E-Bus Based Public Transit System for Indian cities and Its Emission Analysis

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Abstract:
Pollution in the last decade has become a global issue and the planning bodies have been designing various goals to address it. The planning bodies have insisted the countries participating in this global mission to attain the goals in a stipulated time. E-mobility is the most recent approach in almost all these countries in order to reduce vehicular emissions. On contrary, long term implementation of E-mobility will have an adverse effect on the emissions caused by generation power plants. The emissions hence caused is the function of the energy utilized. Hence, it is required to analyze the energy utilized by such E-mobility systems and take measures so that emissions can be reduced to an extent. In this work, various E-mobility systems are considered along with the study of their sub-systems. The work also shows an emission projection using an E-mobility system for an energy generation scenario of India. This is done by calculating the energy utilized by the E-mobility system and then analyzing the emission caused due to generating this energy. Furthermore, the work presents energy acquired by regenerative mode of the vehicle as an idea to efficiently use the electric energy for the purpose of transportation
Keywords: E-bus, emission, regenerative braking, transportation system.

I. Introduction

The population in India has increased due to the mass movement in the urban areas since the 21st century [1]. This movement towards urban areas has resulted in the rapid rise of vehicles in urban cities. As the population continues to grow, the number of vehicles is projected to triple by the year 2035 [2]. These vehicles are the internal combustion engine (ICE) and are the major contributor towards poor air quality [3] in most of the Indian cities. A recent report of the World Health Organization (WHO), India has the 15 most polluted cities in the world these are Delhi, Haryana, Maharashtra, etc. [4]. Air pollution can also cause to generate serious health problems, including asthma, irritation of lungs, pneumonia, cancer [5]. As per the WHO report over 1.25 lakh children in India died in 2016 due to the impact of polluted air [4].

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To overcome the above challenges, shifting the public transportation system from the traditional ICE vehicles system to electric driven vehicles can be a possible solution. The number of studies has proved that electrical driven vehicles are efficient in generating zero pollution in the form of metro systems, trams, trolleybuses, etc [6]. In 2017, the growth of metro systems in Chinese cities was a large contributor to transit in the world, according to the New York based Institute for Transportation and Development Policy. In Europe, almost 75% of the Metro systems have more than 60% of their length underground while some 30% are completely underground [2].

These available electric transit systems are efficient and technically advanced but implementation in India is more complex due to huge energy demand, congested places, and requirement of additional constructions [7]. To address this issue, an electric-based public transportation system (TS) which can satisfy the increasing demand as well as replace the existing system without affecting the present structure can be a possible solution. In [8], such an electric bus TS is proposed which uses a supercapacitor as an on-board energy source. A further study shows that there have been works on energy calculations for the E-bus based transit systems using different types of driving cycles [9]. Additionally, in few reports given that on interconnected solar grid systems with E-bus transit system towards the zero emissions for the public TS [10]. In addition, one more report has focused on various E-mobility bus technologies and grid-connected charging stations of the TS [11].

The thorough study of the above works state that a major question is still unanswered, which is *"What will the effect of the implementation of such a transit system on emissions of the cities?"* The electric-based TS is driven by electricity which will be supplied by various power plants and in India, around 60% of the electrical energy is produced by thermal power plants which are the major contributor to greenhouse gas emissions, specially CO_2 [12]. Hence, the large-scale implementation of such TS will increase the emissions from power plants in the environment. Thus, it is mandatory to give the emission analysis of such TS a check so that the electric-based TS can contribute towards the making of a sustainable society.

In this work, the energy requirements and emission analysis by different E-bus technologies based upon their structure is presented. The different E-bus technologies that are considered in this work are: battery-based E-bus (BEB), battery swap E-bus.

(BSEB) and super capacitor-based E-bus (SCEB). These E-bus technologies are either in installation stage or in project stage world-wide. The energy requirement for these E-bus technologies is calculated and is compared with each other. Based on the energy requirements, emission analysis is done considering two different sources i.e. grid and solar. In order to present the emission comparison on a similar platform, the emission analysis is done for 1 km drive by E-bus in Indian city. The results show that the SCBE needs less energy is compared to E-bus based technology. Hence SCEB technology can be a solution for solving the global warming problem. Further, the energy storage during regenerating is simulated and presented in this work.

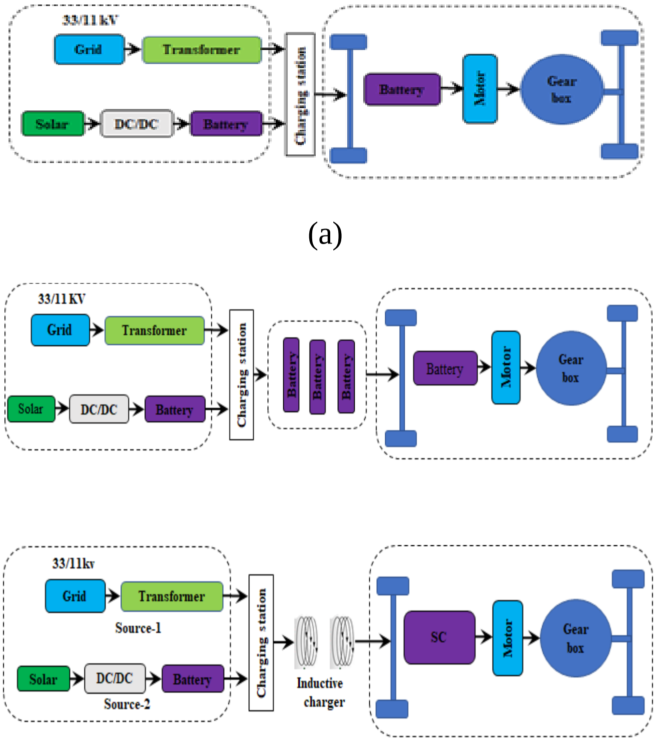
The work has been presented as follows: section 2 shows the structures of the E-bus technologies, section 3 presents the energy calculations for these E-bus technologies. Section 4 presents the emission scenario based on the present energy generation scenario of India. Section 5 presents a concept using which it is shown how the energy is recovered during the regenerative mode of the E-bus and stored in a battery for driving the E-bus. Section 6 presents the simulation model used for regeneration and the results of the analysis. Lastly section 7 presents the conclusion of the work.

II. System Model

In this section different E-bus technologies and their structures are shown in Fig. 1 with grid and solar interconnection. It should be noted that this work does not propose the structures of any of these technologies. The entire infrastructure of the E-bus system has three systems: fuel system, charging system, and E-bus system. The fuel system is connected to a 33/11 kV substation which gets it supply from a 66-kV power plant through step-down transformers. The charging stations are connected to the grid via distribution networks using step-down transformer (11 kV/440 V).

This work aims to implement solar energy as an additional source to drive the transit systems. Hence, distributed solar panels are installed at each charging station. Further, as solar energy is only available during day time, in order to ensure that energy supply is continuous it is required to store it. Therefore, a DC to DC converter is used to store the energy generated by the solar panel in a battery in the charging station.

The work does not present cost analysis and therefore, the sizing of the solar PV system is not presented here. The fuel system is common to all the E-bus technologies as these are driven by electricity. The next subsystem is the charging system (CS) which is equipped with charging technologies which vary for different transit system. The charging technology may be inductive type charging, flash charging and battery swapping.



(a)

(b)

(c)

Fig. 1. Structures presenting the sub-systems of different types of E-bus technologies.

Fig. 1 (a) is representing the structure of the BEB that has been proposed in [13]. The BEB receives the energy from the CS via on-board charger and stored in a 300-kWh battery. The sizing of the battery is considered to be as such that it supplies the electric motor with energy for driving range up to 150 km.

Fig. 1 (b) represents the structure of BSEB that has been proposed in [14]. The batteries in this case can be replaced within a short time and can be charged during off-peak periods in the charging stations. It can be noted that the basic difference between BEB and BSEB is that the battery in case

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of the earlier is larger with respect to the later. This is to ensure that the battery once charged should have enough energy to make the transit system reliable. In the later case, the battery inside the E-bus is swapped/replaced by another charged battery (of same size) from the charging station.

Fig. 1 (c) represents the structure of SCEB that has been proposed in [15]. The supercapacitor is used as the onboard energy storage to drive the E-buses. These supercapacitors are charged from the batteries placed at the charging stations. The supercapacitor is used because of its faster charging and discharging property which makes it suitable for frequent start and stop traffic conditions. The supercapacitors are charged from the batteries via flash charging or inductive charging whenever the bus stops at a bus stop. The energy for a SCEB is stored in an SC to be supplied to the electric motor for driving range up to 150 km. The basic difference between BEB and SCEB is that the battery is kept static in the latter case which helps to reduce the moment of inertia of the E-bus.

III.Energy calculation for different E-bus technologies

The earlier section presented the structure of the E-bus technologies. In this section, the energy calculations for different E-bus technologies for the driving pattern of Guwahati city is presented. Guwahati city is taken as a representation of tier-II cities of India. The energy calculation thus includes the parameters from a driving pattern, the motion of the vehicle and its specifications.

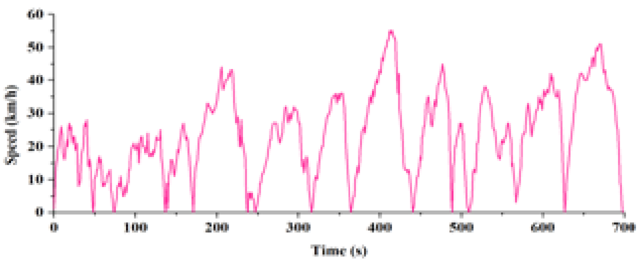

Fig. 2. Speed vs. time graph of the Guwahati city cycle that represents the driving pattern, average speed, etc. of the vehicles driving on the ring road.

A. *Calculation of energy using Guwahati city driving pattern:*

This section discussed about energy calculation for different E-bus technologies. The energy calculation is done by using the Guwahati drive cycle shown in Fig. 2. Following are observation of Fig. 2:

i. The driving cycle is for 700 second and distance travel by this time is 1 km.
ii. The average speed of the cycle is 23.2 km/hr.
iii. The average speed of the cycle is 23.2 km/hr.

The bus specification given in table-1 and the driving cycle are used for energy calculation. Various resistive forces are also considered which will oppose the motion of the EVs in city-driven conditions [9]. The work done against these resistive forces is the energy that accelerates the E-bus. During negative acceleration energy will be recovered by regenerative braking. In this work considered 30% of kinetic energy will be recovered by regenerating braking. These resistive forces are calculated as below:

$$F_{ro} = f_r M g \qquad (1)$$

Where, M (16,200 kg) is mass of the bus, g (9.8 m/s^2) is gravitational acceleration constant, and f_r (0.01) is rolling resistance coefficient. Where $F_{ro}$is a Resistive force.

a. *Aerodynamic resistance:*

$$F_{ar} = \frac{\rho \times v^2 \times C_d}{2} \qquad (2)$$

Where, ρ is a density of air, (in this case, it is taken as 1.184 kg/m^3 at 25^0 C), A_f (6 m2) is a frontal area of the EVs, C_d is drag coefficient = 0.5, and V is the velocity of the EVs.

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c. Acceleration resistance:

$$F_{ac} = \alpha M \frac{dv}{dt} \qquad (3)$$

Where α is rotational inertia constant which is equal to 1.1, M is the mass of bus which is equal to 16,200 kg, dv/dt is the acceleration of the EVs. Since the road angle is zero, gradient resistance is zero.

Table-1: Bus specifications [16]

Specifications	Range
Length	12 m
Width	2.55 m
Height	3.28 m
Travelling Range	120-150 km
Battery range	300 kWh
Number of passengers	40 - 45 nos.

Table-2: Energy required at plug-point to drive 1 km

Forces	BEB	BSEB	SCEB
Rolling resistance	0.17 kW h	0.16 kW h	0.15 kW h
Aerodynamic resistance	0.02 kW h	0.02 kW h	0.02 kW h
Acceleration resistance	1.35 kW h	1.30 kW h	1.28 kWh
Energy recovered during braking	0.32 kW h	0.31 kW h	0.30 kW h
Energy required to drive travel 1km	1.22 kWh	1.17 kW h	1.14 kWh

In order to calculate the required energy of the EV to complete one cycle, it is necessarily required to calculate these forces. Assuming acceleration to be constant in these instants, the distance and acceleration are calculated in very short intervals of time. Given that the acceleration is positive, the engine will run in-spite of these opposing forces. Thus, the work done by the engine is calculated as

$$\text{Work done} = \int f\,(ds) = \Sigma(f)_i(d)_i \qquad (4)$$

Here *f* means force and *d* means distance.

Now the values of the work done calculated against various resistive force is calculated and presented in table-2.

B. Energy required from generating station:

In the previous section the energy calculations of different proposed E-bus transit systems using Guwahati city driving pattern with various resistive forces to drive 1 km distance. In this section discussed about total energy requirement from the power grid to CS plug point and E-bus are considered with work done calculations has been presented.

Furthermore, to calculate the energy requirement from the power grid to EV considered various converter and battery efficiencies are considered. The multilevel inverter efficiency is 96% as per the [17], AC to DC converter have 95% in [17],125HP motor have 95%in [18], battery efficiency is 90% from [19], Both grids connected PV technology have 95% efficiency in [20]. Using these considered efficiencies calculated the energy requirement for different E-bus technologies.

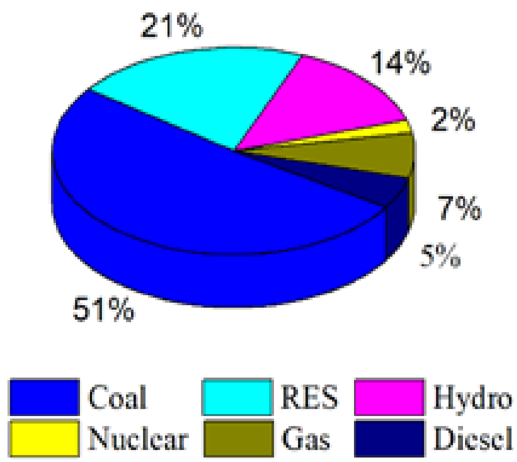

Fig. 3. Energy contribution of power plants

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Table -3: Energy requirements from sources to ensure the energy at plug-point

E-bus	Energy at plug-point	Energy from grid	Energy from solar
BEB	1.22kWh	1.93 kWh	1.69 kWh
BSEB	1.17kWh	1.86 kWh	1.64 kWh
SCEB	1.14 kWh	1.77 kWh	1.51 kWh

Furthermore, the total energy requirement to drive the E-bus for 1km in Guwahati city, total number of components efficiencies are considered for the grid to CS and CS to E-bus system, overall efficiency. Then the efficiency of the power grid to CS is calculated as follows:

Total efficiency $\eta_{overall}$ of the E-bus system is calculated as follows:

$$\eta_{overall} = \frac{\eta_1 + \eta_2 + \ldots + \eta_n}{N} \quad (5)$$

Here $\eta_1 + \eta_2 + \ldots + \eta_n$ is the total no. of component efficiencies of the grid to E-bus system and N is the total no. of components of the system. The energy input E_{input} of the power grid is calculated as;

$$E_{input} = \frac{E_{bus}}{\eta_{overall}} \quad (6)$$

Here E_{bus} is the energy of the E-bus. The total required energy from the power grid to E-bus system with considered 30% energy of auxiliary devices is calculated as follows:

$$E_{total} = E_{input} + E_a \quad (7)$$

Here E_{total} is the total energy required from the grid and E_a is energy of the auxiliary devices. Similarly, the energy requirement from the solar PV system to EV also calculated using E_{bus} is the energy of the E-bus has calculated and total energy requirement from the grid to EV has been described in the table 3.

The energy calculation steps are similar for these E-bus technologies and hence the table 3 shows the energy thus calculated for all these E-buses. It should be noted that the efficiency of the sub-systems that constitute these transit systems will vary with advancement of technology. The advancement intechnology will result in the use of the energy efficiently and hence will reduce the energy requirement with coming years. The next section presents emission projection of these E-buses using the energy calculated in this section.

IV. Emission Analysis

The previous section has presented the steps for calculating the energy requirements to drive these E-buses. This section presents the emission projections for these E-buses using these energy values. It should be noted that as the E-buses are driven by electric energy, there are no tail-pipe emissions from it. The emission that is addressed here is the emission caused from the generating power plants while generating this amount of energy. The generating power plants are major contributor to green-house gas emissions, specially CO_2. Hence, this section presents the CO_2 emission projections for different E-bus systems. The CO_2 emission is calculated from the energy requirement by the E-bus to drive 1 km. The steps for this calculation are:

i. **Calculation of energy required to drive the E-buses for 1 km:** This energy has been calculated and presented in table 2 in the earlier section.

ii. **Calculation of energy to be generated in ensure the energy required for 1 km at the plug-point:** This calculation is done by including the efficiency of the sub-systems that constitute

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the E-bus transit systems (presented in earlier section). To ensure this value of energy at the plug-point, the amount of energy that has to be generated is given in table 3.

The contribution of power plants to ensure energy for 1 km at plug-point: The energy required to drive an E-bus for 1 km has been calculated and presented in table 4.

Table 4: Energy require from different plants to drive 1 km

Power plant	BEB	BSEB	SCEB
	Energy (kWh)	Energy (kWh)	Energy (kWh)
Coal	0.98	0.95	0.9
Hydro	0.405	0.390	0.38
Solar	0.270	0.260	0.25
Nuclear	0.038	0.037	0.03
Gas	0.135	0.130	0.12
Diesel	0.096	0.093	0.09
Total	1.924	1.86	1.77

Table -5: CO_2 emission from different plants to drive 1 km

Power plant	BEB	BSEB	SCEB
	CO_2 emission (kg)	CO_2 emission (kg)	CO_2emission (kg)
Coal	886.85	854.68	845.49
Hydro	47.01	45.30	44.82
Solar	1.08	1.04	1.03
Nuclear	8.10	7.812	7.72
Gas	68.22	65.75	65.04
Diesel	26.055	25.11	24.84
Total	1037.34	999.71	988.96

Hence, in this section emissions analysis is calculated using the present energy contribution which is described in Fig. 3. As per the energy contribution of power plants in India, coal is the major contributor to generate electrical energy for the E-buses. Considering the energy contribution given in Fig. 3, energy required from thermal power plant is calculated for the different E-bus topologies. According to the contributions and the energy required by the E-buses (to travel 1 km), the energy from different power plants is calculated and given in table-4.

The CO_2 emission from there power plants is a function of the energy taken these power plants. Hence the individual power plants the CO_2 emission can be calculated as:

$$EM_{CO_2} = EM_{CO_{2(kWh)}} \times \%\, contribution \quad (8)$$

Where, $EM_{CO_2}$is the total CO_2 emission from different plants, $EM_{CO_{2(kWh)}}$ is the CO_2 emission from different plants to produce 1 kWh energy. The $\%\, contribution$ is the individual contribution from the power plants taken from the energy generation scenario. Using equation 8 the CO_2 emission from the individual power plants has been calculated and given in table 5.

From table 5 it is observed that CO_2 emission is more from coal and lesser from solar. Hence in order to ensure that the E-bus technology does not cause any further emission in the environment, the energy from solar plant can be utilized. Thus, using an equation 8 CO_2 emission for two cases are calculated: when the required energy is entirely taken from energy mix, when the required energy is entirely taken from solar plant. A comparison of CO_2 emission by E-bus to drive a km for these two cases is presented in Fig. 4.

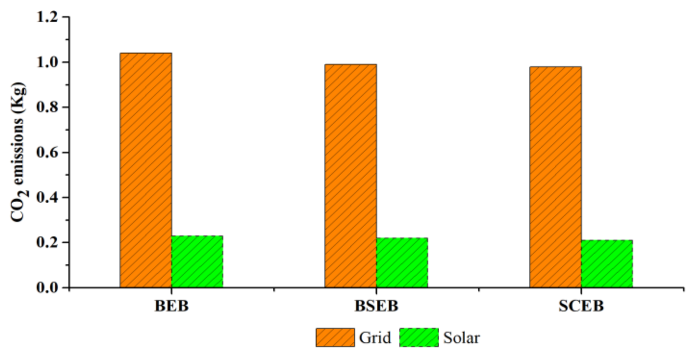

Fig. 4. CO_2 emission comparison between grid and solar

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V. Energy Stored uring Regenerating Mode

Battery fed electric vehicle is required to function in three different modes these are acceleration mode, steady-state mode, regenerative or breaking mode [21]. During acceleration and steady state modes the power flow from the battery to motor drive system. During regenerative mode the kinetic energy of the motor is converted into electrical energy and recharge to the battery. The DC-DC converter with bidirectional power flow required to control the battery to the motor drive system.

In the present work, the closed-loop operation of bidirectional dc-dc converter battery fed E-vehicle and its charging and discharging due to regenerative mode with PI controller has been demonstrated. The characteristics of a battery-operated electric vehicle under different drive conditions are also presented. The effectiveness of the system is verified through the simulations using Simulink/ MATLAB 2018(b) package.

A. Converter operating modes

Fig. 5. shows the proposed Bi-directional dc-dc converter fed DC motor drive. In this topology, boost converter operation is achieved by modulating *Q2* with the anti-parallel diode *D1* for the boost-mode diode. With the direction of power flow reversed, the topology functions as a buck converter through the modulation of *Q1*, with the anti-parallel diode *D2* serving as the buck-mode diode. It should be noted that thetwo modes have opposite inductor current directions. A new control model is developed using a PI controller to achieve both motoring and regenerative braking of the motor. A Lithium-ion battery model has been used in this model to verify the motor performance in both motoring and regenerative mode.

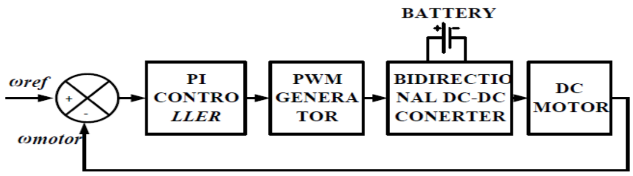

Fig. 6. Control of the bidirectional dc-dc converter

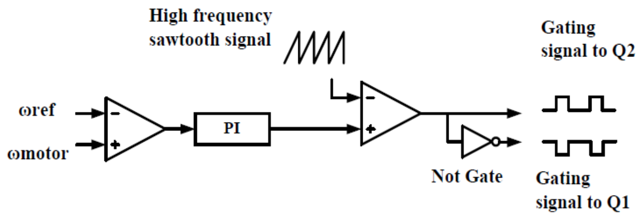

Fig. 7. Closed-loop operation of the drive

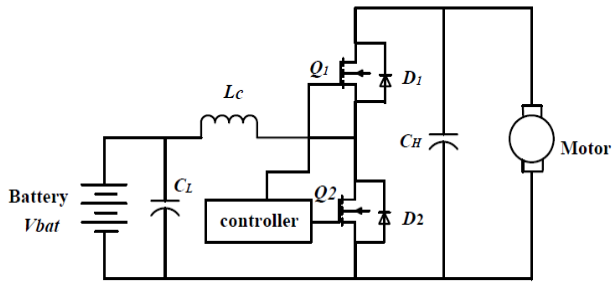

Fig 5. Bidirectional dc-dc converter with battery and dc motor

The bidirectional dc-dc converter shown in Fig. 5 is operated in continuous conduction mode for forward motoring and regenerative braking of the dc motor. The MOSFETs Q1 and Q2 are switched in such a way that the converter operates in steady state with four sub intervals namely interval 1(t0-t1), interval 2.

(t1-t2), interval 3 (t2-t3) and interval 4 (t3-t4). It should be noted that the low voltage is battery side voltage and a high voltage load side is taken.

Interval 1(t0-t1): At time t0, the lower switch Q2 is turned ON and the upper switch Q1 is turned OFF with diode D1, D2 reverse biased. During this time interval the converter operates in boost mode and the inductor is charged and current through the inductor increases.

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Interval 2(t1-t2): During this interval both switches Q1 and Q2 is turned OFF. The body diode D1 of upper switch Q1 starts conducting. The converter output voltage is applied across the motor. As this converter operates in boost mode is capable of increasing the battery voltage to run the motor in forward direction.

Interval 3(t2-t3): At time t3, the upper switch Q1 is turned ON and the lower switch Q2 is turned OFF with diode D1, D2 reverse biased. During this time interval the converter operates in buck mode.

Interval 4(t3-t4): During this interval both switches Q1 and Q2 is turned OFF. The body diode D2 of lower switch Q2 starts conducting.

B. Control design

The control circuit of the bidirectional converter is shown in Fig. 6. To control the speed of the dc drive; one possible control option is to control the output voltage of the bidirectional converter. To control the output voltage of the bidirectional converter for driving the vehicle at desired speed and to provide fast response without oscillations to rapid speed changes a PI controller is used and it shows satisfactory result. In this control technique the motor speed ω_m is sensed and compared with a reference speed ω_{ref}. The error signal is processed through the PI controller. The signal thus obtained is compared with a high frequency saw tooth signal equal to switching frequency to generate pulse width modulated (PWM) control signal.

The block diagram of the feedback speed control system for a DC motor drive is shown in Fig. 7. The control objective is to make the motor speed follow the reference input speed change by designing a proportional-integral controller. The PI controller is used to reduce the steady-state error between the measured motor speed (ω_{motor}) and the reference speed (ω_{ref}) to be tracked.

VI. Simulation and results

The earlier section has presented the concept with which energy can be recovered during negative acceleration. Using this concept, the simulation block diagram is also presented in the earlier section. In this section, the performance of the dc motor drive with the battery model and bidirectional converter is simulated under different speed command. The simulations are carried out using MATLAB/SIMULINK. The inductor parasitic resistance and MOSFET turn-on resistance are not considered in this case. For the test condition of the proposed drive topology, the following values of the different components of the converter are considered. A separately excited DC motor model is used as a load to the bidirectional dc-dc converter. The motor rated at 5 hp, 240 V, and 1750 rpm. The specifications of the bidirectional converter are taken as inductor (L) = 1800 µH, C_H = 470µF,load capacitance (C_L) = 500µF, switching frequency (f_{SW}) = 20 kHz, Battery voltage = 48V, Battery capacity =16 Ah, state of charging (SOC) = 90%.

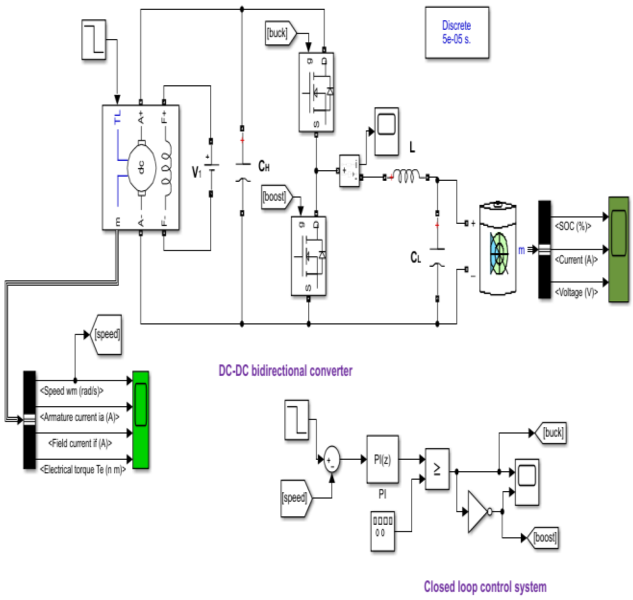

Fig 8. Simulation model of E-bus transit system

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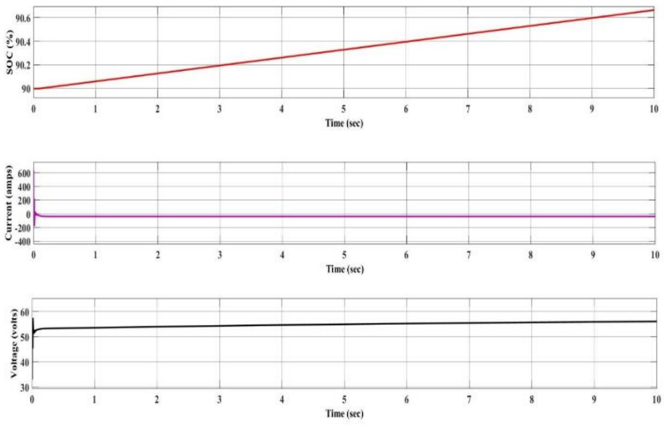

Fig 9. Battery results during charging

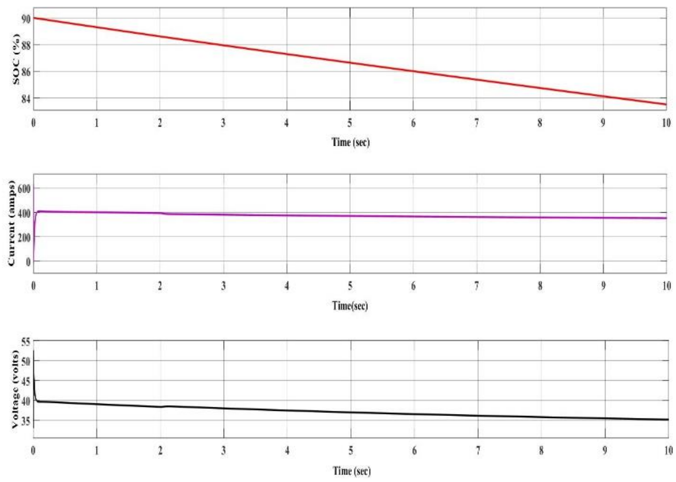

Fig 10. Battery results during discharging

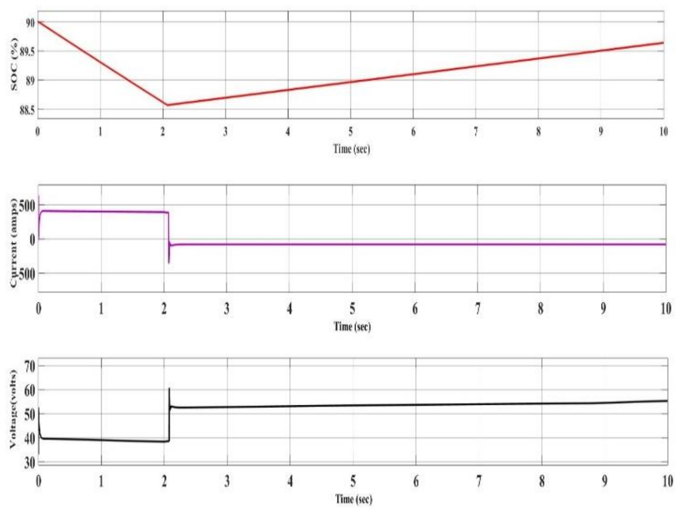

Fig 11. Battery results during charging and discharging

The Fig. 9 shows that the simulation result of the battery system at a reference speed of 100 rad/sec for a total simulation time of 10 sec. It can be observed that E-bus is taking energy from the battery during positive acceleration. The Fig. 9 shows that the SOC of the battery and voltage and current values given when the drive was running for 10 sec and torque is 20 Nm, at a speed of 100 rad/sec. Similarly, the Fig. 10 shows that SOC of the battery and voltage and current values given when the drive was running for 10 sec and torque is -60 Nm. The Fig. 11 show that SOC of the battery and voltage and current values given when the drive was running for torque 20 N-m to -60 N-m, ref. Speed is 50 rad/sec to 100 rad/sec for breaking condition.

VII. Conclusion

In this work the energy required for different E-bus transit systems to drive 1 km and its emission analysis is presented. The energy calculation is done considering Guwahati city driving cycle. The emission analysis is a function of the energy required, and hence in this work the energy requirement has been calculated. From the energy calculation it is observed that the BEB requires more energy compared to other E-buses. Further the percentage contribution of different power plant is considered in order to analyze the contribution of each power plant towards supplying required energy. Based on the contribution of individual power plant, the CO_2 emission from energy mix in order to support the E-bus system is calculated. Further a comparison of CO_2 emission when the required energy is entirely supplied by energy mix and when the required energy is entirely supplied by solar is also presented. The CO_2 emission comparison shows that emission is more if the energy taken from the grid entirely. Whereas, if the energy is entirely supplied by solar energy, it causes in reduction in emission. Hence SCEB (which

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implements the interconnection of grid with solar energy) can be a possible solution towards emission reduction in Indian cities.

Additionally, the regenerating energy storage technique is presented to store the energy produced during braking. A simulation model is presented which shows the control technique and battery charging and discharging towards the E-buses. The results of the simulation show that the E-bus will take energy from the battery during acceleration and will fed energy to the battery during negative acceleration.

VIII. References

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