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EFFICIENT UTILISATION OF REGENERATIVE BRAKING IN RAILWAY OPERATIONS

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Abstract - *Regenerative braking is an energy recovery mechanism which slows down a vehicle by converting its kinetic energy into electrical energy that can either be used immediately or stored for future use. In Indian Railways at present, WAP-5, WAP-7 and WAG-9 class of 3-phase locomotives are capable of saving upto 20% and 3-phase electrical multiple units (EMU) are capable of saving upto 30% energy through regenerative braking. Currently, the regenerated energy is fed back into the OHE and is utilized only if the OHE is receptive i.e. if there is a train load present in the section. This immediate energy exchange between trains needs cooperative operation between the braking and the accelerating trains. However, if there are no other accelerating trains when trains are braking, the regenerative energy will increase the voltage of the OHE to a high level until the tolerable voltage limit is reached. Then, the following regenerative energy will be wasted at the braking resistance to protect the power network. Secondly, the distance between the traction and braking trains should be short to achieve a high efficiency. Furthermore, the drivers of the cooperative trains should apply traction and braking at the same time. But in the present scenario of Indian Railways, there are mixed train operations, where the same line is utilised by Semi-High speed, Passenger and Goods trains. Hence, the traction and braking trains are very difficult to be matched in the time, space and driving strategy. Further, any energy produced above 30% through regenerative braking by 3- phase locomotives is not usable currently in Indian Railways, and is dissipated rheostatically in the form of heat. An effort has been made through this paper to study the utilisation of more than 30% regenerative braking energy to meet station lighting and colony electricity load requirements by suggesting Energy Storage Systems and proposing the development of a smart grid to give back the excess electricity to the grid; thus partially cutting down the electricity load requirements in coal powered thermal power plants, and subsequently helping in minimization of carbon emissions and reducing the energy bill of Indian Railways. The performance of a scaled down AC/DC/AC induction motor drive that is currently being used in Indian Railways has also been investigated in this paper using MATLAB/Simulink.*

Key Words: *converter, induction motor, synchronous link converter, energy storage devices, PWM technique, vector control.*

1. INTRODUCTION

Indian Railways is considered as the lifeline of the nation. It traverses the length and breadth of the country providing the required connectivity and integration for balanced regional development. It is an integral part of the national development. Indian Railways has one of the world's largest railway network, with 117,996 track kilometers (66,030 route km) connecting 8073 stations. In 2014-'15 Indian Railways transported 8.39 billion passengers to their destinations, i.e. more than 23 million passengers a day. In addition, it transported around one billion tons of freight across length and breadth of country. Currently, 35% of total freight traffic (in terms of ton-kilometers) of country moves on rail. Further, share of Railways in certain core infrastructure sectors such as coal, power, steel, cement and in other critical sectors like fertilizer is as high as 70%. But during the last several decades Indian Railways has suffered a huge loss in the share of passenger and freight traffic. At the same time railways has been very slow in terms of capacity augmentation. According to the National Transport Development Policy Committee Report 2013, Railways has grown only 20.27 % in terms of route kilometers during 1950-51 to 2010-11, while during the same time duration highways network has grown 1072 %.

Indian Railways currently has 4160 conventional AC and 1167 3-phase AC traction locomotives, along with 6111 diesel traction locomotives. 116 energy efficient AC/DC rakes with 3 Phase IGBT propulsion systems have already been introduced in Mumbai Suburban area with regenerative braking features since 2007. In Western Railway the total energy regeneration of 64 EMU rakes with regenerative braking is 82.6 million kWH per Annum and the total saving is approx. 65.39 crore per Annum. In Central Railway the total energy regeneration of 52 EMU rakes with regenerative braking is 66.7 million kWH per Annum and the total saving is approx. 53.35 crore per Annum. At present Indian Railways consumes about 43.01 MWh per day for electric traction operations, out of which only 2.12 MWh energy per day is generated by using regenerative braking in Indian Railways. This energy is wholly used for meeting traction requirements and at present is not utilized for meeting non-traction electricity requirements.

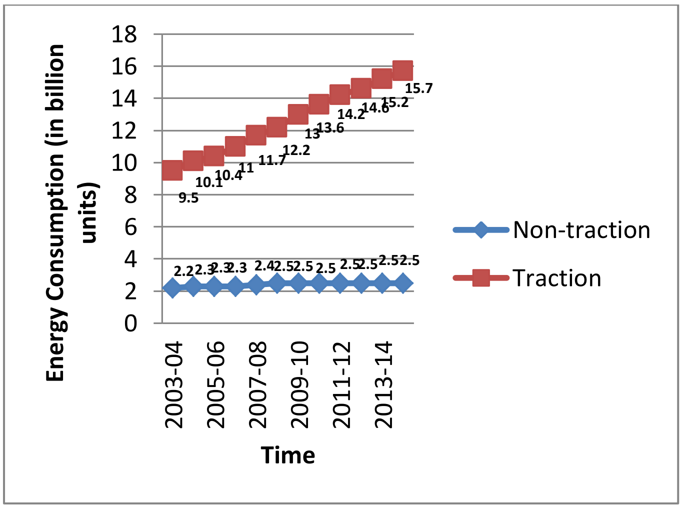

Fig 1: Energy Consumption for Traction and Non-Traction Applications (Source: Mission 41K document, Indian Railways)

Around 6.84 MWh energy per day is consumed by non-traction sources over the 8073 stations, colonies, manufacturing workshops and maintenance depots that we have in Indian Railways. So if no train load is present in the section to utilize the regenerative braking energy, we can store this energy with a stationary electrical storage system (SESS), and reutilize it for the power supply of electric and thermal consumers in a railway station with the help of a microgrid. The idea is to store train braking energy in hybrid storage system (composed of batteries and super-capacitors cells) and to reuse it judiciously at different moments of the day (during peak or low energy consumption hours) to cater various kind of station loads.

1.1 Braking Principle:

Braking is used to control the speed of the running vehicle or to bring it to a dead stop or to prevent a parked vehicle from rolling down. The brake used in railway vehicles can be classified according to the method of their activation into following categories.

- Pneumatic Brake
- Mechanical Brake
- Electromagnetic Brake
- Electrodynamic Brake

Pneumatic Brake may be further classified into two types

- Vacuum Brake
- Compressed air brake

Pneumatic brake is a kind of friction brake in which compressed air presses on the piston that applies pressure on the braking pad. Vacuum brake is no longer used as it has many limitations like fading of brake power, pressure gradient in long trains, longer emergency braking distance etc.

Mechanical braking systems use: wheel tread brakes, axle-mounted disc brakes and wheel-mounted disc brakes. These brake mechanisms use a brake shoe that applies friction force to the disc. In wheel-tread brake, friction force is applied to the wheel tread by the brake shoe thus creating a sliding effect. Such type of brake is not suitable for high-speed trains because doing so may damage the wheel tread. Therefore, axle- or wheel-mounted disc brakes are used in high speed trains. Axle-mounted disc brakes require sufficient space therefore they are used in trailer bogies. Wheel mounted disc brakes are used on motor bogies because they have to accommodate the traction motor only and have insufficient space for an axle-mounted brake. Each disc brake set consists of two pairs of brake pads which press against both sides of a brake disc. The discs are usually made of steel, but they can also be made of an aluminium alloy to save weight.

An electromagnetic brake system does not depend on adhesion between the wheel tread and the rail. It produces a braking force by using magnetic repulsion obtained from eddy currents generated on the top surface of the rails. Thus it is suitable for high speed operations where adhesion decreases as speed increases.

The electrical brakes are either rheostatic (dynamic braking) or regenerative which produce brake force by using the traction motors as generators. In both the cases a braking torque on the wheel axle is produced, which in turn produces a braking force between the wheels and rails. In rheostatic braking the kinetic energy of the train is dissipated as heat in resistors whereas in regenerative braking the electrical energy can be returned to the OHE and used by other trains present in the same section or sometimes it is even possible to feed it back to the public grid. One of the main advantages of regenerative brakes is thus the possibility to re-use the electrical energy that otherwise would have been wasted as heat when using either rheostatic electrical brakes or mechanical brakes. Thus regenerative braking benefits both the environment by reducing the demand of energy from the public grid and the economy for the operator by prolonging the maintenance intervals on account of reduced wear of the mechanical brakes. All the conventional AC traction and diesel locomotives of Indian Railways are fitted with rheostatic braking system, and all the 3-phase AC traction locomotives and 3-phase EMUs are fitted with regenerative braking system.

Regenerative braking occurs when the speed of the rotor is more than the synchronous speed i.e. speed of the rotating air gap field. This reverses the direction of the rotor electro motive force and rotor current. When fed from a source of fixed frequency, regenerative braking is possible only for speeds above synchronous speed. With variable frequency drives, regeneration can be obtained at speeds lower than synchronous speed.

2. LITERATURE REVIEW

2.1 Review of Application of Energy Storage Devices in Railway Transportation (Nima Ghaviha, Javier Campillo, Markus Bohlin, Erik Dahlquist et al.)

The energy storage technologies used in railway industry can be divided into two categories based on their applications: on-board (OESS) and stationary (SESS) energy storage systems. OESSs are those installed inside the train. The power and energy capacity of OESSs are lower than SESSs as they are used to store the recovered energy of only one train. The sizing of the storage device (especially in case of EMUs) and safety issues (especially on passenger trains) are two critical factors in the selection of on-board energy storage device. Storage devices can be used on-board railway cars for three main purposes: energy consumption reduction, peak power reduction and catenary-free operation. Supercapacitors, batteries and flywheels can be used in railway as both SESS and OESS.

1. Supercapacitors: Supercapacitors are great choice to be used as a secondary energy source onboard electric trains due to their high power. The high power allows the train to save most of the surplus of the regenerated energy and their long lifecycle reduces the cost. Experimental results from application of supercapacitors on board a light rail vehicle in Germany shows 30% energy saving. Other than electric trains, supercapacitors have also been used onboard hybrid diesel-electric multiple units. These trains use diesel generators for an electrical traction system. Studies on the application of a supercapacitor-based storage system in a DMU in Germany shows a significant improvement in energy consumption, CO_2 reduction and cost reduction.

2. Batteries: Batteries experience less voltage fluctuations as well as low self-discharge rates as compared to supercapacitors. They can also provide higher energy capacity which makes them more suitable for a SESS rather than an OESS. Batteries have shorter life cycle thus in this respect they are disadvantageous as compared to supercapacitors for application as OESS. But they are the only storage systems that are used as the main energy source for long distance catenary free operation of modern EMUs. Hybrid EMUs that can run on electrified lines using overhead lines, as well as non-electrified lines using the batteries.

3. Flywheels: Application of flywheels as ESS is older than batteries and supercapacitors. Flywheels have been in use as SESS in Japan since 1970 with the reported energy saving of 12%. Flywheels of 300kW and 1MW have also been put in application in UK and US for DC metro lines, respectively. The results show that the proposed flywheel can switch between generation and motoring mode within 5ms and needs minimal maintenance. Flywheels have also been studied to be used as OESS. A recent study on application of flywheels on board heavy haul locomotives suggests that such storage systems are more beneficial than batteries for this application due to the batteries limitations of power, cost and service lifetime.

2.2 Running control of the super capacitor energy-storage system (Jisheng Hua, Yinhai Fan, Qingsheng Feng et al.)

The supercapacitor energy storage system consists of DC link, motor driver (inverter), motor, energy-storage converter and the buffer link between the converter and the DC link. The circuit works in the Buck mode when the motor brakes and the electrical energy is transmitted from the motor driving system to the energy storage converter system through the buffer circuit and it works in the Boost mode when the system enters driving condition, the energy stored in the supercapacitor is transmitted to the DC link through the buffer link and is used by the motor.

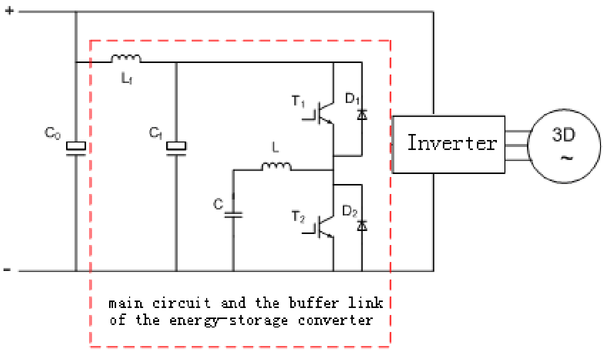

Fig 2: Supercapacitor Energy Storage System

When the system brakes the voltage of the DC link supporting capacitor C_0 is a little higher than the DC link supply voltage because only when this condition is present the energy from the supply source can be kept out of the DC link and we can ensure that the energy stored is totally generated by the motor during the braking condition. Moreover if the voltage of DC link is not higher than the supply voltage, when the supercapacitor discharges the electric energy consumed by the motor may be partly or totally from the DC source, so the energy in the super capacitor cannot be released in time, besides, the capacitance is limited, so the residual capacity of the super capacitor may be not enough for the next braking, causing the braking energy unrecyclable.

When working in the boost condition, the relation between the input voltage (voltage of the supercapacitor) and the output voltage (voltage of the supporting capacitor in the buffer link) is given by:

$$V_{cf} / V_c = 1/(D_0 + \alpha D_0),\ D_0 = 1-D$$

where *D is* the conduction ratio when the circuit is in boost condition and α is the ratio of inductance and switch resistance to the equivalent resistance of the load. When the system is in braking condition, the energy-storage converter works in Buck mode and the relationship between the input current in the converter and the conduction ratio is given by the following equation:

$$\frac{I(s)}{d(s)}=\frac{[sC\alpha+1][Uc-RsIl]}{s^2LC\alpha+s(L+C\beta)+DRs+R}\ ,\ \alpha=R+R_b,\beta=DRR_s+DR_bR_s+RR_b$$

where R is the equivalent resistance of the load, R_b is the resistance of the super capacitor, R_s is the internal resistance of the converter, D is the conduction ratio.

The output voltage of the converter increases monotonously as the conduction ratio increases. The double close-loop system of voltage and current can ensure that the stable voltage value of the DC link supporting capacitor is a little higher than the DC link supply voltage.

The two factors that impact the stability of the voltage of the DC link supporting capacitor are the current in the load and the discharging current. When the voltage of the DC link is relatively stable, the discharging current of the system changes monotonously as V_{cf} (supporting capacitor in the buffer link) changes which in turn changes monotonously as the conduction ratio changes within the inflection point. So by regulating the conduction ratio, the voltage of the supporting capacitor, V_{cf} and the current in the inductance in the buffer link can be controlled, as a result, control over the voltage of the supporting capacitor C_0 in the DC link is realized. Thus in this way the controller can keep the energy-storage system in control when it releases energy.

2.3 Effect of regenerative braking on energy-efficient train control (Gerben M. Scheepmaker, Rob M.P. Goverde et al.)

The energy consumption in railways can be reduced by the use of energy efficient train control (EETC). The EETC problem is modeled as an optimal control problem over distance and solved using Radau pseudospectral method in MATLAB toolbox General Pseudospectral Optimal Control Software (GPOPS) together with the automatic differentiator INTerval LABoratory (INTLAB). The optimal control consists of a sequence of the optimal driving regimes maximum acceleration (MA), cruising (CR), coasting (CO), and maximum braking (MB). Varying gradient profile, curves, signaling and automatic protection system are not taken into account in the model. Only the total traction energy consumption at the pantograph of a single train is considered, so no transmission losses of the energy (like regenerated energy) are taken into account and no other surrounding trains are taken into account and maximum service braking is considered instead of maximum braking as it is more comfortable for the passengers.

Three different models are compared based on the rolling stock data of NS (Netherlands Railways)

1. EETC with only MeB (mechanical braking),
2. EETC with both MeB and regenerative braking (RB),
3. EETC with only RB.

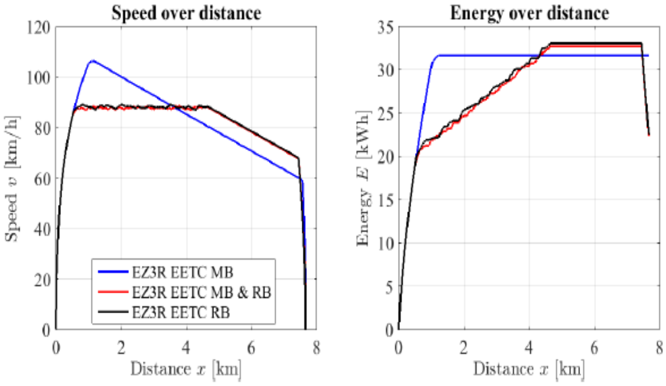

Fig 3: Comparison between the energy-efficient train control (EETC) driving strategies with only mechanical braking (MeB), both MeB and regenerative braking (RB) or only RB of the EZ3R model (left speed-distance graph and right energy-distance graph)

If only mechanical braking is applied, the train is accelerating to a higher speed than when regenerative braking is (also) applied. Secondly when regenerative braking is included, a cruising phase with a lower maximum speed is applied compared to mechanical braking only. The speed at which braking starts with regenerative braking is also higher than with only mechanical braking, since regenerative braking now generates energy. It can be stated that the more energy that can be generated by regenerative braking, the higher the speed at the beginning of the braking phase will be. However, the maximum speed will always be lower than with MeB only, since a cruising phase with a lower maximum speed is included with RB. The differences between EETC with MeB & RB and only RB are minimum. The energy consumption of only RB is slightly higher (1%) which can be explained by the fact that the available braking force with only RB is lower than combining both MeB and RB together. This means the train with only RB starts braking earlier and has a slightly higher cruising speed compared to the braking strategy with MeB & RB. The results indicate that energy savings of 29.5% can be achieved by combining MeB and RB in the EETC compared to EETC with only MeB. The energy savings with only RB are a slightly lower, i.e. 28.8%. With regenerative braking the optimal cruising speed is lower than without, the coasting regime is shorter, and the braking regime starts earlier. This led to an extra energy saving of at least 28%. So it can be concluded that including regenerative braking in EETC has a big influence on the extra decrease in total traction energy consumption.

2.4 Determination of Potential Regenerative Braking Energy in Railway Systems: A Case Study for Istanbul M1A Light Metro Line (Ibrahim Sengor, Hasan Can Kilickiran, Huseyin Akdemir, Beyhan Kilic et al.)

The aim of this study is investigating the potential Regenerative Braking Energy (RBE) of Istanbul M1A light metro line one of the subway lines of Metro Istanbul Co. The voltage levels that are widely used in Turkey are 25 kV AC, 750 V and 1500 V DC. ERSs (Electrical Railway Systems) have a very high investment and operation cost. Hence, ERSs with short payback period are always desirable. The payback period is directly related to regenerative energy potential of ERSs. ERS power system is composed of three main parts. First one is distribution network; the second one is traction substation that includes converter traction transformers with rectifiers and frequency converters if needed. Last part is traction distribution system that is used for energy transmission to train. The energy used for train motion is obtained from other power supply instead of mounted on the train. In Turkey, urban metro lines with short distance are fed from a DC source, as shown in Fig.4.

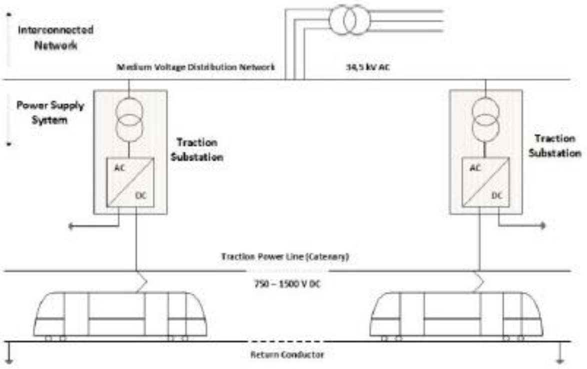

Fig 4: An overview of DC railway power system

In railway systems consumed energy can be categorized under two main topics namely, traction consumption and non-traction consumption. Traction consumption not only energy used for train motion but also energy supplied for an auxiliary load on the train. Non-traction consumption consists of consumption in air conditioning, ventilation, signalization and pumps that used in tunnels or depots. There are three different ways to utilize braking energy. One of the most common methods is timetable optimization; in this method braking train produces energy and accelerating train consume energy from same feeder line. The second method stores the energy by using ESSs. The stored energy can be used by accelerating train. The last method for using RBE is that produced energy can feed back to interconnected network by using reversible substation.

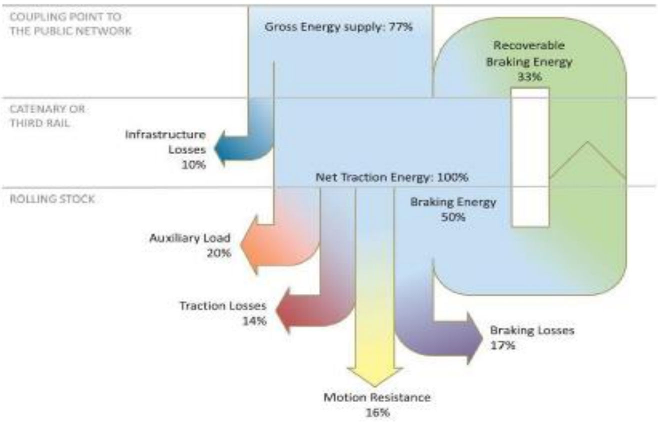

Fig 5: Energy Flow of ERS

Istanbul M1A light metro line is simulated with real data by using RAILSIM simulation program. Average passenger number is assumed as 350 per vehicle and average weight per passenger is taken as 68 Kg. Average dwell time of train at a station is presumed as 25 seconds that is also measured during a journey. Last but not least, it was planned that train would regenerative brake until its velocity decreases to 18 km/h. After train speed is under 18 km/h, mechanical braking process begins and train will stop at the station. Finally, line topology that comprises stations locations, speed limitations, gradient and curve specifications for the M1A light metro line is defined in RASILSIM. After modeling line topology and the train, simulations are run as a single train journey.

Total consumed energy and regenerative braking energy for the first track and the second track can be seen from Fig. 6 during single train journey, the amount of consumed energy is 431.6 kWh, while the amount of regenerative braking energy is 187.3 kWh.

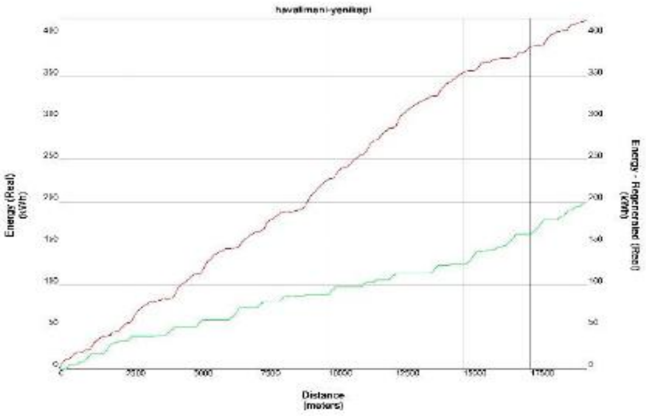

Fig. 6: Consumed and Regenerated Energy for a Journey

As a result of the calculations revealed that 105,54 kWh in first way and 118,13 kWh in second way energy can be regained. And then by using overlap time currently applied by Metro Istanbul Co., energy transfer between the braking and accelerating train with the catenary line are obtained as 31,2 kWh and 17,48 kWh, respectively. In the light of these values, 32% of consumed energy can be compensated from RBE. This also means that $2.2M annual earnings in M1A light metro line, if RBE is used. This study shows that railway system could have great energy saving potential; therefore, new lines should be analyzed carefully before installation to enhance the use of RBE.

3. SIMULATION

In this section MATLAB/Simulink based scaled down model of 25kV AC traction model with regenerating capabilities has been discussed and analysed. The PWM VSI squirrel-cage motor traction drive is shown below. The dc link is supplied from ac source through a transformer and a Synchronous Link Converter (SLC). The diode rectifier is not used because bidirectional power flow is not possible in diode and hence regenerative braking is not possible. Synchronous link converter (SLC) circuit employs IGBT switches and operates at unity fundamental power factor and low harmonic content in source current and gives a fixed DC output with minimum ripple. The output DC link voltage is filtered by the capacitor and fed into three phase inverter that drives the traction.

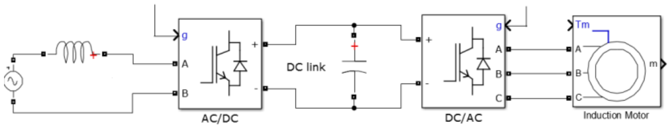

Fig 7: PWM VSI fed induction motor drive

3.1 Control of AC/DC unit:

The converter is operated with outer dc link voltage control loop and inner hysteresis current control loop actions. The dc link voltage is sensed and it is subtracted from the reference voltage and the error is sent to PI controller. A low pass filter is used to remove the ripples in the DC voltage because directly using the DC voltage signal would increase the distortion in the output current due to amplification of the proportional part of the PI controller. The output of the PI controller is peak value of reference current which is multiplied by the unit vector to give single phase reference current. Actual AC current is subtracted from the reference current to obtain the current error. Using the current error the hysteresis current controller generates switching pulses for upper and lower IGBTs. With voltage and current controllers, the dc link voltage is maintained constant and input current is made sinusoidal and in phase with supply voltage.

3.2 Control of DC/AC unit:

The Simulink simulation circuit in which a load torque is changing over time is provided. The current hysteretic band PWM technology is adopted to get the pulse signal to turn on and turn off the IGBT switches. The modulating signal is got by the indirect rotor flux oriented vector control strategy. dq-abc conversion block completes the conversion from dq two phase coordinates to abc three phase coordinates. The abc to dq0 transformation block computes the direct axis, quadratic axis, and zero sequence quantities in a two axis rotating reference frame for a three-phase sinusoidal signal. The rotor position is sensed by a position detector and used in the conversion from dq to abc. Hysteresis regulators regulate the stator currents to generate the driving signals for inverter switches. The motor torque is controlled by the quadrature-axis component of the stator current, i^*_{qs}. The rotor flux is controlled by the direct-axis component, i^*_{ds}. The motor speed is regulated by a control loop which produces the torque control signal i^*_{qs}. The i^*_{ds} and i^*_{qs} current references are converted into phase current references, i^*_a, i^*_b and i^*_c for the current regulators. For generating inverter gate pulses hysteresis current controller is implemented.

4. RESULTS

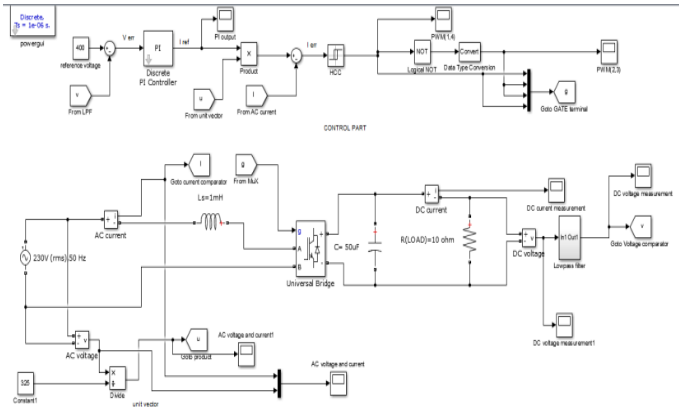

Fig 8: AC/DC unit and its control part

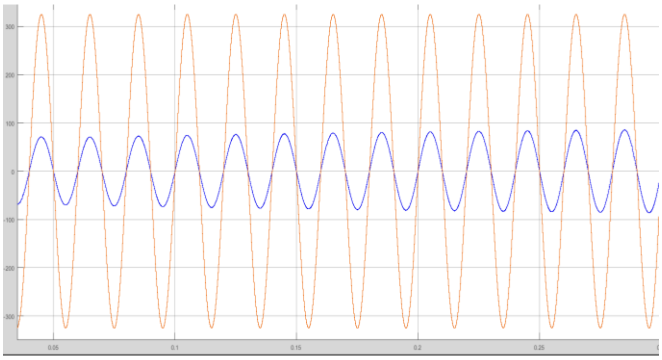

Fig 9: Source side AC Voltage (red) and Current (blue)

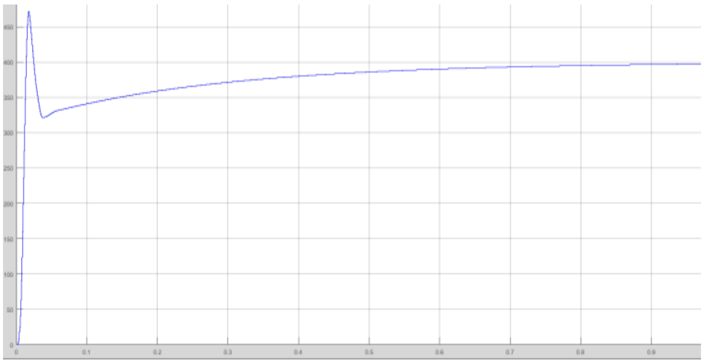

Fig 10: DC link voltage

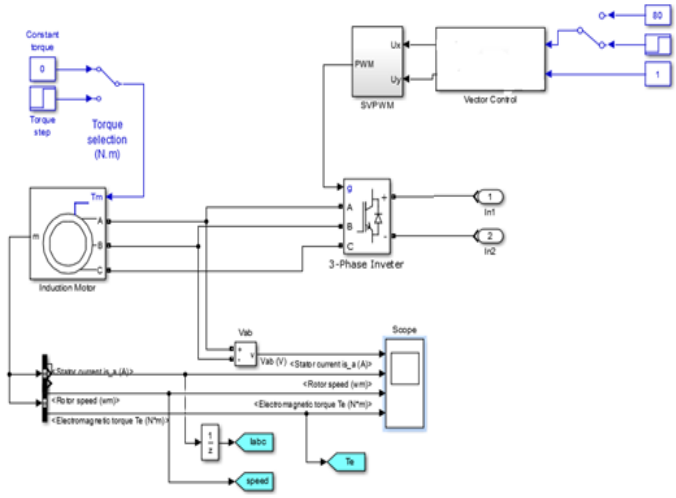

Fig 11: DC/AC unit and its control part

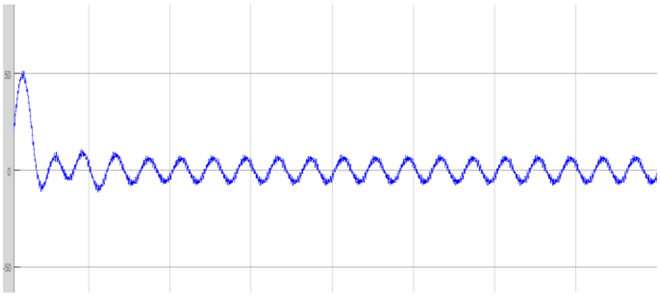

Fig 12: Stator current in phase A

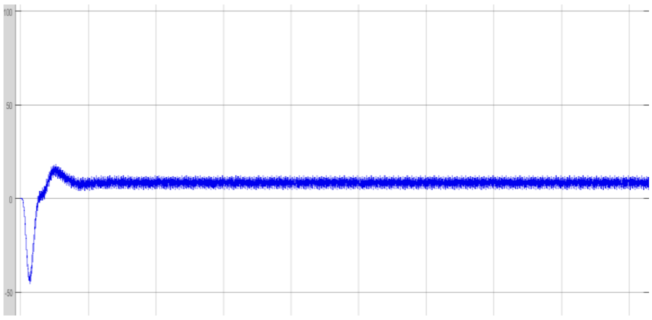

Fig 13: Electromagnetic Torque

5. CONCLUSIONS

1. From the above simulation results, it can be observed that by adopting the classical dual close-loop control method with inner-loop hysteresis current control and voltage outer-loop control of the rectifier we can obtain unity power factor, low harmonic content in the source current and a constant DC link voltage.

2. Vector control method of the inverter adopted in this study offers independent control of the flux and torque, better dynamic performance and long term stability of the system.

3. This paper has described the features and benefits of using on-board and wayside absorption of regenerative electric power using energy storage systems. At present in Indian Railways the regenerated energy is utilized only if the braking and the accelerating trains are in the same section. Adoption of ESS can significantly help in reducing bill cost and minimization of carbon emissions. Simulation of a hybrid system with on board energy storage devices can be done in the future.

4. To reduce the dependence on coal the regenerated energy can be stored in wayside energy storage systems that can be used to provide power to the railways platforms and colonies. Therefore a micro grid having energy storage devices can be simulated in the future.

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