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Analysis of a Novel Battery Model to Illustrate the Instantaneous Voltage for a Hybrid Electric Vehicle

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Abstract

Hybrid electric vehicle (HEV) has two power sources, a conventional internal combustion engine (ICE) and a rechargeable battery. The success of the HEV is much dependent on the reliability of its battery. Battery modelling is the representation of the operation of a battery. An accurate battery model would render an efficient battery management system, reducing the size and fuel consumed by the ICE. In this paper, the instantaneous voltage of the battery has been explained with the help of the proposed electric model. It has been designed in Matlab/Simulink environment and validated against the basic electric models. The model holds true for batteries of different chemistries with minor modifications.

Keywords: Hybrid electric vehicle, battery modelling, state-of-charge (SOC)

1. Introduction

Reduction in the availability of fossil fuel, increasing environmental concern and advancement in automotive technology have influenced leading automakers across the globe to emphasize on research to develop exceedingly fuel efficient, low maintenance, low emission and cheaper means of transport. Hybrid electric vehicle (HEV) is one such form of alternative transportation developed to meet these ever increasing demands that has brought radical changes in the automotive industry and its concerned field of research in the last decade. Unlike conventional vehicles, HEV has two power sources, a gasoline engine and a rechargeable energy storage system such as battery [1]. The fuel efficiency of HEV depends much upon the optimal combination of the drive train which consists of a conventional internal combustion engine (ICE), a rechargeable battery, electric motor, power converter and transmission [1]. The main objective in HEV is to reduce dependency on the engine by sharing the power demand between battery and ICE. The success of HEV banks on the reliability of its battery. Battery modelling is essential for the analysis of dynamic behaviour of battery and predicting its state-of-charge for a given driving schedule. The correct modelling of battery determines and describes its efficiency [2]. Numerous simple electric models have been proposed but relatively a very few are suitable for the dynamic simulation of HEV and are valid for different chemical compositions. This paper discusses the different attributes of basic electric models (Thevenin, impedance and runtime based model) and proposes a new battery model. The model has been designed in Matlab/Simulink environment. The losses and terminal voltage of the battery are explained with help of the model. The internal parameters and their effects are justified. Thus, a better understanding of the battery operation can boost its reliability, reducing the engine size and fuel consumed as compared to a conventional vehicle.

2. Background

The battery forms a very critical part of the HEV drive-train. A battery can ideally be represented as a simple DC voltage source with zero internal resistance. But in reality, the battery contains many other internal parameters that explain its real-time operation. These internal parameters change along the charge-discharge cycle. Temperature, ageing, level of charge and discharge affect these internal parameters. The different battery chemical compositions also render variations in these internal parameters leading to a considerable dissimilarity in the charge-discharge characteristics.

These characteristics of a battery can broadly be represented and explained by electrochemical models, mathematical models and electric circuit models. Electrochemical models are complicated and time consuming although they explain the basic physical characteristics of the battery [3]-[5]. The mathematical models are capable of predicting the efficiency and capacity of a battery but its accuracy is questionable [3], [6]. Unlike mathematical models, electric circuit models are more accurate and can also explain the *V–I* characteristics in relation to the internal parameters [6]. Thus, electric representation is necessary to substantiate the electrochemical changes in the battery which in turn would help in increasing the life of the battery and designing an efficient battery management system.

The electric circuit models can further be broadly classified according to the real time conditions incorporated in them. The models that are mostly studied in different literatures are ideal model, linear model, Thevenin model, impedance based model and runtime based model. In the ideal model, the internal generated cell voltage is the terminal voltage (i.e. zero internal resistance). The linear model [5] represents the cell with a simple resistance as shown in Fig. 1.

The output voltage across the battery terminals is given by:

$$V_{terminal} = V_{internal} - R_{internal} \times I_{battery} \quad (1)$$

Where,

$V_{internal}$ = no-load full charge voltage

$V_{terminal}$ = terminal voltage

$R_{internal}$ = internal resistance and

$I_{battery}$ = battery current

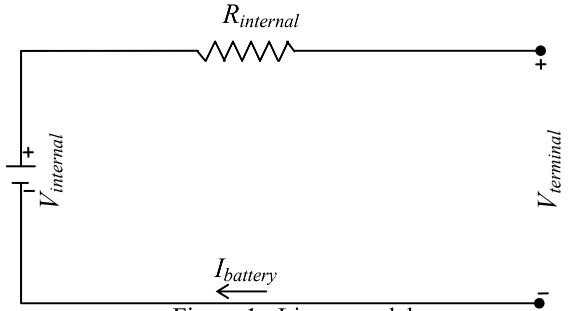


Figure 1: Linear model.

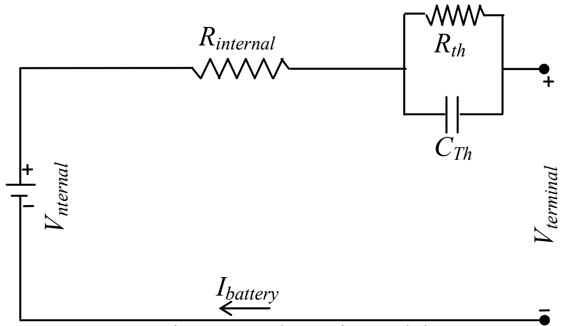


Figure 2: Thevenin model.

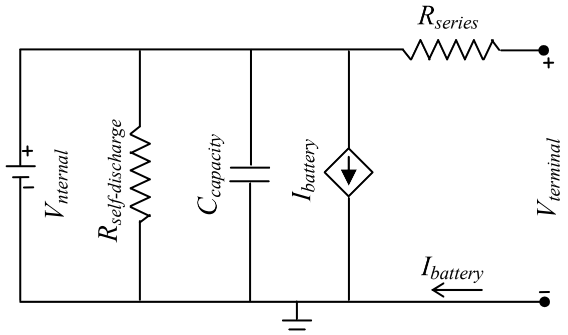


Figure 3: Runtime based model.

This model is unable to predict any transient occurring in the battery. The Thevenin model shown in Fig. 2 has an overvoltage protection incorporated in addition to the linear model. The Thevenin circuit model is applicable for a fixed state-of-charge and constant open circuit voltage [5]. Unlike linear models, it can predict the transient responses [4].

The runtime model as shown in Fig. 3 is one of the most practical models that have been improvised by researchers for predicting the runtime of the battery under real time conditions [4]. In runtime based model $V_{terminal}$is a function of $V_{internal}$.

Where,

$V_{internal}$ = open-circuit voltage

It helps to predict the runtime of the battery in terms of the current flowing through it. The impedance based model as shown in Fig. 4 applies electrochemical spectroscopy to obtain the

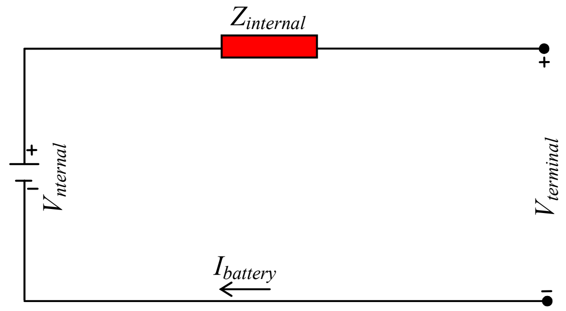


Figure 4: Impedance based model.

ac-equivalent impedance at a given frequency domain [4].

One of the most important challenges that need to be tackled for accurate modeling is the variable charge-discharge characteristics of the different battery chemistries. The models should be able to represent the operation of batteries of different chemistries (such as lithium-ion, lead acid) with minor modifications.

3. Proposed model

The proposed model is focussed on illustrating the terminal voltage of the battery. Fig. 5 shows the model proposed to predict the state-of-charge and analyze the terminal voltage of the battery as a function of the internal resistance.

It is a combination of the basic models by taking their positive attributes into account. The battery model takes into consideration the open-circuit voltage and current for a steady charge-discharge cycle. Runtime of the battery is shown in Fig. 5(a) and the model to analyze its charge-discharge characteristics is shown in Fig. 5(b). The voltage drop across the battery is explained with the help of internal resistances.

$V_{Ibattery}$ is a current controlled voltage source used to represent the battery voltage variation with the charge and discharge current.

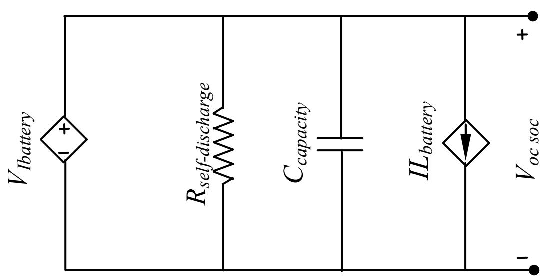
$R_{self\text{-}discharge}$ is used to characterize the losses that occur in a battery stored for a long period of time. Although the effect of $R_{self\text{-}discharge}$ is negligible when the battery is connected across the load, it differs widely with the chemical compositions of the battery at no load conditions. The capacitor $C_{capacity}$ initially has the theoretical generated voltage applied across it representing the state-of-charge of the battery. $IL_{battery}$ represents the load current flowing during charge or discharge of the battery. The runtime of the battery is the time taken to discharge or charge the battery to a pre-determined voltage depending upon its operational requirements and chemistry.

The resistance R_{series} in series with the parallel *RC* networks (R_1, C_1 and R_2, C_2) as shown in Fig. 5(b) has been incorporated from the Thevenin electric circuit model. The *RC* network is used to predict the battery response to transient loads for a fixed state-of-charge. Increase in the number of *RC* networks would increase the accuracy of the transient response but for ease of calculation only two *RC* networks have been considered [5].

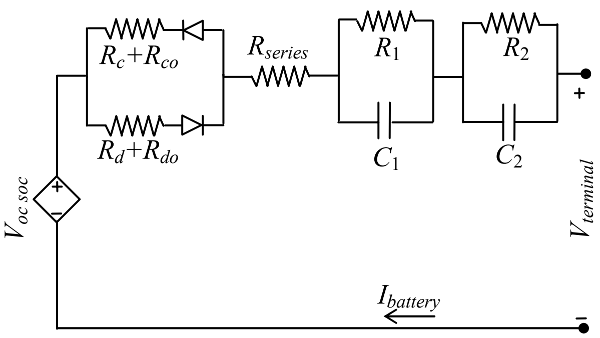
R_c and R_d are the charging and discharging resistances respectively while R_{co} and R_{do} are overcharge and over discharge resistances respectively. The consideration of the charge, discharge resistance and the overcharge, over discharge resistance has been discussed in [7]. The voltage across the terminals is a function of these resistances. The proposed model analyses the voltage loss across these elements for the following conditions:

a) No load condition.
b) Constant load of 50 A.
c) Constant load of 75A.

The diodes ensure that the resistances corresponding to the charging and discharging of the battery act separately. $V_{oc\ soc}$ is a current controlled voltage source that signifies the state-of-charge of the battery. It acts as the reference voltage for the battery when connected to a load.



(a)



(b)

Figure 5: The proposed electric model of a battery for HEV. (a) Runtime. (b) *V-I* characteristics.

4. Simulation

4.1 Model Formulation

The proposed model has been simulated in Matlab/Simulink environment. The assumptions for this model are:

1. The self discharge resistance is negligible at loaded operation.
2. The internal resistance varies along the charge-discharge cycle.
3. No Peukert effect.
4. No memory effect.
5. The charging and the discharging characteristics are assumed to be identical.

The model parameters used for validation of the proposed model are derived from the manufacturer's data sheet. The control circuit has been designed for series-parallel hybrid architecture. It is a precise improvement of the Matlab/Simulink control model against which the proposed model has been validated.

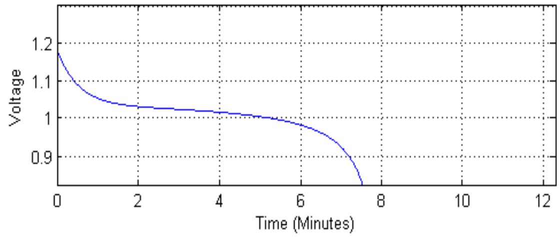


Figure 6: Discharge curve of a Ni-MH cell at constant load of 75A.

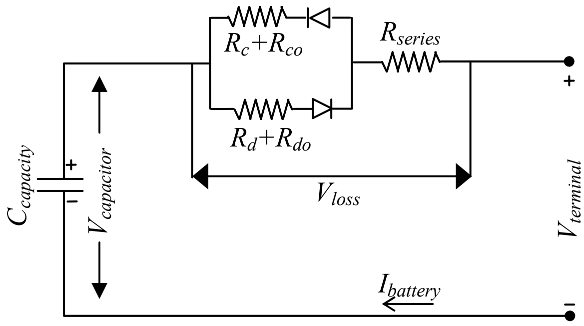


Figure 7: Capacitive representation of the proposed model.

4.2 Capacitive Representation of the Proposed Model

The discharge characteristic of the Ni-MH battery against which the model has been validated is shown in Fig. 6. The charging-discharging capacity of the battery as shown in Fig. 6 is represented by the capacitor $C_{capacity}$ in Fig. 7 [8]. The model to illustrate the *V-I* characteristics as shown in Fig. 5(b) is further improved as shown in Fig 7.

The time constant for the Ni-MH cell on which this model would be validated is derived from the charge-discharge characteristics in Fig. 6. The permissible operating range of the battery varies with the chemical compositions, battery management system design features and energy management system precision.

The voltage ratings and capacity of the battery are provided in the manufacturer's data sheet. The capacitance has been calculated on the basis of this provided information.

We know

$$1\,Ah = 3{,}600\ Coulombs \tag{2}$$

where Ah is the charge of the battery and

$$Q = C \times V \tag{3}$$

where Q is the charge stored in the battery and V is voltage across the capacitor. In this simulation the internal voltage, $V_{internal}$ has been considered to be 1.2 V, corresponding to the Ni-MH cell that being used in HEVs. The rate of resistance change varies along the charge-discharge cycle, according to the charge present and the current flowing through it. The state of charge is calculated by

$$SOC = Q - \int_0^t i(t)dt \tag{4}$$

The initial voltage across the capacitor is the voltage of the battery at full charge no-load condition. The capacitor charges or discharges according to the direction of battery current i.e. charging or discharging mode.

This proposed model can be used to accurately validate batteries of different chemistries like lithium-ion and lead-acid of different ratings by modifying the time constant and the value of the capacitor. It can similarly be used to illustrate the operation of ultra-capacitors.

The pre-information of charge-discharge characteristics and internal resistance provided by the manufacturer are used and verified by the proposed model.

4.3 Analysis of Validation Model

The model is validated against a 175 hp DC machine (Matlab/Simulink model), 1.2 V, 6.5 Ah Ni-MH battery as shown in Fig. 8.

The machine works both as a generator and motor depending upon the power demand and state-of-charge of the battery. The terminal voltage

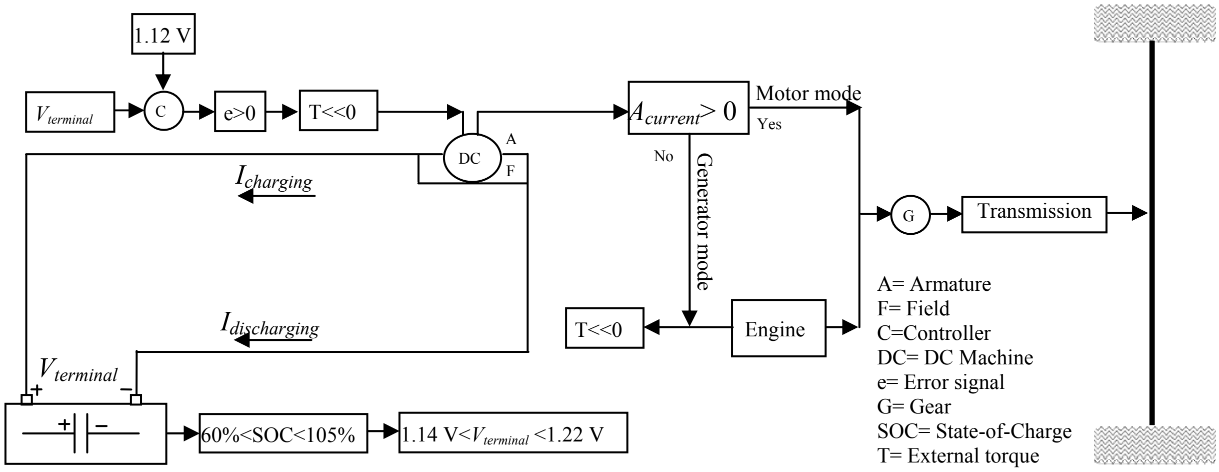


Figure 8. The control architecture for validation of the proposed model.

is operated in a region of 1.2 V to 1.14 V for the Ni-MH battery, where the previous represents the full charge voltage and the latter represents the permissible discharge voltage for real time operation of the hybrid electric vehicle. It has been assumed that initially the battery is completely charged (i.e. at 1.2 V). The battery is discharged for providing power to an external load of 75 A (similar to the operation used in [8], in order to validate the model under similar conditions, with some more precise improvements as per recent developments) until it reaches 1.14 V. The battery is never completely discharged under real operating conditions, but in order to analyse the voltage drop across the complete state-of-charge range, it is pushed to its limits. The 175 hp DC machine acts a generator when the terminal voltage reaches 1.14 V. A negative torque of 75 N.m. is applied to the machine as shown in Fig. 8. The generated current provides power for both the external load and the battery. The changing of the DC machine to the generator and motor mode needs to be precise in order to prevent overcharging or over-discharging of the battery. The capacitor representing the battery, charges and discharges according to the DC machine operating mode. The internal generated cell voltage is always constant, but the terminal voltage varies with the varying resistance at different state-of-charge. The terminal voltage is also dependent upon the direction of the current. The charge acceptance by regenerative braking is neglected for validating the proposed model. The capacitive nature of battery has a dependence on the machine parameters which needs to be precisely optimized in order to improve the overall efficiency.

5. Results

The results are obtained by simulating the proposed model in the control circuit mentioned in Section 4.3.

The battery is initially allowed to discharge completely under a constant load, i.e. the state-of-charge is allowed to reduce to zero by inhibiting the generator operation. It is performed for the analysis of the change in internal resistance across the complete SOC range. It is observed that a steady gain in the battery internal resistance takes place along the discharge. The terminal voltage with respect to the internal resistance is shown in Fig. 9. Fig. 10 shows the variation in internal resistance till the state-of-charge reaches almost 80% of its rated value. The battery resistance is minimum when it is fully charged. The rate of increase of the internal resistance accelerates after attaining 20% degree of discharge. This rate of increase is also dependent on the charge and discharge rates

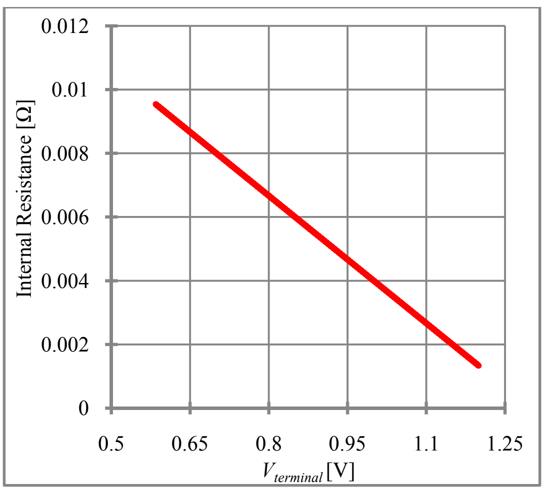


Figure 9: $V_{terminal}$ as a function of internal resistance.

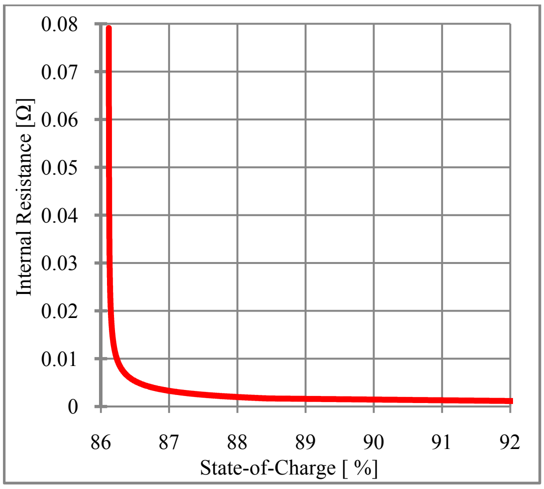


Figure 10: Internal resistance drop across SOC.

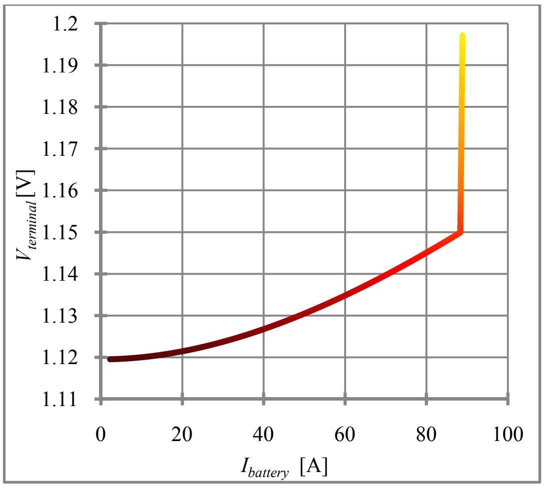


Figure 11: $V_{terminal}$ vs $I_{battery}$ for motoring mode.

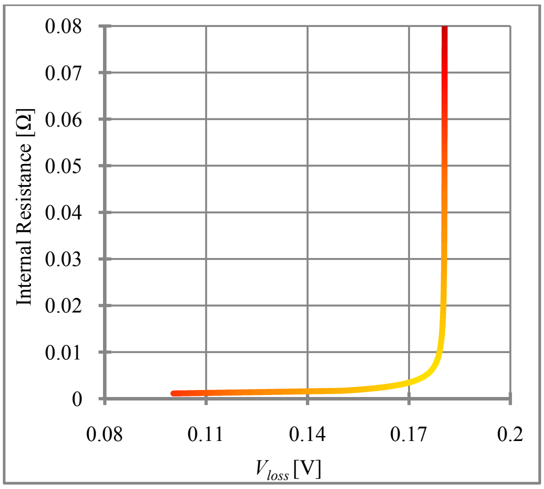


Figure 12: V_{loss} as a function of internal resistance.

along with the load requirements. In Fig. 11, the variation of the terminal voltage with repsect to the battery current is shown. Here the terminal

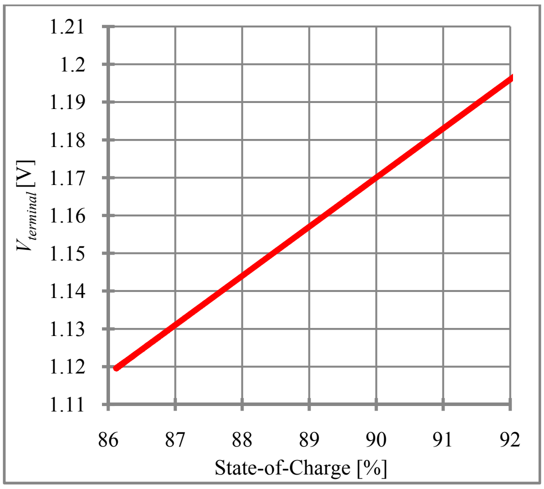


Figure 13: $V_{terminal}$ variation across SOC.

voltage is allowed to operate within a calculated range with certain degree of overdischarging. This is due to the reaction time between the motor/generator changing mode.

The generator pick-up time to produce enough power to meet the load demand and charge the battery is dependent on the external applied torque and machine parameters. It should be noted that $I_{battery}$ becomes zero when $V_{terminal}$ reaches 1.12 V as the DC machine shifts from motor mode to the generator mode. This over-discharging is also due to the generator pick-up time. The terminal voltage can be precisley inllustrated from Figs. 12 and 13. The drop across the resistance at different state-of-charge can be used to define the instantaneous terminal voltage.

6. Conclusion

The proposed model can analyze the variation in the internal resistance of the battery which accounts for the terminal voltage pertaining to the real time operation of HEV. The proposed model can be also used for different battery ratings and chemistries used in the HEVs' with minor modifications, according to their respective charge-discharge characteristics. The capacitive representation of the battery renders a better understanding of the battery operation. The internal resistance dependence on the state-of-charge and the discharge rate of the battery has been inferred. The charging and discharging current also has a considerable effect on the internal resistance variation. It has been observed that the internal resistance increases almost proportionally at lower SOC, thus rendering a faster discharge. It is hence recommended to maintain an optimum range of state-of-charge depending upon the load connected across the battery, in order to prevent abuse.

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