Optimal Charging Strategy for Electric Vehicle Battery

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Abstract— The increase in the emission rate of green-house gases mainly caused by the transport sector has led to growing concerns of global warming. Also, the prices of diesel of the diesel and petrol based fuels are getting higher day-by-day. This demands the inclusion of hybrid and plug-in hybrid vehicles in the transport sector. The major challenges that come in the way for increasing electric vehicle penetration are the charging strategy. The constant current-constant voltage strategy is a conventional method used for charging the batteries. The developed charging strategy in this thesis work is a constant temperature-constant voltage charging strategy. The strategy continuously monitors the charging temperature and with the help of a PID controller and a feed forward current term a charging current is generated. The objective is to develop time optimized charging strategy for electric vehicle batteries. The dynamic model of the charging strategy developed in MATLAB/Simulink software. The simulation studies have been carried out in different operating conditions like varying the charging state of charge of the battery i.e. at 0%, 20%, 50% and 80%. Simulation results show high current levels and faster charging and verify that the charging strategy is effective for real time operations.

Key words: Electric Vehicle Battery

I. Introduction

The environmental concern about climate change caused by global warming has led to growing efforts towards reduction of green-house gases. The transport sector accounts for nearly 23% of global green-house gases emissions. In order to reduce the green-house gas emissions caused by the transport sector, zero emission electric vehicles is the need of the hour. Electric vehicles are the cleanest, most efficient and most effective form of transportation around. Also, the constantly increasing fuel prices as well as the growing environmental concerns are promoting vehicle manufacturers all over the world to bring in the electric vehicle technology into use [1]. The interest in electric vehicle has increased rapidly over the past few years. Many automobile manufacturers have developed modern electric vehicle models and proved that electric drive is technically more suitable and also environmental friendly. Now manufacturers are focused in developing vehicles that are more powerful, have high range, supports fast charging and also cheaper in costs.

The major challenge that comes in front of increasing electric vehicle penetration into the existing system is the charging infrastructure and the type of charging technique adopted [2]. As the range of modern electric vehicle is limited to 100km-300km and also the refueling time can range from 30 minutes to 10 hours or more, the consumers are prompted to stick with the conventional gasoline vehicles that can be refueled within 2-5 minutes or less time. Therefore, fast charging technique must be developed in order to increase the penetration of electric vehicles. The charging methodology which requires 4-8 hours can be implemented at work place or building apartments. Also, home charging can be employed which is actually slow charging but the vehicles can be charged overnight.

The constant temperature-constant voltage charging strategy can be employed for battery charging which is a closed loop charging strategy unlike its conventional method of Constant current-constant voltage. The temperature sensor provides the closed loop feedback path which generates an error signal. Based on the error signal a PID controller can be employed to produce a charging current. The temperature when reaches the set temperature limit of the battery, must be reduced. In order to reduce the temperature the charging current is reduced. Therefore, an exponential decaying current can be used to reduce the charging current. The charging current decreases and when the battery voltage reaches the set nominal voltage of the battery, the charging continues in the constant voltage mode same as in case of CC-CV charging [2].

The temperature rises gradually in the CC-CV charging because the charging current is low. This temperature in this region can be increased by increasing the charging current. Although, now the temperature reaches the set limit early but fast charging is enabled and the temperature limits can be controlled with the help of closed loop feedback system. By using the CT-CV strategy the charging time of the battery can be reduced and also its life cycle and State of Health can be increased.

II. Battery Thermal model

As the battery gets charged, the temperature of the battery increases. Therefore, it is important to model the battery thermal system [3]. The heat generation model of the battery is described by the following equation:

$$mc\,\frac{dT}{dt} = Q_s + Q_o + Q \tag{0.1}$$

Where,

c = Specific heat capacity
m = Mass of the battery
T = Temperature of the battery
Q_s = Reversible reaction heat
Q_o = Energy loss
Q = Exchange of heat

The reversible reaction heat can be described by:

$$Q_s = T\,\Delta S\,\frac{I}{nF} \tag{0.2}$$

$$\Delta S = n_{re}\,F\,\frac{\delta E}{\delta T} \tag{0.3}$$

$$Q_s = T n_{re}\,\frac{\delta E}{\delta T}\,\frac{I}{n} \tag{0.4}$$

Where,
F = Faraday constant
I = Charging current
n_{re} = Number of moles of electron transfer of battery
ΔS = Entropy change
Heat conversion is defined as,

$$Q = hA(T-T_{amb})$$

h = Coefficient of heat exchange
A = Surface area of the battery
T_{amb} = Ambient temperature

Temperature of the battery can be defined by exponential function:

$$T_k = \exp\left(\frac{-hA}{mc}\right)T_{k-1} + \left[1-\exp\left(\frac{-hA}{mc}\right)\right]\frac{Q_s+Q_o+hAT_{amb}}{hA} \quad (0.5)$$

III. PID CONTROLLER MODELLING

Proportional Integral Derivative (PID) control is one of the control strategies and consists of a control loop feedback mechanism widely used in industrial control systems and a variety of other applications which require continuously modulated control. There are various design techniques for designing a PID controller such as Ziegler-Nichols algorithm, Cohen-Coon formula, Refined Ziegler-Nichols tuning etc.

A PID control can be described by the following block diagram. The error signal is used to generate the proportional, integral and derivative signals. There is a feedback signal which continuously monitors the output Y(t) and therefore, the error signal keeps on changing. The control signal u(t) from the controller is applied as an input to the plant model. The control signal has all the proportional, integral and derivative term in it and is given by:

$$u(t) = K_p[e(t)+k_i\int_0^t e(\tau)d\tau + K_d\frac{de(t)}{dt}] \quad (0.6)$$

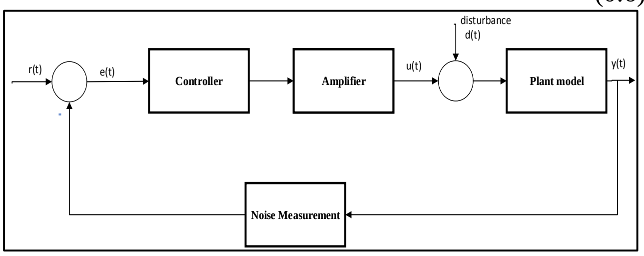

Fig. 1: PID Controller

Where,
K_P, K_d, K_i are the proportional, integral and derivative gains respectively.
u(t) = Input signal to plant
e(t) = Error signal
r(t) = Reference signal
The transfer function in Laplace Domain of PID controller is:

$$L(s) = K_p + \frac{K_i}{S} + K_dS \quad (0.7)$$

Where, S is complex frequency.

For high values of K_p, the response speed as well as the overshoot of the closed loop system increases. Therefore, the steady-state error decreases. But the value of K_p cannot be increased beyond a limit because the closed loop system becomes unstable. If K_d increases, the response has smaller overshoot with slow rise time.

In practical approaches where there is a jump in the error signal, the derivative term is preferred in the feedback path. As the output is not changing for a step input, the response can be made smooth by taking derivative of the output.
The controller transfer function is given by:

$$G(s) = K_p\left(1+\frac{1}{T_i S}\right) \quad (0.8)$$

The feedback transfer function is given by:

$$H(s) = \frac{\left(1+\frac{K_p}{N}\right)T_iT_dS + K_p\left(T_i+\frac{T_d}{N}\right)+K_p}{K_p(T_iS+1)\left(\frac{T_dS}{N}+1\right)} \quad (0.9)$$

IV. CT-CV CHARGING STRATEGY

The constant temperature-constant voltage charging strategy can be employed for battery charging which is a closed loop charging strategy unlike its conventional method of Constant current-constant voltage. The temperature sensor provides the closed loop feedback path which generates an error signal. Based on the error signal a PID controller can be employed to produce a charging current. The temperature when reaches the set temperature limit of the battery, must be reduced. In order to reduce the temperature the charging current is reduced. Therefore, an exponential decaying current can be used to reduce the charging current. The charging current decreases and when the battery voltage reaches the set nominal voltage of the battery, the charging continues in the constant voltage mode same as in case of CC-CV charging.

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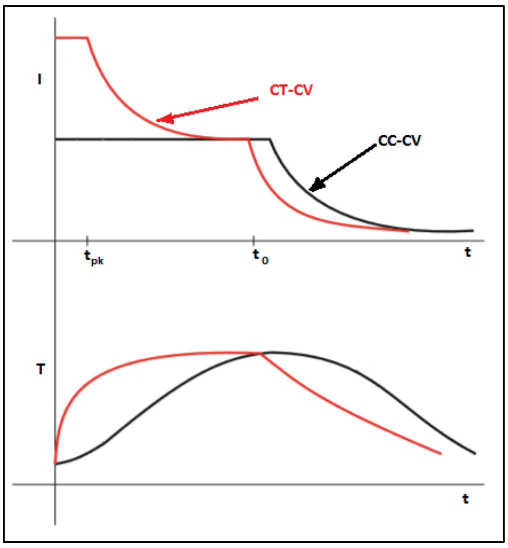

Fig. 2: CT-CV charging current and temperature variation with time

V. CT-CV MODELLING SCHEME

The constant temperature-constant voltage charging scheme uses a temperature sensor to continuously monitor the battery temperature and generate a charging current which is higher than that used in a conventional CC-CV charging. The sensed temperature is fed back and compared to a reference set temperature. The error signal is sent to a PID controller which generates a current signal (I_{pid}). This current together with the feed forward current (I_{ff}) which is exponentially decaying is given to the charger as the charging current.

The PID control equations are:

$$e(n) = T_{set}(n) - T_f(n) \quad (0.10)$$

$$I_p(n) = K_p\, e(n) \quad (0.11)$$

$$I_i(n) = I_i(n-1) + K_i\, e(n) \quad (0.12)$$

$$I_d(n) = K_d\,[e(n) - e(n-1)] \quad (0.13)$$

$$I_{pid}(n) = I_p(n) + I_i(n) + I_d(n) \quad (0.14)$$

Where,
$e(n)$ = Controller error
T_{set} = Reference temperature
T_f = Feedback temperature
K_p, K_i, K_d are controller proportional, integral, derivative gains respectively.

In constant current-constant voltage mode of charging, the temperature rises gradually in the initial constant current charging phase. Therefore, there is a scope that the current during this mode can be increased. So, the current levels can be increased when constant temperature-constant voltage technique is employed. But when the temperature reaches the set point, current must be decreased gradually and thus is decreased by an exponentially decaying current known as the feed-forward current. The feed forward current is given by,

$$I_{ff} = \begin{cases} 2C & : 0 \le t \le t_{pk} \\ C\left(1+e^{-\left(\frac{t-t_{pk}}{\tau}\right)}\right) & : t_{pk} \le t \le t_{cv} \\ 0 & : t > t_{cv} \end{cases} \quad (0.15)$$

Where,
C = Charging rate of the battery
t_{pk} = Time for which constant current is held at peak value
t_{cv} = Time at which constant voltage mode starts
τ = Time constant of exponential decay

The electrical model or the Thevenin model of the Li-ion cell is shown in fig.4.

Here, V_t is the terminal voltage, V_{oc} is the open circuit voltage, R_o is the ohmic resistance, R_1 is the polarization resistance, C_1 is the polarization capacitance.

$$R_{int} = R_o + R_1 \quad (0.16)$$

$$P_{loss} = I_{ch}^2 (R_o + R_1) \quad (0.17)$$

Because of this power loss, the surface, ambient and internal temperature of the cell increases. Therefore, the thermal mode of Li-ion cell is also considered.

The equations depicting thermal model is as follows:

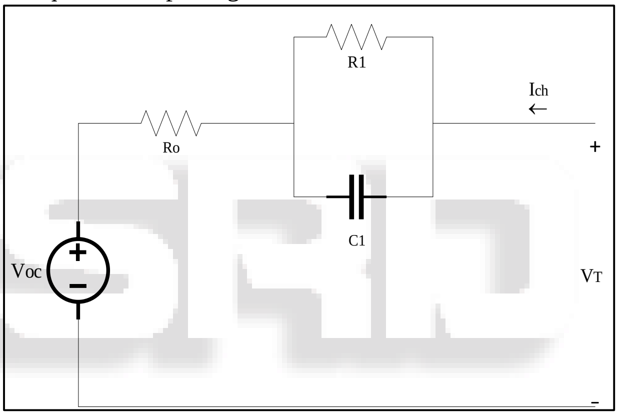

Fig. 3: Electrical model of battery

$$C_s \frac{dT_s}{dt} = \frac{T_i - T_s}{R_{\theta is}} - \frac{T_s - T_a}{R_{\theta sa}}$$

$$T_i \quad \frac{dT_i}{dt} = P_{loss} - \frac{T\ \ T}{T_s} \quad (0.18)$$

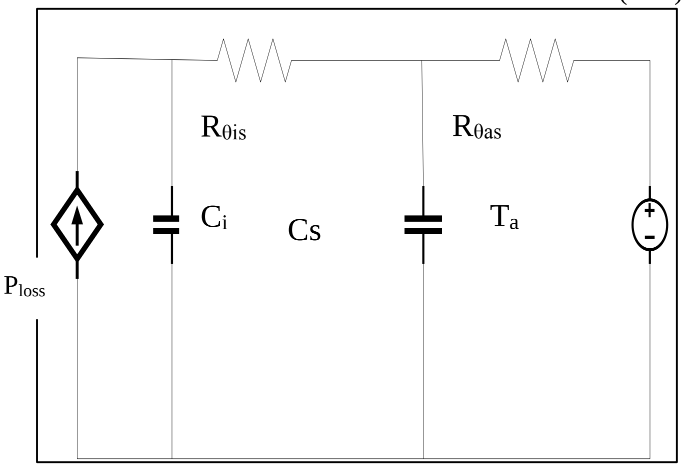

Fig. 4: Thermal model of Li-ion cell

VI. RESULTS

The battery is at 0% state of charge i.e. there is no initial charge in the battery. Figure 4 shows the waveform for input supply voltage and input supply current to the battery, state of charge, temperature CC-CV schemes. The charging current is kept at 2.3 amperes in CC mode for CC-CV scheme and the cell temperature is allowed to increase gradually. The same charging current is kept at 4.8 amperes in case of CT-CV mode initially for some duration to achieve fast charging.

Once the temperature reaches the set point, the feed-forward current term generates exponentially decaying current due to which the charging current and hence, the cell temperature will remain within limits. When the voltage reaches the battery nominal voltage of 3.7V as shown in fig. 4, the charging starts at constant voltage and the current decreases instantaneously at that point. After this the charging continues in the constant voltage mode.

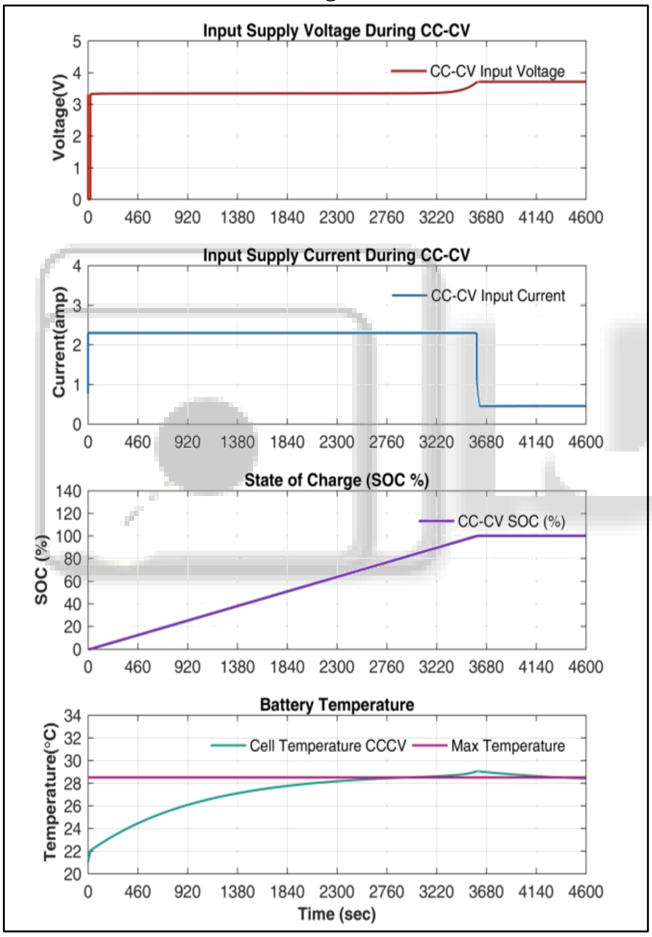

Fig. 5: Simulation results of CC-CV charging method for 3.7V lithium ion Battery at 0% SOC, Waveform of input supply voltage, input supply current, state of charge, battery temperature.

The state of charge curve depicts that it takes 3600 seconds i.e. 60 minutes to charge the battery from 0% SOC to 100% in case of CC-CV mode whereas the same occurs in 2760 seconds i.e. 46 minutes in case of CT-CV scheme. This shows that there is a decrease in the charging time of 14 minutes which is a 23% decrease. The cell temperature curve shows that the temperature rises above a set level in case of CC-CV but the temperature never rises above a set level in case of CT-CV scheme because of the controller.

Figure 6 shows the waveform for input supply voltage and input supply current to the battery, state of charge, and temperature for CT-CV schemes.

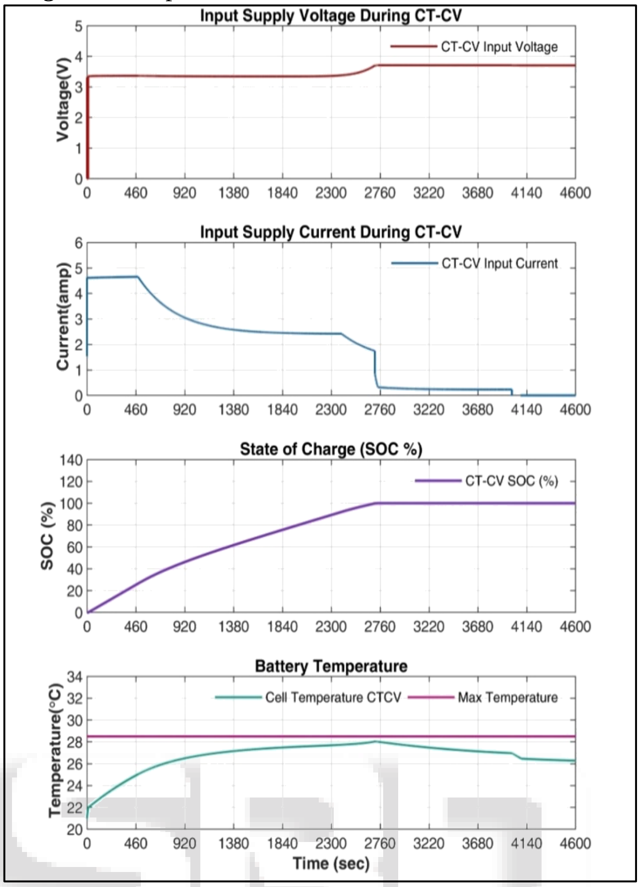

Fig. 6: Simulation results of CT-CV charging method for 3.7V lithium ion Battery at 0% SOC, Waveform of input supply voltage, input supply current, state of charge, battery temperature.

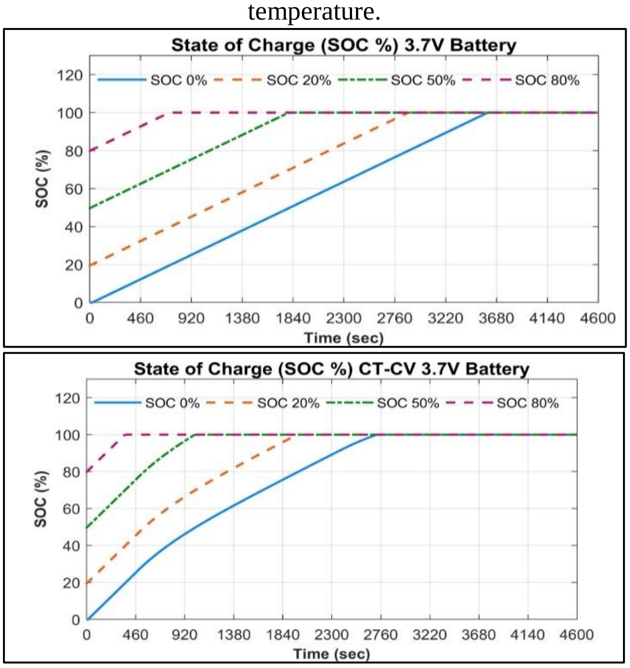

Fig. 7: Response of Battery SOC for 3.7 V Lithium-ion Battery for Both the Schemes

Fig. 7 shows the State of Charge of the conventional CC-CV scheme and proposed CT-CV scheme. The two responses clearly indicate the time required to charge the battery completely from different initial State of Charges. The time for charging in the CC-CV mode is clearly more than that in the CT-CV mode. Therefore, the SOC response is clearly an indication of the time optimized charging strategy.

VII. CONCLUSION

The presented work is carried out for a plug-in electric vehicle battery charging strategy. The conventional Constant current-Constant voltage strategy is widely implemented for charging of electric vehicle's battery. The proposed strategy is based on instantaneously measuring the battery temperature, voltage, current and State of Charge at the time of charging and then decides the charging mode and current based on the instantaneous values. This system of charging is much more efficient than the conventional method and also has many advantages. On the basis of the simulation results and the performance analysis carried out, the following points can be concluded:

- A dynamic model of the proposed charging strategy along with the conventional strategy has been successfully developed.
- The proposed strategy optimized the overall charging time as compared to the conventional method as shown in the simulation results.
- The CT-CV scheme reduces the charging time by 23%, 21% and 41% for initial SOC of 0%, 20% and 80% respectively.
- The strategy also monitors the charging temperature continuously and can improve the Battery State of Health. By increasing the temperature of the battery by 10ºC, the lifetime of the battery becomes half. Therefore, maintaining the charging temperature can enhance the battery life.
- In applications requiring faster charging, this scheme can be quite effective by raising the set temperature even more if the Battery State of Health is not a big issue.

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