeover.

## 4. PROPOSED DESIGN OF THE TRACTION CONVERTERS

A new design of Traction Converter is proposed in this paper. As the Freight Locomotives have to be heavier in weight and work in constant Torque mode only, we propose to have Six Powered Axles which will be driven by Squirrel Cage Induction Motors of rating of 900 kW. The Traction converter will be a three-phase bridge Inverter with IGBTs as switches. This will ensure a three-phase balanced supply to the Traction Motors. Each of the Traction Converter will feed a pair of Traction Motors. Also the existing design of Line Converters will be modified by replacing the GTOs with IGBTs. The replacement of GTOs by IGBTs is expected to give an improved performance in the Converters by reducing the harmonic content in the Voltage and Current Waveforms [5]. Also, an improved performance of the Traction Motors can be expected as the ripples at the output of the Traction Converter will be smoothened by virtue of the properties of IGBTs. The Motors are also expected to reach their steady state speed in very less time as compared to that taken when GTOs are used as switching devices. The proposed circuit will be simulated using MATLAB Simulink software and the results will be analysed and compared.

## 5. SIMULATIONS AND RESULTS

Simulation studies were carried out with Squirrel Cage Induction Motors of the rating of 900 kW powered by IGBT Rectifier-Inverter System and the results were analysed.

### *5.1 Description of the Circuit*:

The circuit is broken up into three parts for analysis namely (a) Rectifier (b) DC Link (c) Inverter. The proposed circuit diagram is shown in Fig. 1.

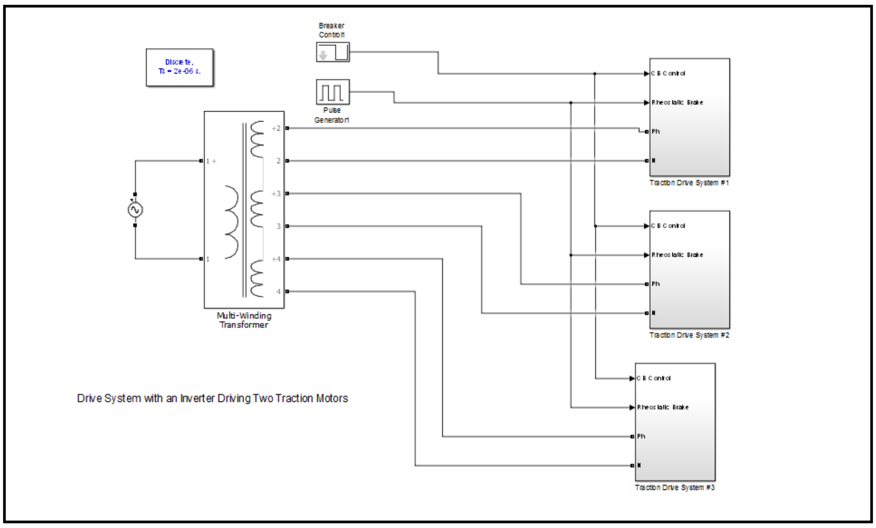


**Fig. 1 Proposed Drive System for Six Axle Locomotive**

### *5.1.1 Rectifier Circuit*:

Two 4-Pulse Bridges are connected in parallel to form one unit of Traction Rectifier. The input to the Rectifier is 4500 V, 50 Hz AC supply fed from an AC source. The output of the Rectifier is fed to the DC Link.

### *5.1.2 DC Link*:

The Traction Rectifier output is connected to the DC Link. The DC Link consists of a Capacitor Bank of 815µF and 11.41 mF connected in parallel to filter out the Harmonics in the DC Voltage. A Diode is connected in the DC Link to ensure unidirectional current. The output of the DC Link is connected to the Traction Inverter. The details of the Circuit are shown in Fig. 2

### *5.1.3 Traction Inverter*:

The Traction inverter is a 6-Pulse Bridge Inverter circuit which is capable of generating Sine waves displaced by a phase difference of 120˚. The Pulses are delivered by means of a PWM generator. The output of the Traction Inverter is fed to the Traction Motors. The system is designed in such a way that, a Traction Inverter will supply Power to One Traction Motor. This means that, for a 6-Axle Locomotive, there will be four Traction Inverters feeding the Motors. This will ensure 100% reliability in operation of the Locomotive. The details of the Circuit are shown in Fig. 3.The circuit diagram shown in Fig. 1 is simulated using MATLAB Simulink.

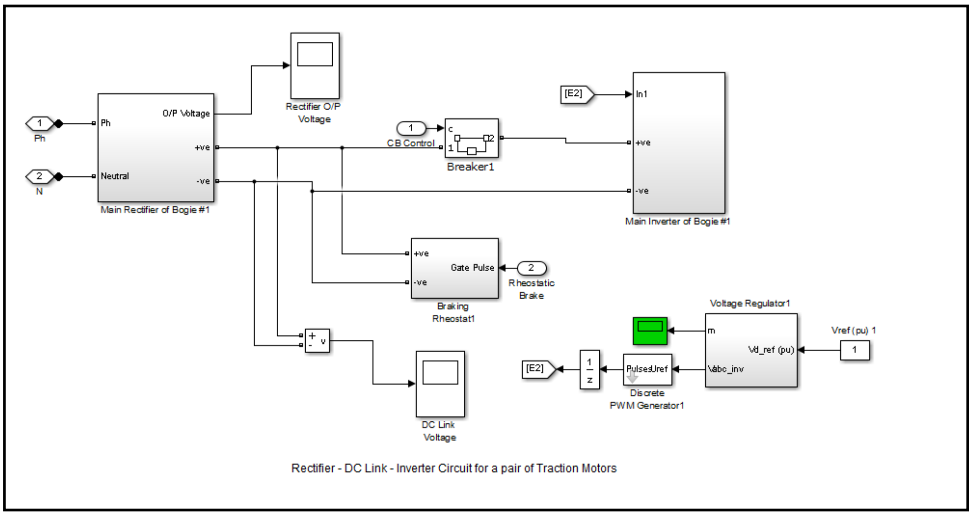


**Fig. 2 Rectifier-DC Link Circuit of one Bogie (Two Axles)**

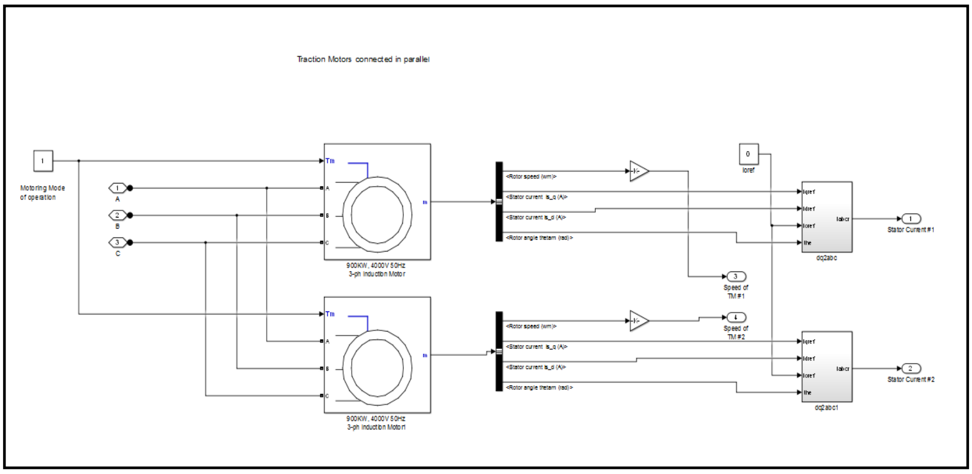


**Fig. 3 Inverters fed Traction Motors of one Bogie (Two Axles)**

The circuit that has been proposed in the Fig.1 was simulated using MATLAB Simulink software. The simulation was carried out for 10 seconds of Simulation Time to study the results in detail. The Tractions Motors were accelerated for a time period of 1 seconds. They reached the steady state speed in about 0.2 seconds. The Circuit Breaker on the Inverter side of the DC Link was opened and the Braking Resistor was introduced into the circuit by delivering pulses to the IGBT connected to the Braking Resistor at time of 3 seconds. The speed of the Traction Motors reduced to zero and went into super-synchronous speed region. Again at a time of 5 seconds, the Circuit Breaker of the DC Link on the Inverter side was closed and the pulsations to the IGBT connected to the Braking Resistor were ceased. This resulted in the Traction Motors accelerating again to the required speed.

**The Traction Rectifier Output:**
The output waveform of the Traction Rectifier is shown in Fig. 4. The Waveforms were observed to be ripple free and with fewer harmonic. The amplitude of the output Voltage was 5000 V. The output Voltage was a pulsating DC waveform. The waveform obtained has been zoomed for better view in the Figure.

**DC Link Output:**
The Capacitors of values 815μF and 11.42 mF were connected in parallel to form the Capacitor bank to filter out the Harmonics and also work as a Voltage Booster. The Diode was connected to ensure uni-directional Power flow. The output Voltage waveform is shown in Fig. 5. The Voltage waveform was observed to be pure straight line DC of the amplitude of 5800 Volts. The variation of amplitude of DC Link Voltage can be observed in the Graph at t = 5 seconds

**Traction Inverter and Motors Outputs:**
The output of DC Link is connected to the Traction Inverter. The Traction Inverter is pulsed by the Discrete PWM Generator based on simple constant V/f principle [4]. The no-load voltage to rated frequency ratio is calculated in the Embedded MATLAB function. The frequency of operation of the Inverter is changed to change the speed of the Traction Motors. The Speed of the Traction Motor is fed to the Embedded MATLAB function. The new speed required is given as a command during run-time at a pre-defined time in the Embedded MATLAB function. The new frequency of firing corresponding to the new required speed is calculated. The Voltage boost required for the new frequency is also computed from the V/f ratio [10]. These inputs are fed to the PI Controller to regulate the Voltage Regulator block. The new Frequency required and the corresponding Voltage required is compared and firing pulses are given to the Traction Inverter. The Voltage level is varied so as to maintain the Torque constant. The Phase-Phase Voltage was 4500 V and the current was 100 Amp continuous. The Braking Chopper was pulsed at t=3 seconds with the opening of the Circuit Breaker. The Inverter Voltages and Currents dropped to zero and the current circulated in the DC Link through the Braking Chopper. At t=5 seconds, the Circuit Breaker was closed and the pulses to the Braking Chopper were stopped. This resulted in Traction Motors accelerating again.

The Traction Motors achieved steady state speed at t=0.2 seconds. After reaching the steady state, the Traction Motors ran at near rated speed of 1500 rpm. The speed observed for the Traction Motors in continuous mode of operation was 1490 rpm with minor oscillations. With the introduction of the Speed reduction command at t=1 seconds, the speed dropped to 750 rpm. The Motors were then stopped with Braking Mode and again Accelerated at t=5 seconds. The Speed curve, Stator Voltages, Stator Currents of the Traction Motors is shown in Fig. 6, Fig. 7 and Fig. 8 respectively.

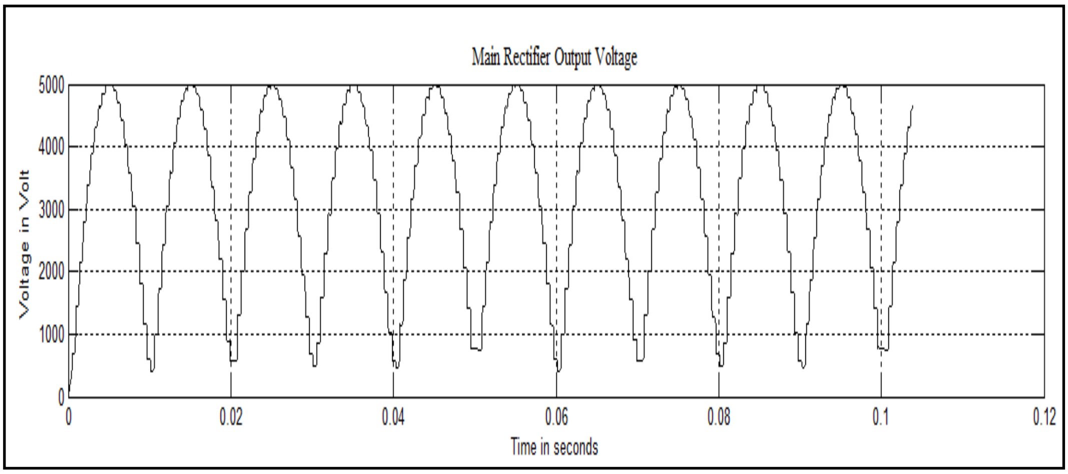


**Fig. 4 Rectifier Output Voltage Waveform**

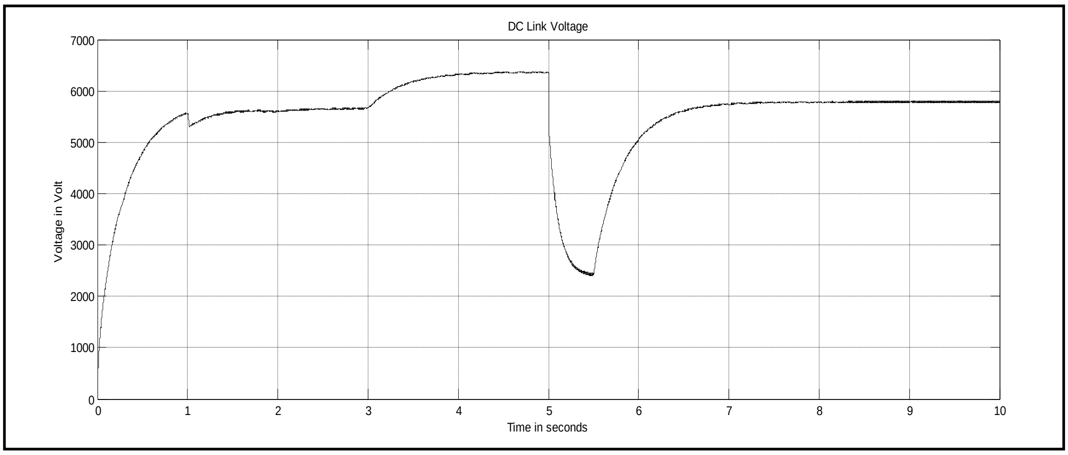


**Fig. 5 DC Link Voltage Waveform**

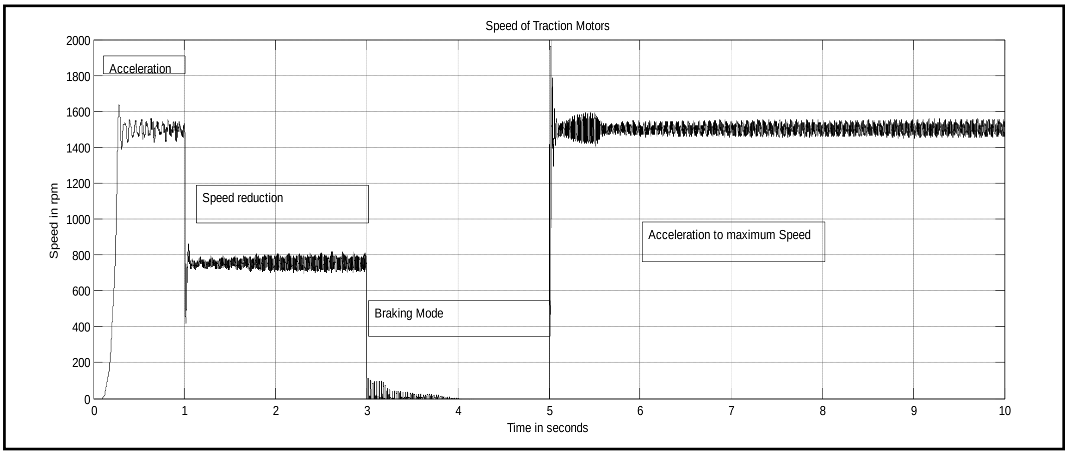


**Fig. 6 Speed Developed by Squirrel Cage Induction Motors**

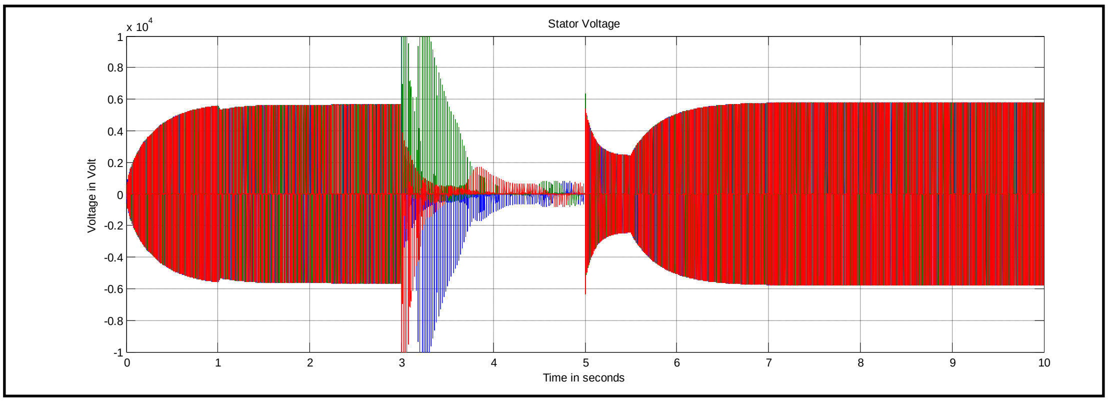


**Fig. 7 Stator Voltages of Traction Motors**

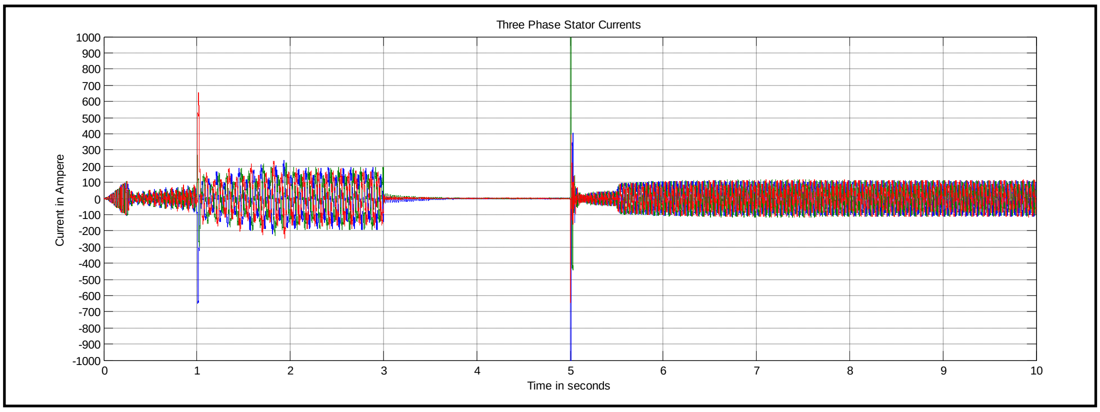


**Fig. 8 Stator Currents of Traction Motors**

## 6. EQUATIONS AND CALCULATIONS

The Equations and Calculations related to the proposed Traction Drive systems are presented in this section in brief.

### 6.1 Calculation of Tractive Effort Required:

The various Tractive Efforts required by a Locomotive are:

Tractive Effort for Acceleration ( $F_a$):

$$F_a = 277.8\, W_e\, \alpha \;\; Newtons \qquad \text{Eq. (1)}$$

Tractive Effort to overcome Gravitational Pull ( $F_g$ ):

$$F_g = 9.81\, W.G \;\; Newtons \qquad \text{Eq. (2)}$$

Tractive Effort required to overcome Train Resistance for a Locomotive ( $F_r$ ):

$$F_r = 9.81(\, 0.65\, W_l + 13\, n + 0.01\, W_l\, v + 0.52\, v^2 \,) Newtons \qquad \text{Eq. (3)}$$

Tractive Effort required to overcome Curve Resistance ( $F_c$ ):

$$F_c = 9.81\, W \left(\frac{700}{R}\right) \; Newtons \qquad \text{Eq. (4)}$$

Total Tractive Effort = $F_t = F_a + F_g + F_c + F_r$ Eq. (5)

## 6.2 Assumptions for Calculations:

It is assumed that the Locomotive starts on a plane surface without Gradient and Curvature hence, the Tractive Effort required would be only Tractive Effort for Acceleration. Let us assume that the Locomotive has to accelerate a trailing Load of 4500 tonne to 70 Kmph in 400 seconds.

***(a) Calculation of Tractive Effort:***

Acceleration, α in Kmphps will be given as, $\alpha = \frac{70}{400} = 0.175\ Kmphps$
Weight of the Locomotive = $W_l$ = 150 tonnes
Weight of the Trailing Load = $W_t$ = 4500 tonnes
Total Weight = W = ( $W_l + W_t$ ) = 4650 tonnes
Effective weight of Locomotive and Trailing Load = $W_e$ = 5115 tonnes
Tractive Effort required for Acceleration = $F_a$ = $277.8 \times 5115 \times 0.175 = 248.7\ kNewton$

***(b) Calculation of Power, Torque developed:***

Voltage per phase = 5000 V
Current per phase = 100 A
Power Factor = 0.95 (Assumed)
Rated Power = 900 kW
Efficiency of the Machine = 95% (Assumed)
Frequency = 50 Hz, No. Of Poles = 4, Diameter of the Wheel = 1092 mm
Efficiency of Transmission Gear = $n_e$ = 0.9
Gear Ratio for Freight Locomotive = $G_r$ = 5.13
Power input to the Traction Motor = $\sqrt{3}\ \times Vph\ \times Iph\ \times Cos\varphi$ Watts
= $\sqrt{3}\ \times 5000\ \times 100\ \times 0.95$ Watts
= 822700 Watts (per Motor)
Power Output per Motor = 0.95 x 822700 = 781565 Watts
Speed of the SCIM = $N_{tm} = \frac{120 \times f}{p}$ rpm = $\frac{120 \times 50}{4}$ = 1500 rpm
Torque developed per Machine = $\frac{60 \times P}{2 \times \pi \times N}$ Nm = $\frac{60 \times 781565}{2 \times \pi \times 1500}$ Nm = 4976 Nm
Total Torque developed by 6 Traction Motors = $T_d$ = 29853 Nm
Tractive Effort Developed (For Freight Locomotive) = $\frac{n_e \times T_d \times G_r}{R_w} = \frac{0.9 \times 29853 \times 5.13}{0.546}$ = 252 kN
Speed of the Locomotive at Wheel = $V = \frac{\pi \times D_w \times N_{tm} \times 60 \times 10^{-3}}{G_r}\ Kmph$
= $\frac{\pi \times 1.092 \times 1500 \times 60 \times 10^{-3}}{5.13}$ = 60.1 Kmph (For Freight Locomotive)

## 7. CONCLUSIONS

The proposed circuit was simulated and it has been observed that the performance of the Traction Motors is on the expected lines with quick response to Deceleration and

Braking Modes of operation. The net Tractive Effort developed was 252 kN and the Speed observed was 60 Kmph which are the required features for a Freight Locomotive. As this Drive System is reliable in operation, it can be implemented for the Freight Locomotives.

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