

Design and Analysis of Drive System with Slip Ring Induction Motor for Electric Traction in India

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ABSTRACT

The use of Squirrel Cage Motor for Traction has revolutionised the motive power of a Locomotive. The Asynchronous Motor is rugged, has high starting Torque, very smooth Voltage and Speed control as compared to a DC Series Motor. When looking at the Traction perspective, a Wound Rotor Induction Motor can be an alternative to the Squirrel Cage Motor as it has higher starting Torque at lower starting current and better efficiency than a Squirrel Cage Motor. The Slip Power Recovery scheme also plays a proactive role as there can be substantial savings of energy in case of a Wound Rotor Induction Motor as the Slip Power recovered can be used to drive the Auxiliary Loads of the Locomotive and also for powering the trailing Passenger Cars. A detailed design and analysis of a Drive System with Wound Rotor Induction Motor for Electric Traction is presented in this Research Paper.

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1. INTRODUCTION

The invention of Gate Turn-Off Thyristors revolutionised the modern Electric Traction. Considerable advancements have taken place from the use of Diode Rectifiers for series-parallel control of the DC Series Motors to the use of simple Pulse-Width Modulation Technique for the control of Asynchronous Motors. The Inverter driven Induction Motor maintain a low-slip operation even during starting [1]. As a result, the Three-phase Squirrel Cage Induction Motor became very popular as the Traction Motor because of its properties of ruggedness, high starting torque, easy Motor Control through Micro-processor, regeneration up to zero speeds, efficiency of operation and better adhesion provided by it in preventing Wheel Slips. It is also observed that a WRIM can produce more starting torque as compared to a SQIM at lesser starting current. Also the Braking capability of WRIM has been found superior to SQIM [2]. With the ever increasing loads to be hauled, multiple operations of Locomotives have become the norm of the day. Under these conditions, the production units manufacturing Locomotives are working out ways and means to increase the Power of the Locomotives. In near future one might find Locomotives of the capacity of 7000 HP hauling heavy loads over various gradients in Indian Railways. When it comes to ratings of Motors for this kind of ultra high power Locomotives, the Motors could be rated at order of 900 kW to 1 MW.

In this given scenario, if one can harness the Power wasted due to 'Slip', the energy savings can be substantial. It has been proved in the case of high capacity Roller Mills, that the high initial cost of a Slip ring Induction Motor is overcome by the Slip Power Recovery Scheme implemented by a simple Kramer Drive. The Slip Power thus harnessed can be pumped back to the supply bus bars through a step up Transformer.

This has resulted in energy savings of the order of 360 kW worth \$300,000 per annum for a 5000 HP Wound Rotor Motor running at 90% full speed in the grinding Mills used in large Cement Plants [3]. Also, as the starting Torque developed by the Wound Rotor Motor is directly proportional to 'Slip', the Machine develops higher starting Torque as compared to a Squirrel Cage Motor at lower values of Current. Hence, a Drive system is designed and analysed with Wound Rotor Machine as Traction Motor in this paper.

2. SALIENT FEATURES OF WRIM

With the advancement in technology in construction of Electrical Machines, large WRIM are being manufactured of the rating of 18,000kW with a voltage range of 13,800V by leading manufacturers like ABB. These machines are manufactured to work at near unity power factor and at about 95% efficiency. The WRIMs have high starting torque, high inertia and low starting current with an enhanced feature of producing high torque over entire speed range. The machines come with automatic Brush lifting gears in which, the slip rings made of stainless steel having a smooth and non-grooved surface. After attaining the full rated speed, the Brush Lifting and Slip Ring short Circuiting Gear short circuits the Rotor and then lifts the brushes from Slip Rings. The other design is to have permanent contact brushes wherein the Slip Rings are manufactured from highly corrosion resistant Copper-Tin-Nickel alloy and helically grooved. The WRIM of ultra high ratings also come with self-ventilation with a fan mounted on the machine Shaft itself. Hence, adequate cooling is provided for safe and reliable operation [4]. The above mentioned features of WRIM are of advantage from the Locomotives point of view as the Traction Motors need to be robust to withstand vibrations, need to have better cooling for reliable and safe operation, need to have high starting Torque with low starting current and need to save on the reactive Power consumed as it needs to higher Power Bills.

The added feature of Slip-Power Recovery scheme in a WRIM would result in substantial savings in energy and hence reduce the cost of operation. The Slip-Power Recovered can be utilised to run the Locomotive Auxiliary units like the Blower Motors, for Lighting the cab and Machine units, charging of Battery used for raising the Pantograph etc. There is also a demand for Head-On-Generation of power for power the trailing Passenger Cars in Express trains like Rajdhani/Shatabdi/Durontos in order to bring down the dependence on Diesel Generators used in End-On-Generation [5].

3. SLIP-POWER RECOVERY SCHEME

The efficiency of an Asynchronous Motor is considerably reduced because of the presence of 'Slip'. The Slip Power gets wasted as heat in the Rotor of the Machine. This power can be harnessed in the case of a WRIM by means of either Static Kramer Drive or Static Scherbius Drive. The difference between the two is that a Scherbius Drive is a bi-directional Drive wherein power flow can be in either direction. If super-synchronous speed is required, power can be injected into the Rotor Circuit from the Bus-Bars. The Power thus harnessed can be used to Drive Auxiliary Loads of a Locomotive instead of being fed back to the Bus-Bars through Step-Up Transformer as this could add to the initial Cost. It has been found that the PWM Slip-Power Recovery does not create torque ripples in the Rotor of WRIM and hence, the efficiency of the Motor is not compromised [3]. In this paper a simple modified Kramer Drive is used to harness the Slip Power from the Rotor of the WRIM.

4. DESCRIPTION OF PROPOSED CIRCUIT

The proposed circuit with its detailed circuit Diagram is discussed in this section. For the purpose of simplicity the Circuit will be broken up into various parts like Supply system, Rectifier, Inverter, Auxiliary Converter etc. Both Rectifier and Inverter used in this paper use Insulated Gate Bi-polar Transistor (IGBT) as the switching device as the IGBTs have been found to have better thermal capabilities and also have been found to withstand sudden short-circuit conditions as compared to GTOs [6]. The other reasons for using IGBT as switching device are that soft-switched IGBTs have lower turn-on and turn-off losses, they require lower switching power and are capable of switching at high speeds [7]. The proposed circuit diagram is shown in Figure 1.

4.1. The Traction Supply System

The Traction Supply system consists of an AC Voltage source supplying 25kV AC at a frequency of 50Hz. This is to simulate the 25kV supply supplied from the Over-Head Equipment in the Indian Railway System. The supply is fed to a multi-winding Transformer with a primary rating of 25kV and secondary rating of 4500 V. The secondary of the Transformer is connected to Traction Rectifier.

4.2. Traction Rectifier System

The main rectifier is a parallel connected two 4 – Pulse Bridge units forming one of Traction Rectifier. They are two sets of such Traction Rectifier systems in this proposed circuit diagram, each individually fed from the secondary of the Traction Transformer. Eight IGBTs are used to form the Traction Rectifier Unit. The input to the Rectifier is 4500 V, 50 Hz AC supply fed from secondary of the Main Transformer. The output of the Rectifier is fed to the DC Link.

4.3. DC Link

The output of Traction Rectifier is connected to the DC Link. The DC Link consists of a Capacitor Bank of 815 μ F 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. A Braking Rheostat is connected in the DC Link through an IGBT. This acts as the Braking Chopper. The purpose of this Resistor is to introduce Dynamic Braking. If Braking is to be introduced, then the Circuit Breaker in the DC Link on the Inverter side can be opened by an external command and the Braking Resistor is inserted into the circuit by delivering Pulses from the Pulse Generator to the IGBT. The Pulse Generator is also controlled externally so that Braking can be done at anytime. If the Motors are to be accelerated again, the Pulses to the IGBT connected to the Braking Resistor are stopped and the Circuit Breaker on the Inverter side of DC Link can be closed. The output of the DC Link is connected to the Traction Inverter.

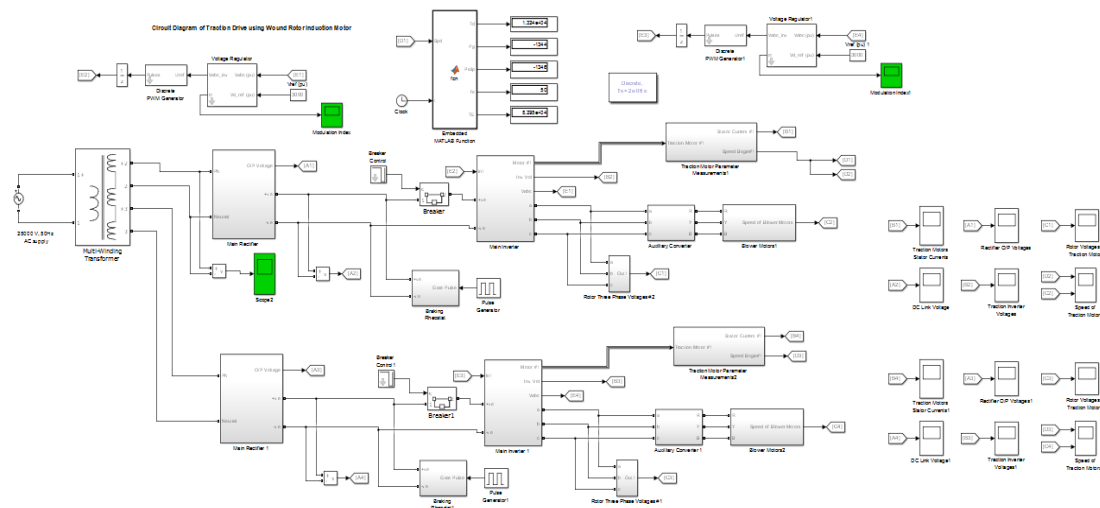


Figure 1. Proposed Circuit Diagram of the Traction Drive System using WRIM

4.4. Traction Inverter

A constant V/f Variable Voltage Variable Frequency control of Induction Motor will match the supply and demand torque by eliminating the use of a Flywheel [8]. Hence a three-phase Inverter is proposed in this paper. 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 control of the Inverter is achieved by means of a simple constant V/f Technique where in the Three-Phase Voltages of the Inverter are measured and compared with the reference value of Voltage required and then the required frequency of Pulses are generated by the PWM generator so as to maintain a constant torque even at lower speed. The system is designed in such a way that, a Traction Inverter will supply Power to Two Traction Motors connected in parallel. This means that, for a 6-Axle Locomotive, there will be three Traction Inverters feeding the Motors. This will ensure 100% reliability in operation of the Locomotive.

4.5. The Traction Motor Circuit

An Asynchronous Motor with Wound Rotor is used as Traction Motor. The present circuit consists of a set of six Traction Motors one each for an Axle. The Motors are controlled from the Stator side for the simplicity of operation. The Motors are rated at 900kW, 3000 V, 50Hz with 2 Poles. The rated speed is 3000

rpm. The Rotors of the three Traction Motors are connected to one Auxiliary Converter, thus making two sets of Auxiliary Converters for the six Traction Motors. The speed is continuously measured and given as input to the Embedded MATLAB function which calculates the Power generated in the Air-Gap, the Slip-Power, the Torque developed and the Tractive Effort developed continuously. The required frequency according to the new speed required is also calculated in the Embedded MATLAB function.

4.6. The Auxiliary Converter

The Auxiliary Converter is basically Static Kramer Drive. It consists of a Three-Phase Rectifier with Diodes as switch. The Inverter is connected via a DC Link. The Inverter is an IGBT based Inverter. Hence, the Auxiliary Converter is uni-directional Converter capable of transferring Power from the Rotor Circuit of the Traction Motors to the Load. The Inverter is fired using a simple PWM Generator. The Auxiliary converter in the proposed design can drive a Load of six 15kW, 400 V, 50 Hz, 4-pole Squirrel Cage Induction Motors. These kinds of Three-Phase Squirrel Cage Machines are normally used as Blower Motors for cooling the Traction Motors. The circuit diagram shown in Figure 1 is simulated using MATLAB Simulink. The simulation results are discussed in the next section in detail.

5. SIMULATION AND RESULTS

The circuit that has been proposed in the Figure 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 Traction Motors were accelerated for a time period of 5 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 5 seconds. The speed of the Traction Motors reduced to zero and went into super-synchronous speed region. Again at a time of 7 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.

5.1. The Traction Rectifier Output

The output waveform of the Traction Rectifier is shown in Figure 2. 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.

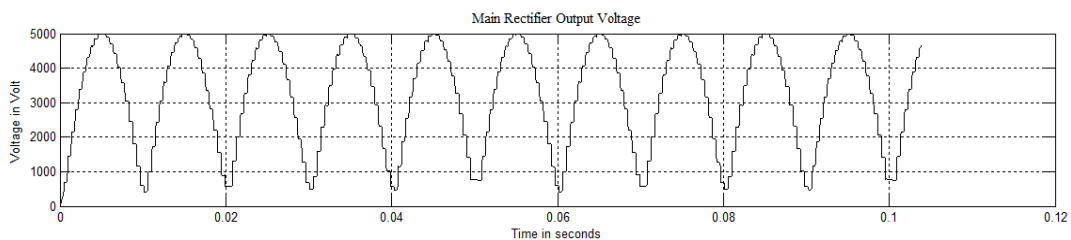


Figure 2. Traction Rectifier Output Voltage Waveform

5.2. DC Link Output

The Capacitors of values 815 μ F 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 Figure 2. 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.

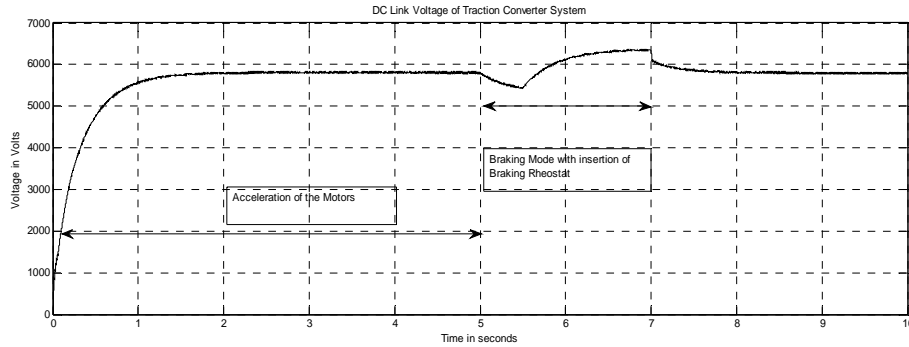


Figure 3. DC Link Output Voltage Waveform

5.3. 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. 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 Waveforms of Three-Phase Inverter output Voltages are shown in Figure 4.

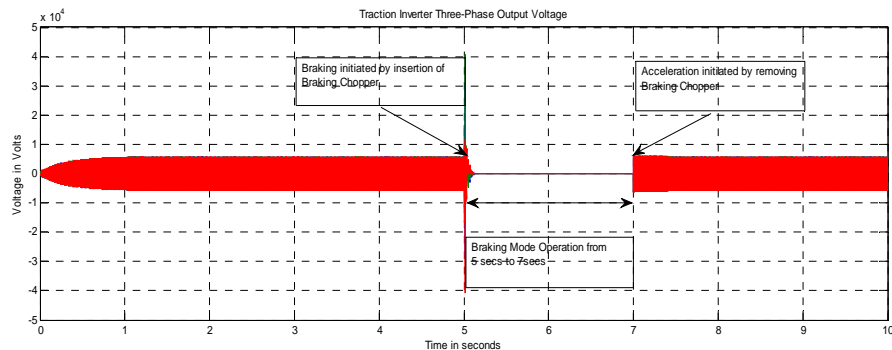


Figure 4. Traction Inverter Three-Phase Output Voltage Waveforms

The Phase-Phase Voltage was 4500 V and the current was 100 Amp continuous. The Braking Chopper was pulsed at $t=5$ 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 $t=7$ 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 3000 rpm. The speed observed for the Traction Motors in continuous mode of operation was 2900 rpm with minor oscillations. With the introduction of the Braking Chopper at $t=5$ seconds, the speed dropped to zero. The Motors accelerated again to near rated speed after the Braking Chopper was removed from the circuit at $t=7$ seconds. The Speed curve of the Traction Motors is shown in Figure 5.

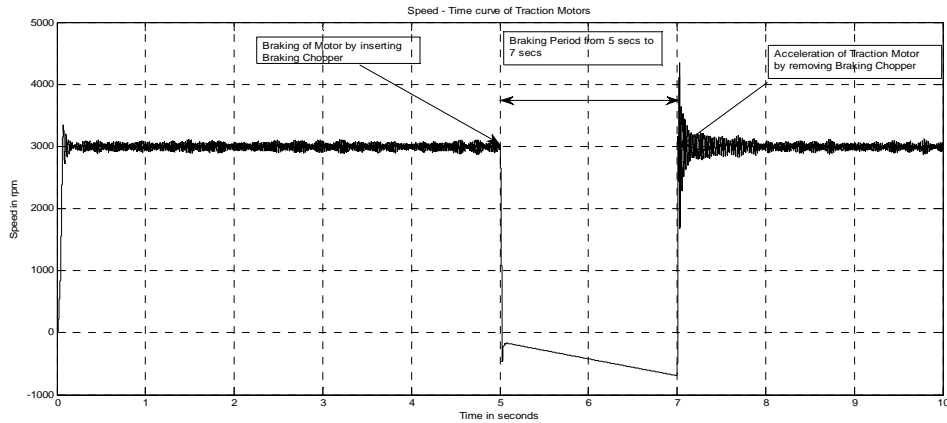


Figure 5. Speed of the Traction Motors

5.4. The Auxiliary Converter Output

The Three-Phase Rotor output Voltages of the Traction Motors were fed to the Three-Phase Auxiliary Rectifier. The Rectifier was a Diode Rectifier and hence there was no bi-directional flow of current. The Three-Phase Rotor Voltages of the Traction Motors are shown in Figure 6. The Phase – Phase Voltage of 300V was observed. The Capacitor Bank in the DC Link of the Auxiliary Converter of the capacity 815 μ F filtered out the harmonics and also boosted the DC Link Voltage to 400V. The Three - Phase IGBT Auxiliary Inverter developed a Voltage of 450V ph-ph and this was fed to the Blower Motors.

Six Squirrel Cage Motors were connected to the circuit in two sets of three Motors each. The Blower Motors could achieve the rated speed of 1500rpm in about 4.5 seconds during which the Traction Motors accelerated to 3000rpm. The continuous speed observed for the Blower Motors was 1490rpm. As expected from the theoretical calculations, the Slip Power recovered from the Traction Motors was able to drive the Blower Motors with the Blower Motors achieving the desirable rated speed.

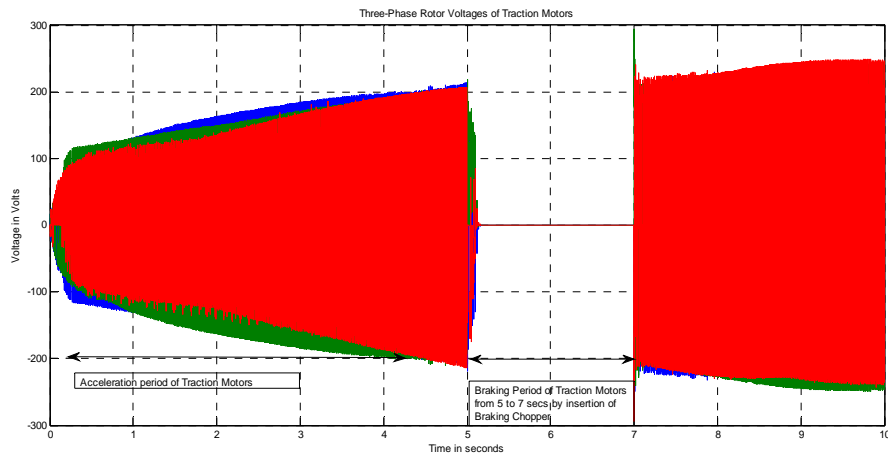


Figure 6. Three – Phase Rotor Voltages of the Traction Motors

The Speed Curve observed for the Blower Motors when Braking Chopper was introduced in the Traction Converter system is shown in Figure 7. It was observed that the Blower Motors took longer time duration to reach the steady state speed and rated speed as compared to the time duration taken when there was no Braking Chopper in the circuit. The Blower Motors took 15 seconds to reach the near rated speed of 1490rpm with Braking Chopper.

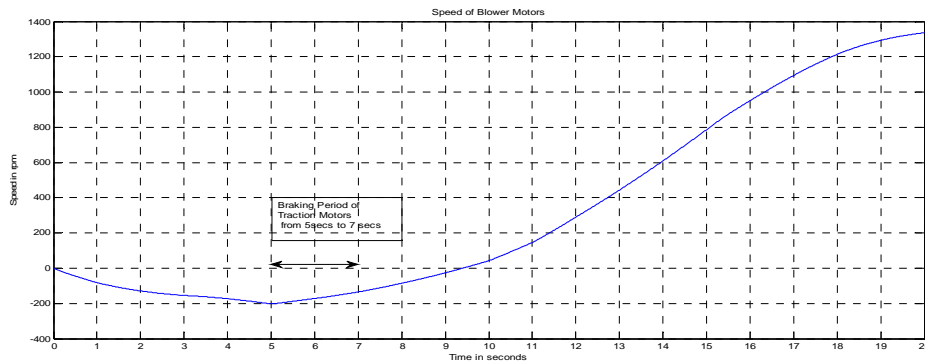


Figure 7. Speed of the Blower Motors in rpm with Braking of Traction Motors

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):

$$F_a = 277.8 W_e \alpha \text{ Newtons} \quad (1)$$

Tractive Effort to overcome Gravitational Pull (F_g):

$$F_g = 9.81 W.G \text{ Newtons} \quad (2)$$

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

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

Tractive Effort required to overcome Curve Resistance (F_c):

$$F_c = 9.81 W \left(\frac{700}{R} \right) \text{ Newtons} \quad (4)$$

$$\text{Total Tractive Effort} = F_t = F_a + F_g + F_c + F_r \quad (5)$$

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 1500 tonne to 120 Km/h in 400 seconds.

(a) Calculation of Tractive Effort:

Acceleration, α in Km/phs will be given as, $\alpha = \frac{120}{400} = 0.3 \text{ Km/phs}$

Weight of the Locomotive = $W_l = 123$ tonnes

Weight of the Trailing Load = $W_t = 1500$ tonnes

Total Weight = $W = (W_l + W_t) = 1623$ tonnes

Effective weight of Locomotive and Trailing Load = $W_e = 1785.3$ tonnes

Tractive Effort required for Acceleration = $F_a = 277.8 \times 1785.3 \times 0.3 = 149 \text{ kNewton}$

(b) Calculation of Power, Torque developed:

Outputs from the Embedded MATLAB function,

Torque developed by one Traction Motor = 13240 Nm

Air-Gap Power of one Traction Motor = 840 kW

Slip = 0.03

Slip – Power of one Traction Motor = $0.03 \times 840 \text{ kW} = 25.2 \text{ kW}$
 Tractive Effort developed by one Traction Motor = 30 kN
 Rotor Voltage developed at the Rotor of Traction Motor = 300 V
 Output Voltage of Auxiliary Converter = 450 V
 Power consumed by each Blower Motor = 15 kW

If the Locomotive works for 15 hours a day and maintains the rated speed for atleast 10 hours during running, the Slip-Power energy recovered will be $S_p = 10 \times 15 \text{ kW} = 150 \text{ kWh}$ per Traction Motor.

For a period of 300 days of running of Locomotive in a Calendar year, the total Slip-Power energy recovered will be $S_{p\text{total}} = 6 \times 150 \text{ kWh} \times 300 \text{ days} = 270000 \text{ kWh}$.

One Unit of energy is sold at an average of Rs. 8 in India and hence the amount of money saved by Slip-Power Recovery Scheme would be = $8 \times 270000 = \text{Rs. } 2160000/-$ per annum per Locomotive.

For a Fleet of 2000 Electric Locomotives, the amount of money saved would be = $2000 \times 270000 = \text{Rs. } 54,00,00,000/-$ per annum

Table 1. Traction and Blower Motors Parameters:

S. No	Parameter	Traction Motors	Blower Motors
1.	Rated Voltage	3000 V	400 V
2.	Rated Power	900 kW	15 kW
3.	Operating Frequency	50 Hz	50 Hz
4.	Efficiency	95 %	95 %
5.	Power factor	0.85 lag	0.85 lag
6.	No. Of poles	2 poles	4 poles

7. CONCLUSION

From the Simulation studies carried out with MATLAB for the above proposed circuit, it can be concluded that the use of a Wound Rotor Induction Motor would result in enormous amount of savings in energy. As the Slip-Power recovered from the Traction Motors will be able to drive the Blower Motors, the use of power drawn from the Over-Head 25kV supply through Auxiliary winding of Main Transformer for driving the Blower Motors can be reduced resulting in reduction of cost of buying Power from the Distribution Companies. Though the initial cost of the Wound Rotor Induction Motor and the required enhanced circuitry may be high, it can be recovered in few years time during the life of a Locomotive, which is about 40 years. This scheme can be further studied and implemented as the future technology for Electric Traction Systems in India, where the Railways are aiming at cost cutting initiatives to enhance the profitability of running the whole network.

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