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Load Calculation of Air Conditioner for an Electric Bus in Indian Climate Condition

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Abstract: The rapidly increasing number of vehicles and the alarming levels of air pollution is the recent issue India is dealing with. One of the possible solutions is a paradigm shift towards electric based mass transit systems. The large-scale implementation of electric based transit systems for India is challenging due to its weak electricity grid, further given with the climatic conditions the passenger comfort of such transit system is also an issue. Hence, in this work the common comfort of the passengers by using the auxiliary device in the electric based transit system (air-conditioner) has been addressed. From the study of research works, it has been observed that though there are many works on the architecture, storage and interconnection with grid of such transit systems, the loading analysis with the auxiliary equipment has not been presented yet. This work presents cooling load analysis of an E-bus considering the climatic conditions of Indian cities. A simulation model is also presented to show the battery charging technique for an electric based transportation system. The results of the analysis show that with proper cooling load analysis and rating of the air-conditioner, the passenger comfort is ensured in the Indian climatic conditions.
Keywords:*Air conditioner, electric bus, cooling load.*

I. Introduction

India is the 2nd most populous country after China [1]-[2] and given with the present growth rate it will become the world's most populous country by 2050. As a result, urbanization is increasing in the Indian cities leading to increased demand for transportation. This rapidly increasing transportation demand has led to an increased number of vehicles on the road. India has the world's 3rd largest road network, the total number of vehicles in the year 2016 stood at 230 million [3]-[4]. Additionally, road travel is the preferred choice in India and over 60 percent of the population use personal vehicles for commute [3]. This increased number of vehicles has not only resulted in traffic congestion but also in deterioration of air quality. Reports show that deadly air pollution is not only restricted to Delhi-NCR (National Capital Region) but has eventually become an alarming condition and emergency has been called off due to deteriorated air quality. Eventually, it has become a reason for killing around 1.2 million Indians every year affecting the major cities [5].

In a country like India, people are more attracted towards private transit systems than public transit systems [6]. This is because public transports are not reliable and comfortable during the journey. Hence it is the result of an increased number of vehicles on the road. Shifting towards a reliable public transit system can be a possible solution. Hence, efforts need to be taken so that people get more attracted to public vehicles rather than switching to personal ones. This can be attained by electrification of the public vehicles which will

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help to reduce pollution as well as making the electrified public transit more reliable and comfortable. Metros, trams are currently working examples of electrified vehicles and also have proved efficient in reducing vehicular level emissions [7]. Although, the need for dedicated constructions, extra space, and direct connection to the grid are issues that are challenging for Indian cities to overcome [8]-[9]. Therefore, if the electrified public transit system can replace the existing bus transit system, it will be the best possible scenario for the congested Indian cities.

Architecture and the modelling of such an electrified transit system have been proposed in [10]which uses electric buses with supercapacitor as on-board energy source. In [11], the authors have developed a model of supercapacitor based electric bus and named it CAPA bus. The work in [10] also presented the power supply system, tractions system and load simulation of such electric vehicles. Besides proposing the electric vehicle models many authors have analysed the energy management of the electric vehicles [12]-[16]. Further in more advanced studies authors are proposing Electric vehicles using Power Transfer Technology deals with the on-line electric vehicle (OLEV) [17].

In the research works presented above three major things has not been considered. Firstly, the energy management of the auxiliary system of electric vehicle (air-conditioning system) has not been included or analyzed. Although some works have considered the load analysis of air conditioning system but these were not done for Indian climate situations which is totally different from others. Moreover, the mechanical design of the auxiliary system is presented in a few works without considering the electrical specification. Furthermore, the sizing according to a specific load and climate condition has not been addressed in these works.

The paper is organized as follows: section II presents the data analysis which explains the data used for analyzing the load calculations. Section III presents the cooling load calculation based on the data provided in the earlier section. Section IV presents the system model and the simulation model of the system; it also presents the rating calculation of the air-conditioner. Section V presents the results of the simulation and lastly the conclusion is given in section VI.

II. DATA ANALYSIS

This work presents an analysis of the air conditioning system for an E-bus transit system. In order to present the analysis, it is required to understand the climatic condition of the city. This section presents the environmental parameters based upon which the analysis of this work has been further established. Fig. 1 and Fig. 2 present the annual temperature and relative humidity data of Delhi city. Delhi has been considered as a test case in this work as the climate conditions of Delhi has a wide variation throughout the year

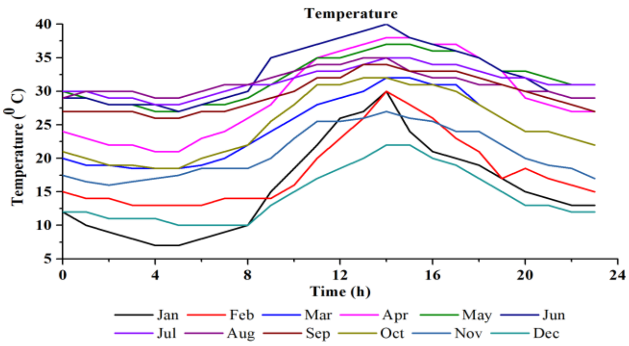

Fig.1. Annual temperature data for Delhi city.

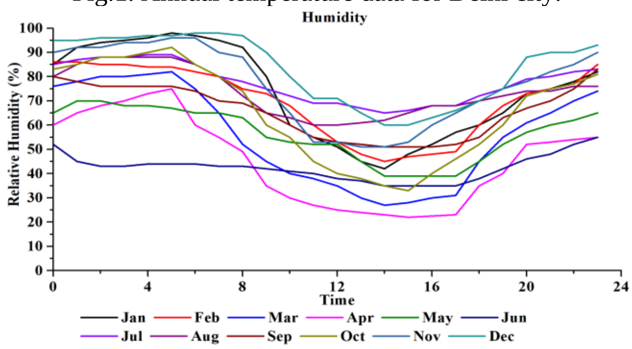

Fig. 2. Annual relative humidity data of Delhi city.

From these graphs, it can be observed that:

i. Maximum temperature is in the month of June, which presents a Summer month and it reaches 40^0 C (approx.) by daytime.

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ii. Minimum temperature is in the month of January which represents a winter month and the temperature reaches 7^0 C (approx.) by midnight.

iii. Maximum relative humidity is in the month of December

Minimum relative humidity is in the month of April.

The climatic conditions will help in the cooling load calculation of the E-buses. Later the environmental parameters, the physical parameters of the bus have been collected and presented in Table I below. Along with the physical parameters the properties of the building materials of the E-bus are also presented in Table II.

Table-I
Bus specification [18]

Parameters	Specification
Wheelbase	5200 mm
Length	10120 mm
Rear Overhang	3300 mm
Front Overhang	1800 mm
Overall Height	2900 mm
Maximum Width	2340 mm
Internal Height	1900 mm
Seating Capacity	56

Table-II
Material properties of the Bus [19]

Surface	Area (m^2)	U-Value (m^2-K)	Shade Coefficent
East Exposure			
Side Panel	12	2.801	-
Side Windows	13	2.569	0.811
Door	2	4.89	0.811
West Exposure			
Side Panel	12	2.801	-
Side Windows	13	2.569	0.811
Driver Windows	2	4.89	0.811
South Exposure			
Rear Body	2	2.667	-
Rear Window	3	2.611	0.811
North Exposure			
Front Body	3	2.667	-
Front Window	2	5.02	0.811
Others			
Roof	32	0.532	-
Floor	33	2.267	-
Skylight	1	4.89	0.811

The physical parameters will help in calculating the energy requirements of the E-bus and the materials property will help in calculating the cooling load of the E-bus. The E-bus parameters presented here are considered for 56-seater bus and hence is the calculation in the later sections.

This section therefore presented the data required for load calculation and system analysis. Using these data, the load calculation steps are presented in the next section.

III. COOLING LOAD CALCULATION OF AIR CONDITIONER

The earlier section has presented the physical and climatic parameters required for calculating the cooling load of the E-bus. This section presents the stepwise description required for calculating the cooling load of the E-bus (specification given in Table I). The cooling load of a vehicle is the summation of the sensible cooling load and latent cooling load. The sensible cooling load depends on the temperature of the vehicle (inside the cabin) and the latent cooling load depends on the humidity. The cooling load is concerned of the work done by the vehicle to reduce the ambient temperature of the vehicle. The following assumptions has been considered for the calculations:

i. The air conditioning system in the E-bus is fully operated throughout the day.

ii. The cabin temperature is maintained at 25^0 C.

iii. Relative humidity maintained inside the bus is 50%.

iv. During winter air conditioning system acts like warm air blower.

Calculation of the cooling load of air conditioning system is essential to get the estimation of energy required to run an air conditioning system in the electric vehicle. As per the reports air conditioning system consumed around 30 to 35% of the total energy supplied to the system [20], [21]. So, while installing the air conditioning system in the electric vehicle estimation of the energy required is must. Cooling load calculation takes into an account of all types of loads experienced by the vehicle under the specific set of assumed conditions. Total cooling load comprises heat transferred through the vehicle envelope (opaque bodies such as side panels, roof, doors, windows, etc) and the heat generated by the occupants, lights and appliances installed in the vehicle [19].

The total heat generated from the electric bus system is the summation of the total sensible cooling load and the total latent cooling load considering each and every component in the electric bus [19].

$$\dot{Q}_{total,bus} = \dot{Q}_{sensible,bus} + \dot{Q}_{latent,bus} \quad (1)$$

Here $\dot{Q}_{total,bus}$ is the total heat energy generated from the electric bus, $\dot{Q}_{sensible,bus}$ is the total sensible cooling load of the electric bus whereas $\dot{Q}_{latent,bus}$ is the total latent cooling load of the electric bus.

A. Sensible Cooling Load Calculation

Sensible cooling load is defined as the measurement of the amount of the heat energy which is required to be provided by the system in order to maintain the required temperature inside the bus. Sensible cooling load also refers to the capability of the system which ensures that a cooling system must be capable of cooling the air of the system. There are various factors that are considered in calculating total sensible cooling load.

The heat transfers rates from the opaque surfaces (side panels, roof, doors, floor, windows, front and rear body surface, etc.) is given by [19]:

$$\dot{\mathrm{Q}}_{\mathrm{oaque}} = \mathrm{U}_{\mathrm{opaque}} \times \mathrm{A}_{\mathrm{opaque}} \times \mathrm{CLTD} \quad (2)$$

Here $\dot{Q}_{oaque}$ is the heat transfer rate through opaque surfaces, U_{opaque} is the overall heat transfer coefficient, $\mathrm{A}_{\mathrm{opaque}}$is the area of the surface of the vehicle, CLTD is the temperature difference of the cooling load.

The heat transfer rate through the glass is given by:

$$\dot{Q}_{glass} = A_{glass}\left[\, U_{glass}(T_{out} - T_{in}) + SHGF_{max} \times SC \,\right] \quad (3)$$

Here $\dot{Q}_{glass}$ is the heat transfer rate through glass, A_{glass} is the glass area, U_{glass} is the heat transfer coefficient of glass, T_{out} and T_{in} is the outside and the inside air temperature of the bus respectively, $SHGF_{max}$ and SC are the maximum solar heat gain factor and the shading coefficient respectively.

The heat transfer rate due to infiltrated air is given by:

$$\dot{\mathrm{Q}}_{\mathrm{s,infiltration}} = \dot{m}_0 \times c_{p,m} \times (T_{out} - T_{in}) \quad (4)$$

Here $\dot{Q}_{s,infiltration}$ is the heat transfer rate due to infiltration, $\dot{m}_0$ is the mass flow rate of the outside air, $c_{p,m}$ is the specific heat of the infiltrated air, T_{out} and T_{in} is the outside and the inside air temperature of the bus respectively.

The heat transfer rate due to the by-pass ventilation air is given by:

$$\dot{Q}_{s,\,by-pass} = \dot{m}_o \times BPF \times c_p \times (\,T_{out} - T_{in}\,) \quad (5)$$

Here $\dot{Q}_{s,\ by-pass}$ is the heat transfer rate due to the by-pass ventilation, BPF is the by-pass factor, c_p is the specific heat of the moist air.

The calculation of BPF can be done by:

$$BPF = \frac{T_s - T_{ADP}}{T_m - T_{ADP}} \quad (6)$$

Here T_s, T_m and T_{ADP} are the supply air temperature, mixed air temperature and the cooling apparatus dew-point temperature respectively.

The heat transfer rate due to the ventilated air is given by [22]:

$$\dot{Q}_{s,vent} = \dot{m}_{vent} \times (1 - BPF) \times c_{p,v} \times (T_{out} - T_{in}) \quad (7)$$

Here $\dot{Q}_{s,vent}$ is the heat transfer rate due to the ventilated air, $\dot{m}_{vent}$ is the mass flow rate of the ventilated air, $c_{p,v}$ is the specific heat of the ventilated air.

In the above section cooling load arise due to heat is transferred through the bus envelope. Heat generated by the occupants, lights and appliances present in the bus also contribute to the total cooling load.

The heat transfer through the occupants is given by [23]:

$$\dot{Q}_{occupants} = \sum_{occupants} M \times A_{Du} \quad (8)$$

Here $\dot{Q}_{occupants}$ is the heat transfer through the occupants, M is the occupants metabolic heat production rate and

$$A_{Du} = 0.202 \times W^{0.425} \times H^{0.725} \quad (9)$$

Here W is the mean weight of occupants, H is the mean height of occupants.

The heat transfers through appliances installed in the bus is given by [24]:

$$\dot{Q}_{s,appliances} = I_W \times U_F \times CLF \quad (10)$$

Here $\dot{Q}_{s,appliances}$ is the heat transfer through the appliances, I_W refers to the rating of the installed appliances, U_F accounts for the appliances installed but are not switched on at the time at which the cooling load calculation is performed, CLF is the cooling load factor which is the function of the number of hours after the appliances are turned on, operations of the appliances and type of appliances fixtures.

The heat transfer through lighting in the bus is given by [24]:

$$\dot{Q}_{s,lighting} = (I_W) \times (U_F) \times (B_F) \times CLF \quad (11)$$

Here $\dot{Q}_{s,lighting}$ is the heat transfer rate through lighting in bus, B_F takes into account the load imposed by ballast used in the florescent light.

Adding (2), (3), (4), (5), (7), (8), (10) and (11) gives total sensible cooling load:

$$\dot{Q}_{sensible,bus} = \dot{\mathrm{Q}}_{\mathrm{oaque}} + \dot{Q}_{glass} + \dot{\mathrm{Q}}_{\mathrm{s,infiltration}} + \dot{Q}_{s,\ by-pass} + \dot{Q}_{s,vent} + \dot{Q}_{occupants} + \dot{Q}_{s,appliances} + \dot{Q}_{s,lighting} \quad (12)$$

B. Latent Cooling Load Calculation

Latent cooling is a measure of the amount of energy that is necessary to dehumidify the air in a bus to the required conditions regardless of the outside conditions. Latent cooling load refers to the wet bulb temperature. There are various factors that needs to be considered in calculations of the latent cooling load.

The latent heat transfer rate due to by-pass ventilation is given by [19]:

$$\dot{Q}_{l,by-pass} = \dot{m}_0 \times BPF \times h_{fg} \times (w_{out} - w_{in}) \quad (13)$$

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Here $\dot{Q}_{l,by-pass}$ is the latent cooling load due to by-pass ventilation, $h_{fg}$is the latent heat of vaporisation, w_{out} and w_{in} are the relative humidity ratios of outside and inside the bus.

The latent heat transfer rate due to infiltrated air is given by:

$$\dot{Q}_{l,infiltration} = \dot{m}_0 \times h_{fg} \times (w_{out} - w_{in}) \quad (14)$$

Here $\dot{Q}_{l,infiltration}$ is the latent cooling load due to the infiltrated air.

The latent heat transfer rate on the coil due to ventilation is given by [22]:

$$\dot{Q}_{l,vent} = \dot{m}_{vent} \times (1 - BPF) \times h_{fg} \times (w_{out} - w_{in}) \quad (15)$$

Here $\dot{Q}_{l,vent}$ is the latent cooling load heat transfer rate due to the ventilated air on the coil.

The latent heat transfer rate through occupants in the bus is given by [24]:

$$\dot{Q}_{l,occupants} = (N_{people}) \times (h_{people}) \quad (16)$$

Here $\dot{Q}_{l,occupants}$ is the latent cooling heat transfer rate through occupants, (N_{people}) refers number of persons in the bus, (h_{people}) is the latent heat gained per person.

The latent heat transfer through lights and appliances are given by [22]:

$$\dot{Q}_{l,light+appliances} = (Installed\, wattage) \times (h_{la}) \quad (17)$$

Here $\dot{Q}_{l,light+appliances}$ is the combined latent cooling heat transfer rates from lights and appliances; h_{la} is the latent heat fractions from lights and appliances.

Adding (13), (14), (15), (16) and (17) gives total latent cooling load:

$$\dot{Q}_{latent,bus} = \dot{Q}_{l,by-pass} + \dot{Q}_{l,infiltration} + \dot{Q}_{l,vent} + \dot{Q}_{l,occupants} + \dot{Q}_{l,light+appliances} \quad (18)$$

IV. SYSTEM MODEL AND AIR CONDITIONERRATING CALCULATION

The earlier sections presented the data required for calculations and analysing the energy requirements. This section presents the system model using which the energy pathway of the E-bus transit system and the air conditioner rating calculation.

A. System Model

Fig. 3 presents the system model; the blocks present the building blocks of the E-bus transit system. The air conditioner is the auxiliary element used inside the E-bus to regulate the temperature inside. The earlier section has presented the calculation of the energy requirement by this auxiliary device for a specific E-bus. In figure above, the air conditioning system is run through the battery setup which stores energy to drive the vehicle and its auxiliary devices. The battery can be charged through grid system as well as through the solar medium. For charging the battery through grid system AC to DC converter is used which is being controlled through the controller. For charging the battery through solar medium a DC to DC converter is required. After the battery is being charged, the power is supplied to the air conditioning system to maintain interior conditions of the bus cabin. The rest of the power is used to run the bus. To charge the battery using solar connected system, boost converter is used as the DC to DC converter. Perturb and Observe MPPT technique is used for the maximum output from the solar energy absorbed through the solar panels.

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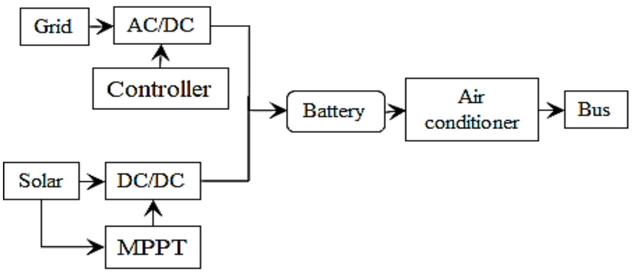

Fig. 3. System proposed model

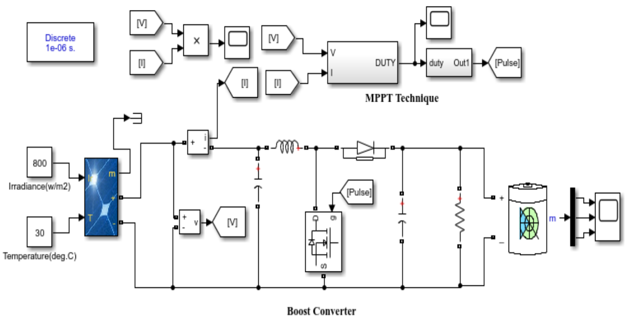

Fig. 4. Simulation Model

The simulation of a small part of the system model is shown in Fig. 4. The simulation model presents the electric simulation of the battery charging technique using boost converter from the solar PV panels. It should be noted that it is not ascertained that what will be the most optimum location for solar PV panel installation. The results of the simulation are discussed in the later section. The next subsection discusses the steps of calculating the rating of the auxiliary device (air conditioner).

B. Air Conditioner Rating Calculation

In the earlier sections, the total cooling load has been calculated stepwise. The cooling load gives the idea about the total work done in order to cool down the vehicle. In this section the energy consumption of the air conditioning system is calculated. It should be noted that the energy required to drive the E-bus and to operate the auxiliary devices inside the E-bus is stored in the battery. Hence, to ensure efficient usage of the energy thus stored, it is required is required to calculate the rating of the air conditioner for an E-bus with the given specifications. The input wattage rating of the air conditioning system has been calculated by using the parameters such as total cooling load, EER, efficiency of the compressor, and the total working time of the air conditioning system.

It should be noted that the rating of the air conditioner is based on the maximum cooling load of the vehicle at a given point of time. The maximum cooling load signifies the maximum temperature attained inside the vehicle while operating.

Therefore, power required by the air conditioner is given by:

$$P_{req} = \frac{CL_{max}}{EER} \tag{19}$$

Here P_{req} is the power required by the air conditioner, CL_{max} stands for maximum cooling load per hour, EER stands for energy efficiency rating which is the amount of heat removed in watt to the power consumed in watt. For 5-star rating value of EER is 3.5 [25].

Compressor runs only 70% of the time during normal run [26] so, power input to the air conditioner is given by:

$$P_{in} = \frac{P_{req}}{\eta_{Comp}} \tag{20}$$

Here P_{in} is the input power to the air conditioner, η_{Comp} gives the efficiency of the compressor.

Using the data given in Fig.1, Fig. 2 and the stepwise calculation of cooling load of the air conditioning system and the equations given in this section, rating of the air conditioning system has been calculated. Considering 5-star rated air conditioning system for the 56-seater E-bus maximum required rating is around 5 ton.

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V. RESULTS

The work presents an analysis of load calculation for auxiliary equipment of an E-bus. The auxiliary equipment that is considered here is the air-conditioner. This section presents the results of load calculation and analysis from the simulation model presented in the earlier sections. Fig. 5 represents the sensible cooling load of the air conditioning system. In this the maximum load is during the month of June and the minimum occurs in the month of September. From the Fig. 5 it can be concluded that cooling load varies with the variation in temperature. Fig. 6 represents the latent cooling load of the air conditioning system. Latent cooling load is maximum in the month of February and it is minimum in the month of December. From the Fig. 6 it can be concluded that latent cooling load varies with the variation in the relative humidity.

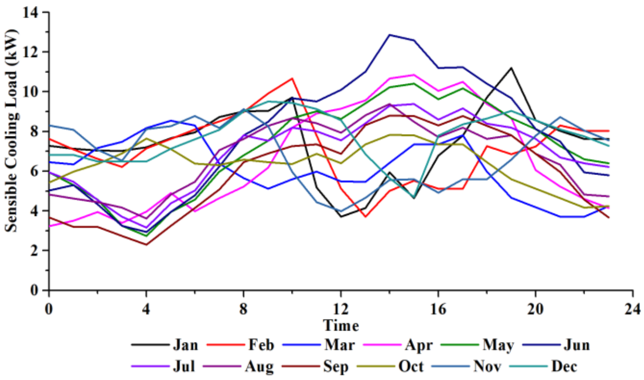


Fig. 5. Annual sensible cooling load

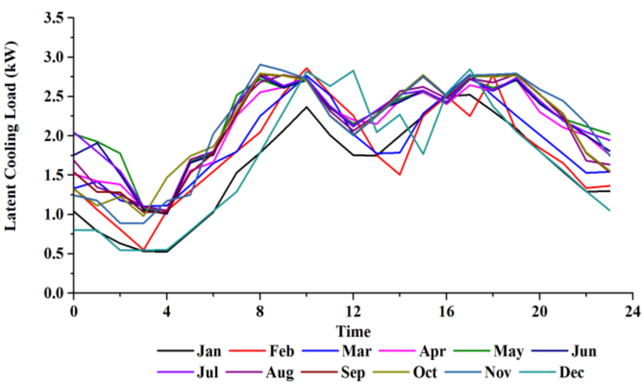


Fig. 6. Annual latent cooling load

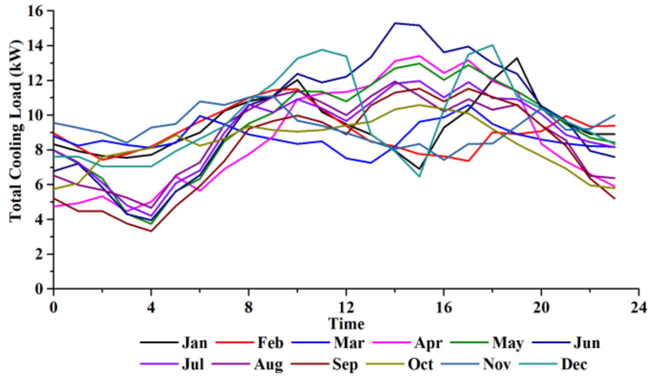


Fig. 7. Total annual cooling load

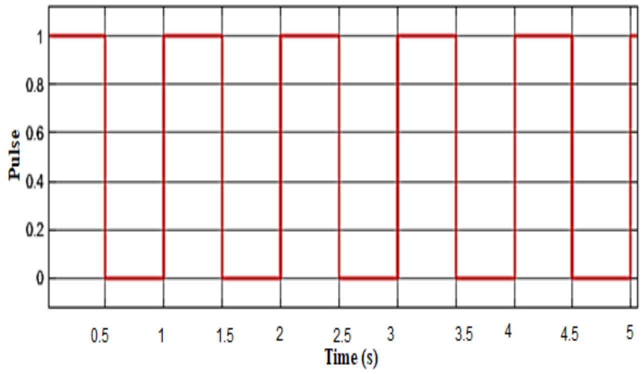
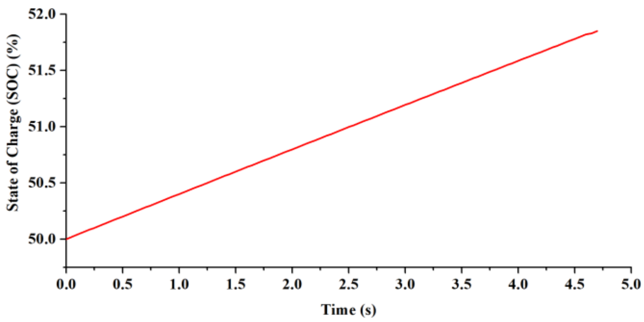
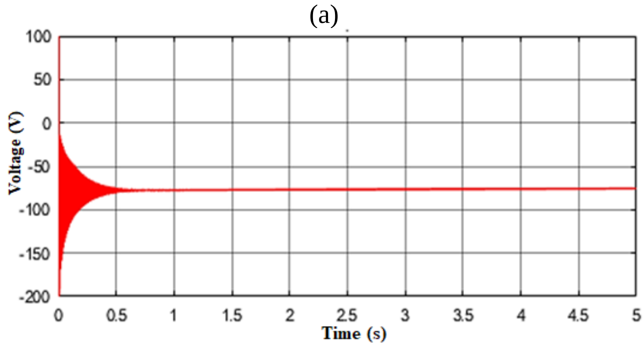


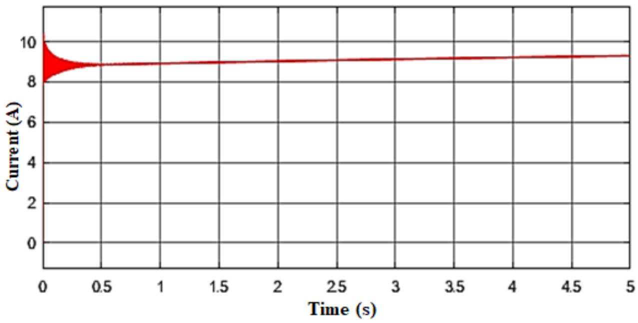
Fig. 8. Pulse generation for the boost converter



(a)



(b)



(c)

Fig. 9. Battery charging output waveforms

Fig. 7 shows the total cooling load which is the summation of the sensible and latent cooling load represented by Fig. 5 and Fig. 6. From the figure it can be observed that maximum cooling load is in the month of June and minimum cooling load is in the month of September. From the figure it can also be observed that as time progresses total cooling load required also varies.

The work has also presented a simulation model to present a technique to charge the battery from grid and solar using a boost converter. Fig.8 shows the pulse generation for the boost converter from MATLAB Simulink. This pulse has been generated through the Perturb and Observe MPPT technique. Through this generated pulse, boost converter works and boost the voltage for the charging the battery. Fig. 9 (a-c) shows the MATLAB Simulink output for the state of charge (SOC), voltage and current of battery charging. From these figures, it can be observed that as the SOC of the battery increases, the current waveform also increases.

VI. CONCLUSIONS

The work presents the load analysis for the auxiliary equipment (Air-conditioner) for an E-bus transit system. The loading calculation has been presented along with the climate conditions of an Indian city (Delhi) and the physical parameters of a 56-seater bus. The rating calculation has also been presented and done considering the maximum temperature that the vehicle may reach, which ensures that the air-conditioner will be fully utilized according to the change in climatic conditions. Lastly, a simulation model has been presented to show technique to charge the battery which will store energy to drive the E-bus and its auxiliary equipment. The battery is charged from the grid and solar using a boost converter. The model also shows that the output from the solar panel is collected using MPPT technique. The results of the simulation model are presented which show the charging of the battery through the boost converter. Thus, the work shows the cooling load analysis of an air-conditioner for an E-bus transit system. The E-bus system will not only help in lowering the vehicular level pollution, but will also help to reduce congestion on road by increasing the reliability of public transport system.

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