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DC Feeder Voltage Control Strategy of Bidirectional DC to DC converter for Railway Traction

Sachin V. Kale, N. R. Bhasme

***Abstract:** The regenerative energy which is generated during the period of braking of railway traction increases voltage of DC feeder line which makes it crucial and important to consider. Regenerative energy storage system is one of the key solutions to use regenerative energy more effectively and efficiently. Super capacitor has advanced version of the conventional capacitor because of its instant charging and discharging, making it suitable to use as energy storage device for traction system. In this paper, operation of half bridge type bidirectional DC-DC converter for both running and braking operation of traction motor is modeled & simulated and performance analysis is carried out. During charging mode of supercapacitor this converter works as buck converter and during discharge works as boost converter to control the DC feeder voltage at appropriate levels.*

Keywords*: bidirectional DC-DC converter, traction motor, supercapacitor.*

I. INTRODUCTION

All over the world, reduction of CO_2 emission for improving global environment is main concern for the researchers now a days. Earlier railways used petroleum as a fuel to run railway which emits harmful gases like CO_2, nitrogen into the atmosphere. In the year 1887 traction system is introduced in the railway. Due to use of traction system, requirement of petroleum is reduce resulting reduction of pollutant emission in atmosphere. This promoted, implementation of electric traction system which becomes more eco-friendly by using proper braking energy recovery system.[1]

In a traction system, a large amount of power is taken from the overhead lines, in order to operate it. In the traditional method, the regenerative energy is wasted in braking resistor in the form of heat. This power consumption also includes various losses and wastage of energy. In the last decades or more, there have been relentless efforts made in order to reduce direct power consumption and utilization of loss of energy or breaking energy again for powering management of traction system. Among the various methods, regenerative braking is more efficient. In this case, during braking region, motor acts as a generator and feed regenerative energy back to supply. In modern methods of regeneration, the bidirectional Dc to DC converter and energy storage system like battery, supercapacitor, flywheel and hydraulic devices are in use. Considering railways application conditions, frequent start up process have occurs only for several seconds and require higher power during that time. Therefore Supercapacitors and flywheels are becoming best options for regenerative energy storage systems. Super capacitor has a capacity of instant charging and discharging but it has disadvantage of having higher cost and low rated voltage capacity. Bidirectional DC to DC converter is connected between DC feeder and energy storage system. By the buck- boost operation, bidirectional converter could control the charging and discharging operations of supercapacitor. During the braking, braking energy will be stored in the supercapacitor by Bidirectional DC/DC converter which works as Buck converter and during acceleration process or reduction of feeder voltage, supercapacitor discharging through same converter which work as boost converter. [1]

II. SYSTEM DEVELOPMENT

The basic block diagram of DC feeder voltage control strategy of DC to DC converter using super capacitor for traction system as shown below Fig.1

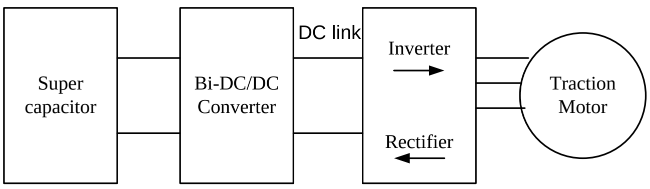

Fig. 1 Block diagram of traction system with Supercapacitor

Supercapacitor, DC feeder, Bidirectional DC to DC converter, inverter, rectifier and traction motor are main elements included in this system.

A. Bidirectional DC-DC Converter

The regenerative power which is generated by induction machine during the time of braking. increased DC feeder voltage.

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Thereby it disturbances in system. So it is very important to control that regenerative energy to keep the DC feeder voltage constant which is done by bidirectional converter through Charging and Discharging operations of supercapacitor.

In this paper high power non isolated half bridge type bidirectional DC-DC converter is modeled and simulated. This converter has low inductance and capacitance values and also has low rated voltage. During charging mode of supercapacitor, converter works as buck converter and during discharging its works as boost converter to control the DC feeder voltage at appropriate level. Gate controlled signal of power semiconductor switches (S1 and S2) are controlled by PI controller to operate the bidirectional DC-DC converter in buck and boost mode. In case of buck mode, duty ratio is below 0.5 and In Boost mode, it operates above 0.5. Prototype design as shown in Fig.2. [3]

The Converter operates in following two modes

- Charging Mode
- Discharging Mode

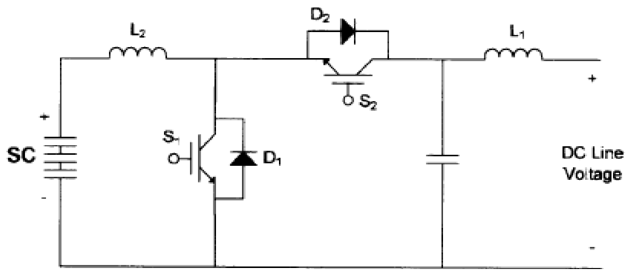


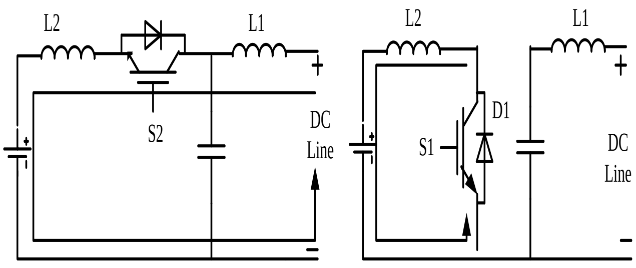
Fig. 2 Half bridge bidirectional DC to DC converter

- **Charging mode**

The regenerative energy of induction machine increases DC line voltage, In this case, converter works as buck converter and power flow from DC line to supercapacitor. During buck mode operation, switch 2 operates as active switch and switch 1 operate as diode. Charging mode of converter is shown in fig 3 and output waveform in charge mode shown in Fig.4. According to voltage balance law, we get equation 1 and duty ratio of converter is as per equation 2

$$(V_0 - V_S) = (1 - D) \tag{1}$$

$$D = \frac{V_S}{V_0} \tag{2}$$



(a)$0 \leq t < t_{on}$ (b)$t_{on} \leq t < T$

Fig. 3 Operation of DC-DC converter during charge mode

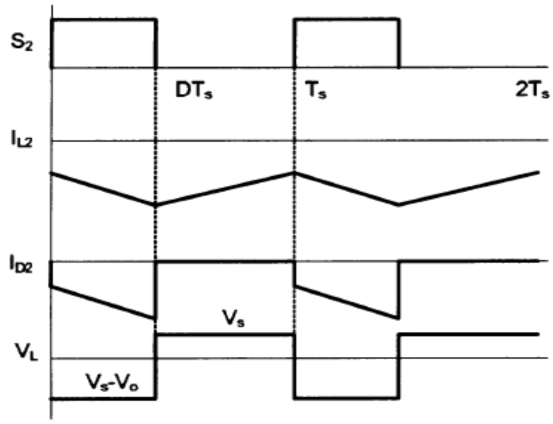


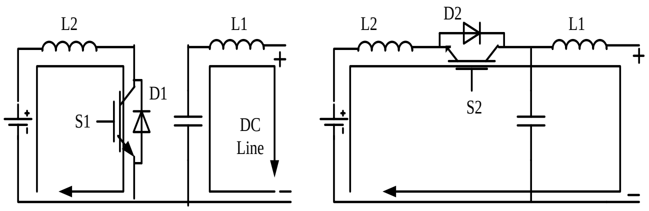
Fig. 4 Output waveform of charge mode

- Discharging mode

During starting or acceleration of induction machine, it takes more power from DC feeder which cause decrease in voltage. In this case, converter works as boost converter and supply stored energy of supercapacitor to DC feeder to maintain its voltage constant. During boost mode of operation, Switch 1 operates as active switch and switch 2 operate as diode. Discharging mode of converter is shown in Fig 5 and output waveform of discharging mode shown in Fig. 6. According to voltage balance law, we get equation 3 and duty ratio of converter is as per equation 4. [6]

$$V_S D T_S = (V_0 - V_S) = (1 - D) \tag{3}$$

$$D = \frac{V_0 - V_S}{V_0} \tag{4}$$



(a) $0 \leq t < t_{on}$ (b) $t_{on} \leq t < T$

Fig. 5 Operation of DC-DC converter during discharge mode

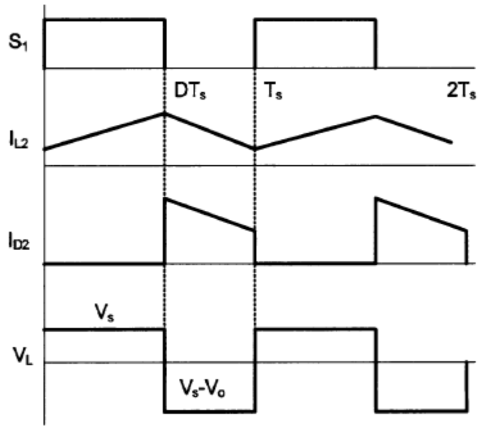


Fig. 6 Output waveform of discharge mode

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B. Supercapacitor

The supercapacitor also known as Ultracapacitor with high value of capacitance but with lower voltage limits. It is used in application where rapid charging and discharging processes takes place. N number of cells can be connected in series and parallel to form super capacitor.

Lets assume that N cells cascaded in series and parallel to form supercapacitor unit. The capacity of supercapacitor is given by, [7]

$$C_{\sup-c} = \frac{C_{cell} \times N_{parallel}}{N_{series}} \tag{5}$$

Supercapacitor with following specifications is used for modeling & simulation purpose in this paper.

Table- I: Supercapacitor parameters

Parameter	Value
Capacity	99.5 F
Rated voltage	370 V
Initial voltage	350 V
Series capacitors	18
Parallel capacitor	1

$$R_{\sup-c} = \frac{R_{cell} \times N_{series}}{N_{parallel}} \tag{6}$$

Where,

C_{Cell} - Cell capacity

R_{cell} - Cell Resistance

$C_{\sup-c}$ - Capacity of Supercapacitor

C. Traction motor

The traction system in general supplied by multilevel substations and AC to DC converter which converts high voltage AC to 1500 V DC. This DC voltage again fed to the DC to AC converter to drive railway traction motor. [8]

AC induction motor is used as a traction motor which is multivariable, nonlinear and easy to use as a generator during braking operation. The rating of induction motor is 400 V, 50 Hz, 4 poles is considering for modeling and simulation. Stator and rotor of motors consists three winding. In case of motoring its runs at 1450 rpm and in case of braking it runs at 1550 rpm.

$$V_{abc} = R_{abc} i_{abc} + p\phi_{abc} \tag{7}$$

Where, $V_{abc} = [U_{sa} U_{sb} U_{sc} U_{ra} U_{rb} U_{rc}]^T$

$$i_{abc} = [i_{sa} i_{sb} i_{sc} i_{ra} i_{rb} i_{rc}]^T$$

$$R_{abc} = diag[R_s R_s R_s R_r R_r R_r]^T$$

$$\phi_{abc} = [\phi_{sa} \phi_{sb} \phi_{sc} \phi_{ra} \phi_{rb} \phi_{rc}]^T$$

$$T_e = -n_p L_m (i_{sa} i_{ra} + i_{sb} i_{rb} + i_{sc} i_{rc}) \sin\theta + (i_{sa} i_{rb} + i_{sb} i_{rc} + i_{sc} i_{ra}) \sin(\theta + 120) + (i_{sa} i_{rc} + i_{sb} i_{ra} + i_{sc} i_{rb}) \sin(\theta - 120) \tag{8}$$

Equation of movement

$$T_e = T_1 + \frac{J}{n_p}\frac{dW_\theta}{dt} + \frac{D}{n_p}W_\theta + \frac{K}{n_p}\theta \tag{9}$$

Where, Te and Tm are induction motor electromagnetic and load torques.

III. SIMULATION RESULTS

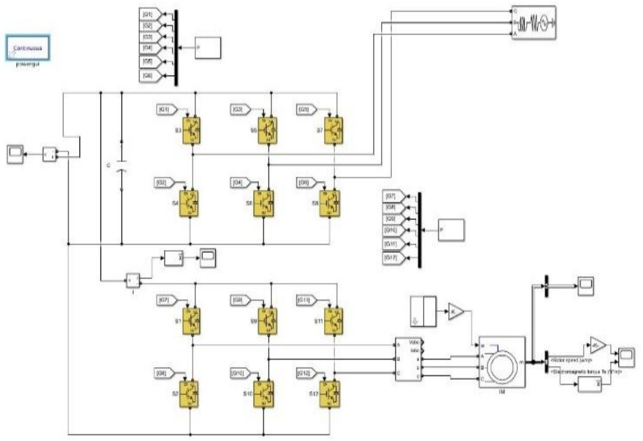

Fig.7 Simulation Model without supercapacitor

- **Without Supercapacitor**

The simulation model without super capacitor is shown in fig.7. The model is simulated for 1.5 seconds in which the motoring mode operates for 0.5 Sec, braking mode operates between at 0.5-1 seconds and then again runs as a motor.

In the braking mode of induction motor, DC feeder voltage increases due to the regenerating energy which causes undesirable dc voltage in feeder.

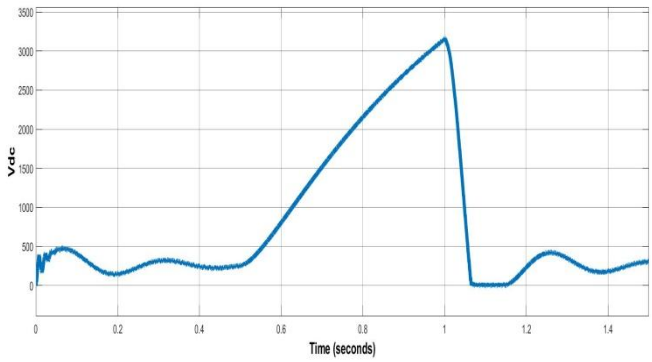

Fig. 8 Feeder Voltage without Supercapacitor

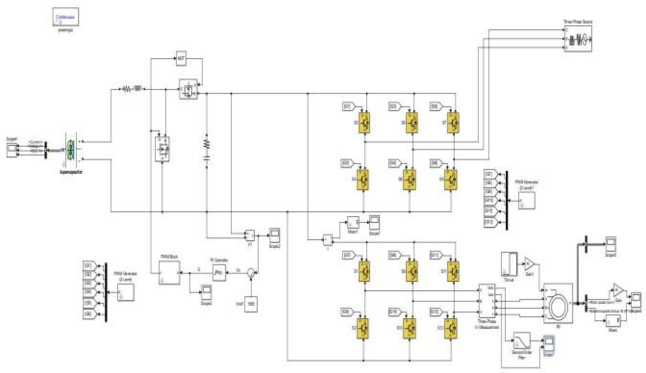

Fig. 9 Simulation model with supercapacitor

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- **With supercapacitor**

The simulation model with super capacitor along with Bidirectional DC-DC converter is shown in fig. 9. The model is simulated for 1.5 seconds in which the motoring mode operates for 0.5 Sec, braking mode operates between 0.5-1 seconds and then again runs as a motor.

In Motoring mode (0.5 Sec), the traction (AC induction) motor runs at 1450 rpm (which is less than synchronous speed) and takes power from DC line voltage, thereby slight dip in DC line voltage. In order to maintain the constant DC line voltage, the converter works as boost converter and releases the energy which is stored in super capacitor.

In braking mode (0.5-1 Sec), the traction motor operates as induction generator (above synchronous speed) and fed reverse power to the DC feeder line which increases its voltage gradually. In order to maintain the constant DC line voltage, converter works in buck converter and starts charging of Super capacitor. Torque speed characteristics of traction motor shown in fig.12. Duty ratio of converter shown in fig 13 and charging discharging process graph supercapacitor shown in fig 16.

Table- II: Conditions of Simulation

Condition	Value(feeder voltage)
Charge	Over the 1500 V
Discharge	Below the 1500 V

- **Frequency range of converter**

The model is simulated over different frequency ranges. When model is simulated under less than 50 kHz frequency shows more ripple in DC feeder voltage. For frequency greater than 50 kHz, the ripple gets reduces.

DC feeder voltage with converter frequency at 1 kHz and 50 kHz is shown in fig.10 and 11 respectively.

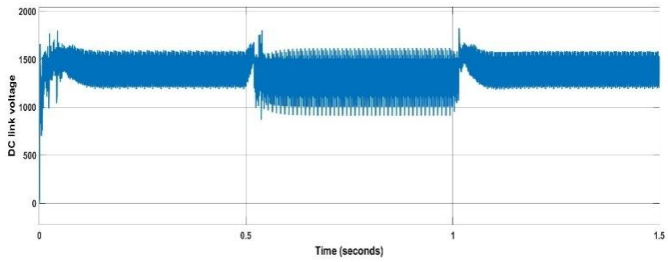

Fig. 10 DC feeder voltage with converter frequency 1 KHz

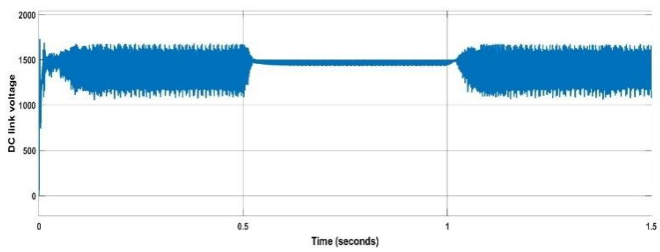

Fig. 11 DC feeder voltage with converter frequency 50 KHz

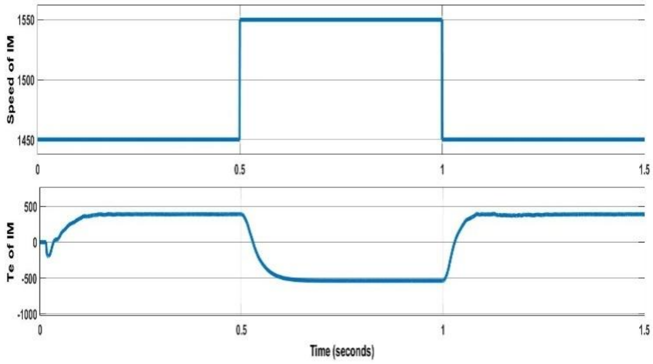

Fig. 12 Speed and Torque of traction machine

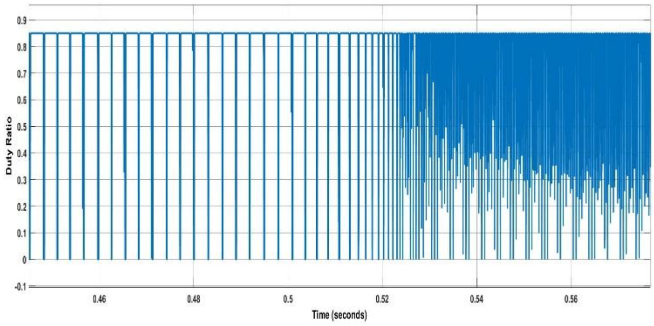

Fig. 13 Duty ratio of converter

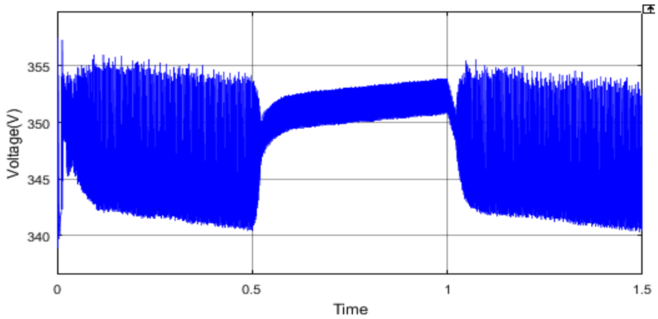

Fig.14: Voltage across Supercapacitor

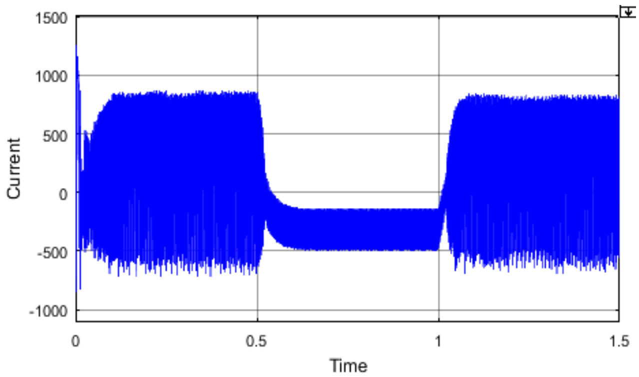

Fig. 15 Current of Supercapacitor

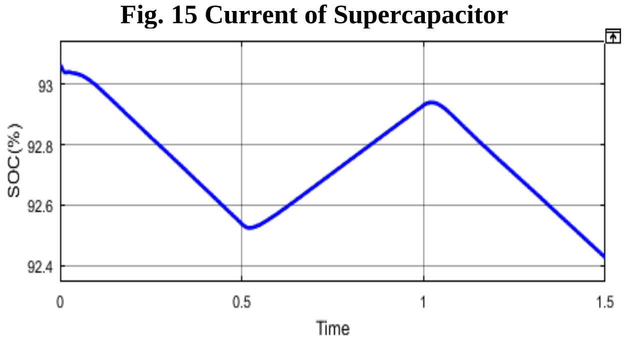

Fig. 16 % State of Charging of Supercapacitor

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IV. CONCLUSION

In this paper, Bidirectional DC-DC converter is designed to maintain DC bus voltage constant, during motoring and braking operations of traction motor with the help of supercapacitor. At the time of braking the regenerative energy of traction motor is stored in super capacitor and reused during motoring operation.

From simulation results it has confirmed that braking energy is not disturbed the DC feeder voltage. It can easily store and reused in super capacitor with the help of buck and boost operation of bidirectional DC-DC converter. The model is simulated for various frequencies to results are studied. It is observed that as the frequency increases, better stability of DC feeder voltage can be obtained. The converter shows better results with proposed model with supercapacitor where its helps in power management of railway traction system.

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AUTHORS PROFILE

Sachin Kale received his Bachelor's Degree from Jawaharlal Nehru Engineering College affiliated to BAMU University, Aurangabad, India in 2017, from Electrical and Electronics Engineering. he is currently working towards her Master's Degree from Government college of Engineering, Aurangabad, India in Electrical Machines & Drives specialization from department of Electrical Engineering, 2019. His interested research areas are Power electronics and electrical drives. He has published Review paper on DC to DC Converters and its Applications for Railway Traction System.

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