A Rate-capacity and Recovery-effect aware Battery Management System for Electric Vehicles

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Abstract

The work proposed in this paper discusses improving the performance of Electric Vehicles (EVs). EVs use Permanent Magnet Synchronous motors, which are driven by the rechargeable batteries. Lithium-ion batteries are used in EVs. The present technology can cover a distance of around 340 kilometers in a single charge of the battery module. The present Battery Management System (BMS) is focusing on the thermal aspects for improving the performance of the battery. It is possible to further enhance the performance of the battery module exploiting the electrochemical properties of the batteries. The two important properties of an electrochemical battery are the Recovery effect and Rate Capacity effect. Experiments conducted earlier on other loads have shown an improvement in the discharging efficiency of the battery, which has a direct impact on the battery lifetime. This would further increase the distance covered by the EV for a single charge.

Keywords: Electric vehicle, Battery management system, Battery lifetime, Rate-capacity effect, and Recovery effect.

I. Introduction

The proposed idea is based on a very important observation that the actual lifetime of the battery is not only dependent on the energy consumed by the load but also the way it discharges the battery. Also, very little attempt was made to thoroughly understand the non-ideal behavior of the battery concerning its electrochemistry based characteristics such as Rate capacity effect, Recovery effects. It is also important to note that progress in battery technology is very slow.

Rate-capacity effects: Available active reaction sites over the entire cathode region chiefly govern the lifetime of the battery. When the connected load to the battery is low, the battery also sources less current resulting in uniform distribution of the inactive reaction sites throughout the cathode. However, when the discharge current increases at higher loads, the outer region of the cathode electrode will be concealed with inactive regions. Thus many internal active sites become inaccessible. Further, this leads to a reduction in battery capacity at higher loads. Thus the most of the battery's energy is unused resulting in its untimely death.

Recovery effects: When the load is connected to the battery, positive ions diffuse through the electrolyte and are consumed at the cathode. And anode generates fresh cations. When the connected load is high, the ions required by the cathode are more than ions supplied by anode which results in the reduced battery output voltage. However, if the load is disconnected from the battery for a while, the ion concentration gradient decreases resulting in an apparent charge recovery. This results in an increase in battery capacity as well as its lifetime.

Thermal effects: The surrounding temperature of the battery affects its efficiency and the extent of its effect depends on the chemistry of the battery. Battery performs well at room temperature. However, higher temperatures result in increased mobility of the electrolyte material, which results in lower internal resistance. This increases the effective capacity of the battery. But, continuous exposure to elevated temperature has other undesirable effects, such as increased rate of self-discharge. At lower temperature, the battery internal resistance increases which reduce its capacity.

It is very clear that heavy loads connected to the battery increase the rate-capacity effect and hence increases the discharge from the battery and this ultimately reduces the usable energy that can be delivered by the battery. This leads to the battery's untimely death [1, 2, 4]. Therefore there is a need to reduce the Rate-capacity effect, which reduces the unused energy of the battery; thereby improving the discharging efficiency of the battery [1, 2, 3].

If the idle time during which the battery recovers is calculated then it is possible to mitigate the recovery effect.

The temperature of the sensing node has a direct impact on the lifetime of the battery. Specifically, when the ambient temperature of the battery is very cold, the internal resistance of the battery increases due to less mobility of ions in the electrolyte. This is the reason for the pre-exhaustion of the battery at low temperatures [4, 5, 6]. This problem can be overcome by operating the battery at the optimum temperature which increases its lifetime.

II. Present methodology

In general electric vehicles are implemented with permanent magnet synchronous motors (PMSM) coupled to the wheels of the vehicle. PMSM receives power through an inverter. Research is going on to improve the number of kilometers covered by the vehicle in a single charge of rechargeable electrochemical battery modules. At present only a single module of batteries is used to drive the motors. In such conditions, when the vehicle is on move the load discharges the battery continuously. Further, if the load requires higher currents, the battery life is reduced although the battery has still unused energy. This is due to the Rate capacity and Recovery effects of the electrochemical battery module. Therefore to overcome the shortcomings of the existing method there is a need to provide a complete battery management system (BMS) aiming at the enhancement of lifetime of the battery module and hence increasing the number of kilometers covered in a single charge. Also, when the vehicle travels in colder environmental conditions, the battery module lifetime is further reduced. Most of the present work is based on the thermal management of the battery system. Hence there is a need for developing a BMS taking the Rate-capacity and Recovery effect of the battery into consideration. Most of the present work is based on the thermal management of the battery system. Hence there is a need for developing a BMS taking the Rate-capacity and Recovery effect of the battery into consideration.

III. Factors affecting the performance of the battery

The performance of a battery is influenced by numerous factors. It is important to note that even for a specific design of the battery, a variation in the performance can be observed from company to company. Further, different variants of the same battery as premium, standard, or heavy-duty can be noticed. It is always worth to examine the specifications of the battery given on the datasheet before being used.

a. Voltage level

The lower voltage of the discharged battery which is less than the theoretical voltage is because of IR due to the cell (battery) resistance and polarization of active materials during discharge. The voltage drop due to internal impedance is usually referred to as ohmic polarization or IR drop and is proportional to the current drawn from the system. The total internal impedance of a cell is the sum of the ionic resistance of the electrolyte, the electronic resistance of both electrodes, and the contact resistance between the active mass and the current collector. These resistances are ohmic in nature, and follow Ohm's law, with a linear relationship between current and voltage drop.
Accumulation of discharge products increases the cell internal resistance which causes the voltage to drop during discharge. Fig. 1 shows typical discharge curves.

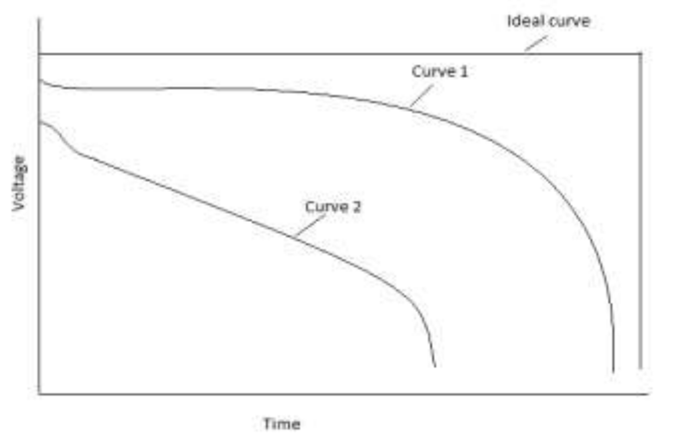


Fig.1 Characteristic discharge curve

Curve 2 and curve 1 are similar, but a higher internal resistance or a higher discharge rate, or both is reflected by curve 2. With the increase in the discharge current or cell, internal resistance results in the decrease in voltage and the discharge show more sloping profile. The practical energy delivered by a battery is lower than the theoretical energy as the average voltage delivered is less than the open-circuit voltage and also battery cannot be discharged to zero volts and therefore battery cannot be utilized for its total ampere-hour capacity.

b. Current drain of discharge

At the higher discharge levels of the battery, the IR losses increase causing the discharge at a lower voltage which results in the reduced service life of the battery. Discharge curves at different current drains are depicted in Fig. 2.
At extremely low current drains the discharge can approach the theoretical voltage and theoretical capacity as depicted by curve 1. As evident from the discharge curves with progressively increasing drain currents as depicted by 1, 2,3,4,5 the life of the battery is reduced.

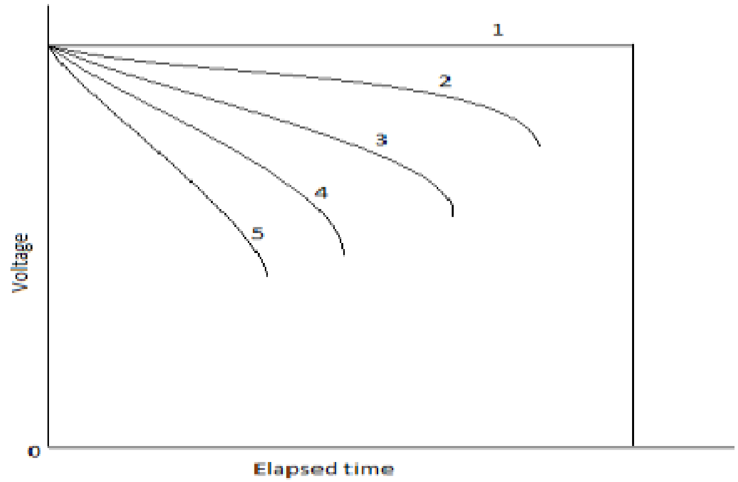


Fig.2 Discharge curves for different drains of current

c. Effect of temperature of battery during discharge

The ambient temperature of the battery has a vital effect on its life. At lower temperatures, the battery internal resistance increases because of the decline in chemical activity. Fig.3 illustrates the discharge curves for the same current drain but at different temperatures.

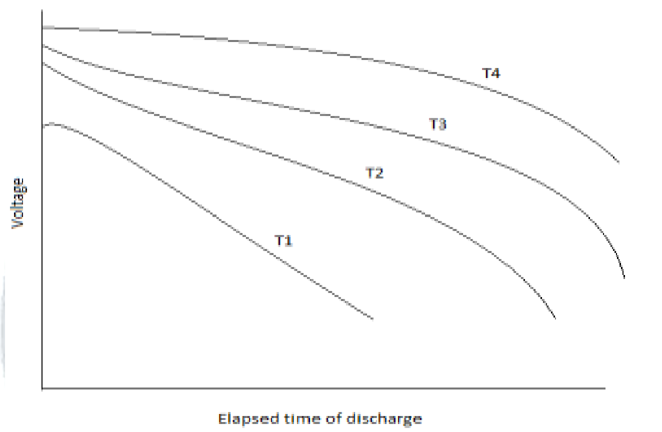


Fig.3 Effect of temperature on Battery capacity, T_1 to T_4-increasing temperatures

At lower temperatures, the capacity of the battery is reduced which is evident by the higher slope of the discharge curve. Fig. 4 and Fig. 5 depict the same. Higher discharge rates of the battery unusual effects that result in heating up of the battery. Discharge curve T6 of Fig.5 illustrates the reduction in the capacity at high discharge rates and high temperatures. From the characteristics shown in Fig. 4 and Fig. 5, it is clear that battery life depends largely on the availability of active reaction sites throughout the cathode. At low discharge currents, inactive reaction sites get uniformly distributed throughout the volume of the cathode. However, during intervals when the discharge current is large, the outer surface of the cathode gets covered with inactive sites, making many internal active sites unreachable. These rate capacity effects lead to an overall reduction in battery capacity at higher rates of discharge.

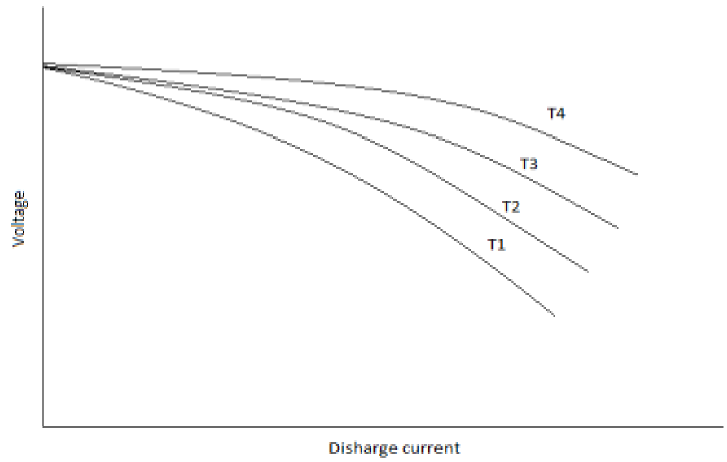


Fig.4 Effects of temperature and discharge rate on the battery's discharge voltage

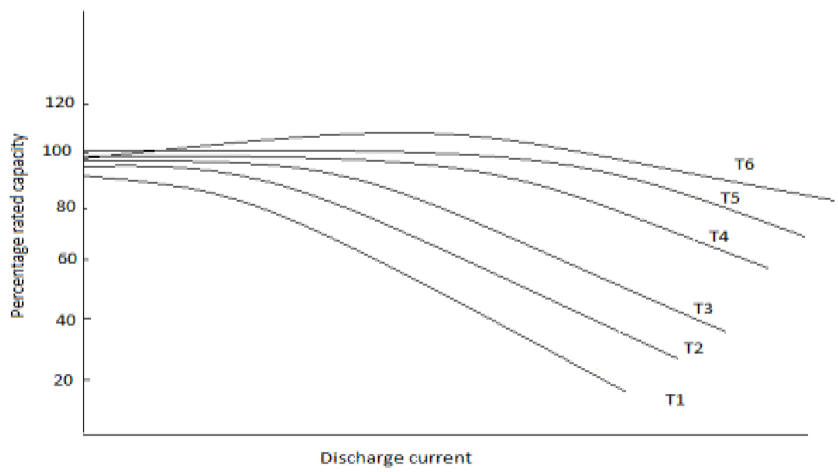


Fig.5 Effect of discharge load on Battery capacity at various temperatures T_1 to T_6-Increasing temperatures, T_4-normal room temperature

d. Type of discharge

A battery when standing idle after a discharge, certain chemical and physical changes take place which can result in a recovery of battery voltage. Thus the voltage of a battery that has dropped during a heavy discharge will rise after a rest period, giving a saw tooth-shaped discharge as shown in Fig. 6. This can increase service life. When current is drawn by the load from the battery, positively charged ions are consumed at the cathode-electrolyte interface and are replaced by new ions by the anode that diffuse through the electrolyte. When the current drawn is high, the rate of diffusion is unable to keep up with the rate at which ions are consumed at the cathode. This results in positively charged ions near the cathode and increases near the anode, degrading the battery's output voltage. However, if the battery is disconnected from the load for a brief period, the concentration gradient reduces due to diffusion, leading to an apparent charge recovery. This results in increased battery capacity as well as its lifetime.

It is vital to identify that the service life of the battery is determined when the cut-off or end voltage is reached under the higher discharge load. There are conditions where a battery has to handle multiple loads simultaneously, which results in multiple discharge loads. Under such conditions; a battery with lower internal resistance would exhibit a better capacity.

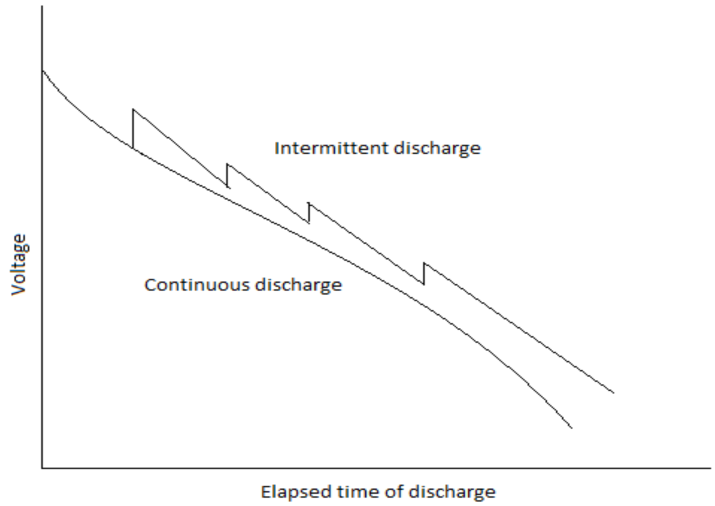


Fig.6 Effect of intermittent discharge on the battery capacity

IV. Lithium batteries

EVs use rechargeable lithium-ion batteries. Owing to its good conductivity, high voltage, high electrochemical equivalence, and lightweight, Lithium metal has been a popular choice as a battery anode material. Due to its exceptional features, lithium is dominating in the domain of high-performance non - rechargeable and rechargeable batteries. The era of lithium batteries has begun in the initial 1970s in defense applications. Sizes range from less than 5mAh to 10000Ah. Shapes vary from the tiny coin and small cylindrical cells which are used in portable and memory devices, to large prismatic cells used as backup power in missile applications.

The meritorious features of lithium batteries are:

1. High voltage: Lithium batteries have high voltages up to about 4V, governed by the material used for cathode. Because of this higher voltage the cells required in a battery pack will be reduced.

2. Better energy and specific densities: Lithium battery has energy output which is over 200 Wh/Kg and 400 Wh/L many times better than that of traditional batteries.

3. Operating over an extensive range of temperature: Normally lithium batteries operate over a large range of temperature as high as $70℃$ to as low as $-40℃$.

4. Better power density: High current and power levels are delivered comfortably by the lithium batteries.

5. Higher end discharge characteristics: Lithium batteries are typically characterized by discharge curves that maintain the same resistance and voltage.

6. Longer storage life: The reliability study of Lithium batteries permits them for storage lifetime of 10 years, at higher temperatures also. Investigations have shown that they can be preserved up to 10 years at 70℃ for one year. Even twenty years storage time has been demonstrated.

The popular electrolytes used by the Lithium batteries are acetonitrile, dimethoxyethane, propylene carbonate, and these are organic solvents. One of the common choices is thionyl chloride, which is an inorganic solvent. Owing to its reactivity with aqueous solvents, lithium batteries use non-aqueous solvents for the electrolyte. Electrolyte conductivity is facilitated by adding an appropriate solute. Carbon monofluoride, sulfur dioxide, iron disulfide, and manganese dioxide are commonly used for the cathode. The term "lithium battery" is used to represent several diverse chemistries, with lithium as the anode but a different electrolyte and cathode material. The term Lithium battery applies to a wide range of chemistries. Classification of Lithium batteries depends upon the cathode material and electrolyte chosen.

V. Suggested methodology

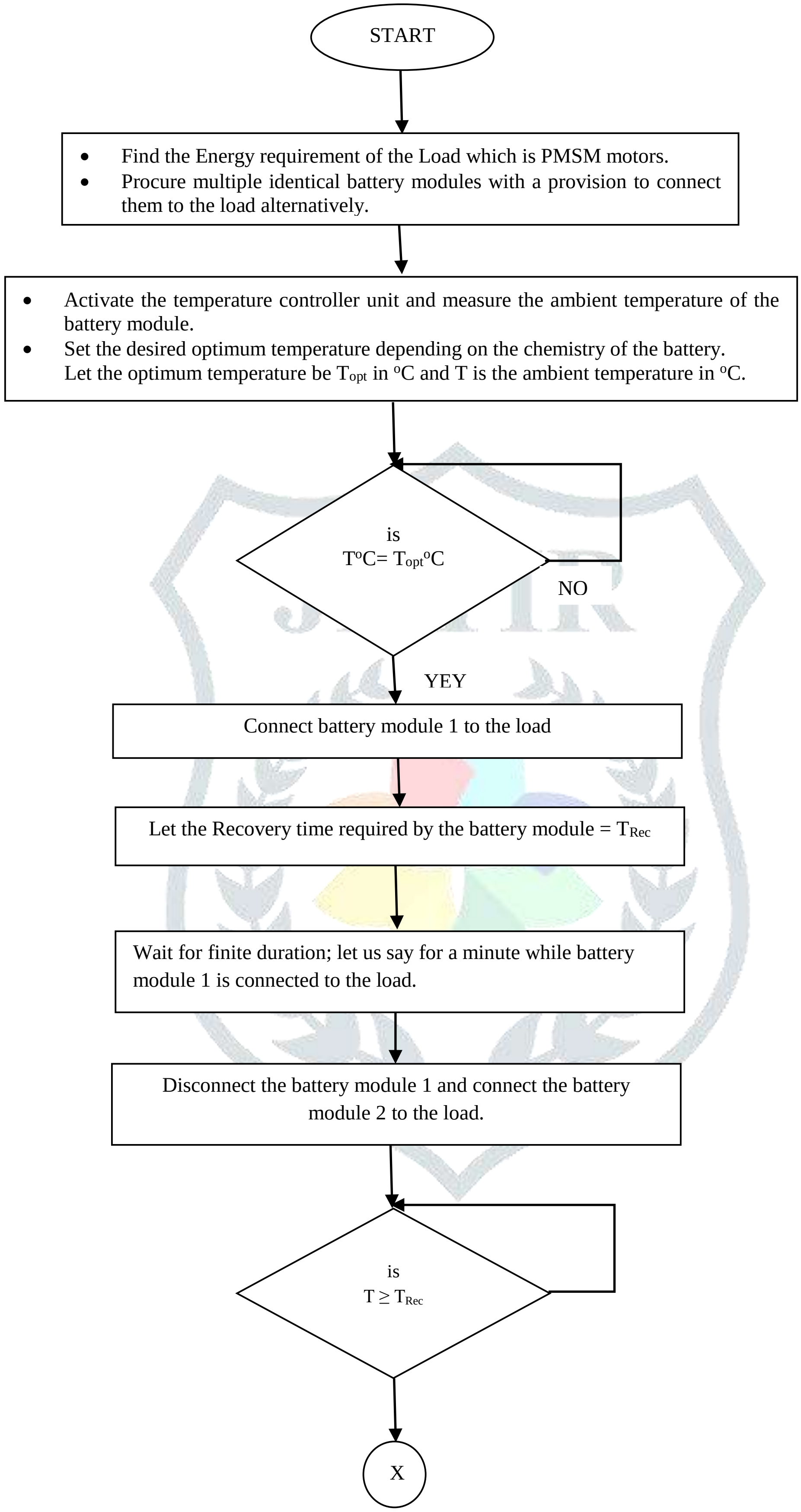
The suggested methodology provides the design and implementation of a life-enhancing technique for battery modules used to drive the permanent magnet synchronous motors of electric vehicles. This technique proposes an intelligent and effective battery management system to overcome the Rate capacity and Recovery effects of the electrochemical battery which shortens the lifetime of the battery. Further, the lifetime of the battery is enhanced by maintaining battery modules at the optimum temperature.
The proposed technique makes use of multiple sets of battery modules. PMSM is connected to first battery module while the other module is rested for a time equal to recovery time of the battery module. Connecting of the motors between two sets of the battery modules alternately is facilitated by a microcontroller. It is important to understand that the discharge of the battery modules depends on the speed of the motors. Normally discharge of the battery modules will be high in electric vehicles. As a result of this, the

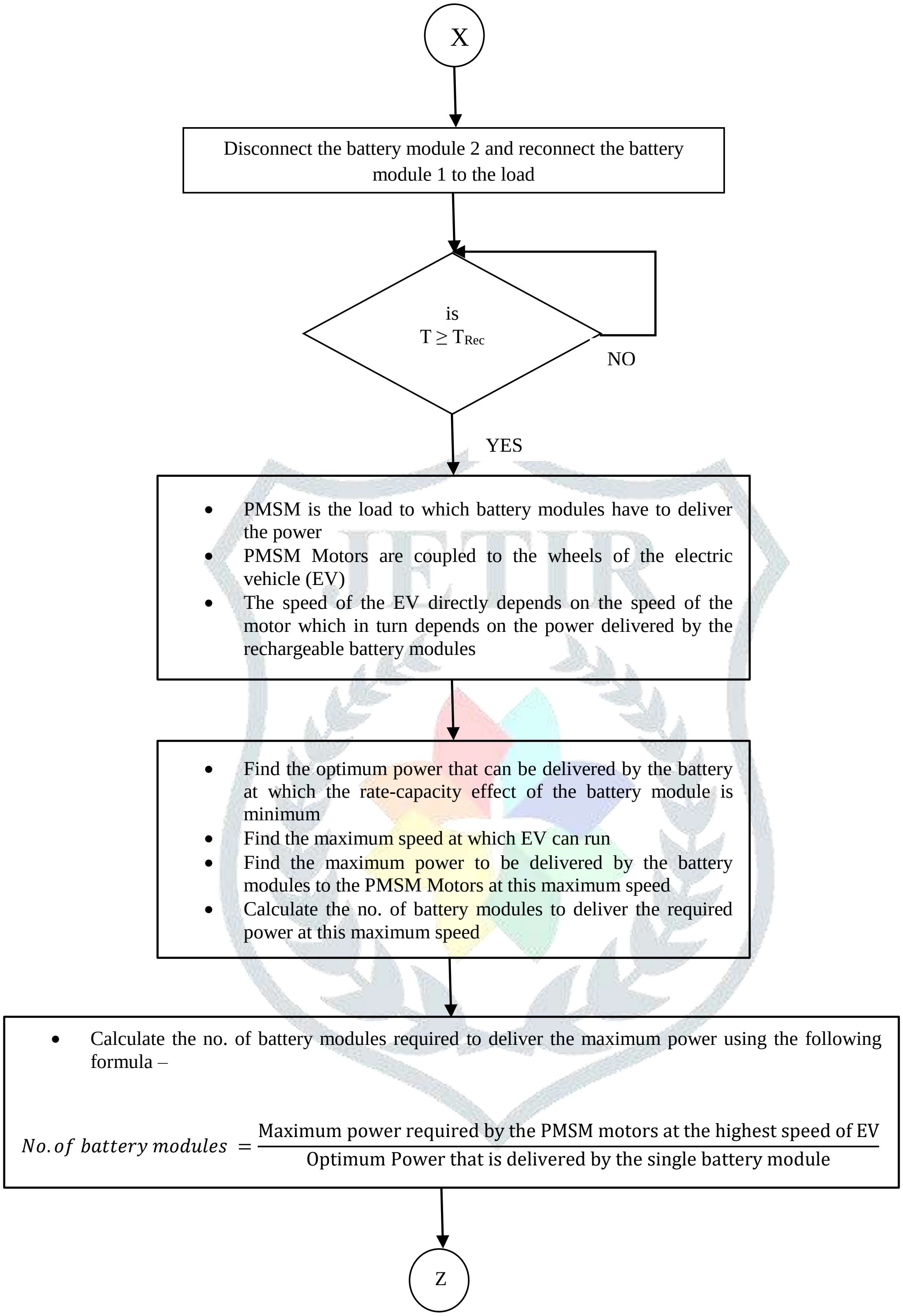
detrimental effects of the rate-capacity effect will be high leading to the early discharge of the battery which leads to reduced kilometers per charge. Most of the current battery management system technologies are focusing only on the thermal effects of the battery. But the bottleneck of rate-capacity effect is not addressed which is one of the main reasons for the inferior performance of the electric vehicles.

The proposers [7, 8, 9, 10, 11] of this methodology have already developed a systematic procedure to mitigate the rate-capacity effect of the electrochemical battery. In this method, the optimum power delivered by the battery module is found. When the battery module is operated at this optimum power, the rate-capacity effect is minimal and the life of the battery module is extended, thereby increasing the number of kilometers per single charge. However, the optimum power delivered by the battery module may not be sufficient to drive the permanent magnet synchronous motor of the electric vehicle. Hence, power is calculated when the EV moves with the highest speed. The calculated power is divided with the optimum power that is found earlier which gives the total number of battery modules required by the electric vehicle.

The microcontroller is programmed to find the speed of the vehicle with help of speed sensors at every instant of time and calculates the number of battery modules to be connected to the load (PMSM motors) while isolating the others. Further, to overcome the recovery effect, the number of battery modules is doubled to facilitate the idling of the batteries for recovery time. Proposers of the present invention have already established a reliable procedure to find the recovery time of the battery.

The suggested methodology is detailed in Fig.7.


START
Find the Energy requirement of the Load which is PMSM motors.
Procure multiple identical battery modules with a provision to connect them to the load alternatively.
Activate the temperature controller unit and measure the ambient temperature of the battery module.
Set the desired optimum temperature depending on the chemistry of the battery.
Let the optimum temperature be T_{opt} in °C and T is the ambient temperature in °C.
is
T°C= T_{opt}°C
NO
YEY
Connect battery module 1 to the load
Let the Recovery time required by the battery module = T_{Rec}
Wait for finite duration; let us say for a minute while battery module 1 is connected to the load.
Disconnect the battery module 1 and connect the battery module 2 to the load.
is
$T \geq T_{Rec}$
X


X
Disconnect the battery module 2 and reconnect the battery module 1 to the load
is
T ≥ T_Rec
NO
YES
PMSM is the load to which battery modules have to deliver the power
PMSM Motors are coupled to the wheels of the electric vehicle (EV)
The speed of the EV directly depends on the speed of the motor which in turn depends on the power delivered by the rechargeable battery modules
Find the optimum power that can be delivered by the battery at which the rate-capacity effect of the battery module is minimum
Find the maximum speed at which EV can run
Find the maximum power to be delivered by the battery modules to the PMSM Motors at this maximum speed
Calculate the no. of battery modules to deliver the required power at this maximum speed
Calculate the no. of battery modules required to deliver the maximum power using the following formula –
No. of battery modules = Maximum power required by the PMSM motors at the highest speed of EV / Optimum Power that is delivered by the single battery module
Z

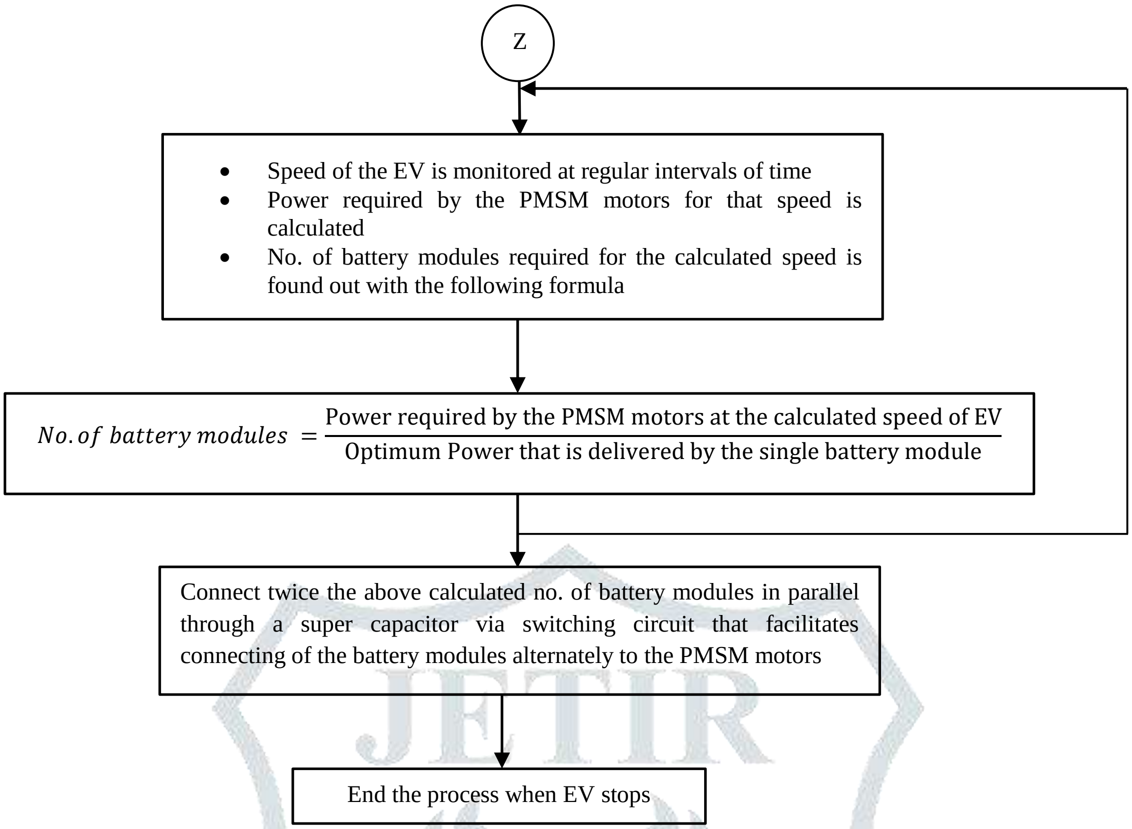


Fig. 7: Algorithm for an improved battery management system for Electric Vehicles

VI. Conclusion

The world is looking for a pollution-free environment. It is a known fact that the major pollution comes from automobiles which are powered by fossil fuels. The pollution caused by fossil fuels is very severe in the cities making them unsuitable for human habitation. Economies across the globe have realized the menace caused by the pollution of the automobile industry. Governments have already set the target time to replace fossil-fueled vehicles by electric vehicles. Most of the developed countries have already implemented them. The proposed battery management system will have a long-lasting impact in terms of improved efficacy of electric vehicles while creating a pollution-free environment. It is envisaged that with the proposed techniques the lifetime of the battery modules can be extended by over 40%. This would lead to an increase in the number of kilometers per charge of the electric vehicles.

References:

1. Satyanarayana Chanagala and Mohammad Mushir Khan, "Maximizing the life time of wireless sensor networks: A survey with a possible solution to further enhance the life time of WSNs," Journal of Electronics and Communication Engineering, Volume 8 Issue 2, Nov. -Dec. 2013.pp 45-51.
2. Satyanarayana Chanagala and Mohammad Mushir Khan, "Effect of battery dynamics and the associated technologies on the lifetime of Wireless Sensor Networks" 2014, Journal of Electronics and Communication Engineering, Volume 9 Issue 1, pp 32-37.
3. Satyanarayana Chanagala and Zafar Jawed Khan, "An approach to maximize the performance of WSN for sampling time less than the optimum value," IDES- Fifth International Conference on Research Methodologies in Electronic Devices and Circuits (EDC 2016).
4. Satyanarayana Chanagala and Zafar Jawed Khan, "A Battery and Environmental Aware Approach to Maximize the Lifetime of Wireless Sensor Network," IEEE- International Conference on Energy, Communication, Data Analytics and Soft Computing (ICECDS 2017).
5. Satyanarayana Chanagala and Zafar Jawed Khan, "Temperature critical boundary conditions for maximizing the lifetime of Wireless Sensor Network," IEEE- International Conference on Computing Methodologies and Communication (ICCMC- 2017).
6. Satyanarayana Chanagala, Zafar Jawed Khan et al, "A Rate Capacity aware approach to maximize the Lifetime of Wireless Sensor Network", International Journal of innovations & Advancement in Computer Science, 2017, Volume 6, Issue 9. (ISSN: 2347 – 8616)

7. Zafar Jawed Khan and Satyanarayana Chanagala, “A Transmission Power level aware approach to maximize the Lifetime of Wireless Sensor Network”, WJERT, 2017, Volume 3, Issue 5, 336-350. (ISSN:245 4-695X)
8. Zafar Jawed Khan and Satyanarayana Chanagala, “The Impact of ambient temperature on the Battery of a Sensor node,” Journal of Electrical Engineering, Elixer Elect. Engg. 113(2017) 49144-49150. (ISSN:2229-712X)
9. Satyanarayana Chanagala and Zafar Jawed Khan, “An approach to mitigating the premature death of the Battery of Sensor Node,” International Journal of Engineering & Technology. 7 (3), 1014-1018 (2018). (ISSN: 2227-524X)
10. Chanagala, Satyanarayana & Khan, Z.. (2019). Energy Efficiency. 10.1007/978-3-662-57277-1_11.
11. Satyanarayana Chanagala and Zafar Jawed Khan, “Investigating the effect of the Sensor node Parameters on its Lifetime”, Journal of the Institution of Engineers (India): Series B. In the review process.