# Digital Twin based Capacity Prediction of Ultracapacitors

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*Abstract*—**Predicting an ultracapacitor's failure or degradation is a key component of the power management system. This paper provides a capacity prediction approach based on the digital twin model of ultracapacitors. The available energy data collected from the ultracapacitor are periodically transferred to the digital twin model and tuned to its capacity prediction. An experimental study validates the effectiveness of the proposed method. Note that the source codes and the test data of the proposed algorithm are publicly available at GitHub (github.com/KangshiWang/SupercapacitorCapacityPrediction).**

*Index Terms*—**ultracapacitor, digital twin, capacity degradation**

## I. Introduction

Ultracapacitors play an essential role in rail transportation, renewable energy, and power systems. The electricity stored in the ultracapacitors is vital for the power supply. Therefore, accurate prediction of the lifetime of ultracapacitors is crucial for the related energy storage systems.

Some studies have shown that the ultracapacitors can be charged and discharged millions of times [1]. Yanting Zhou et al. [2] proposed a life prediction approach based on a neural network with long short-term memory (LSTM). LSTM is used to determine the ultracapacitor's decreased capacity. Alon Oz et al. [3] proposed a novel approach to analyzing electrochemical impedance spectroscopy of ultracapacitors. The ultracapacitors' operation mechanism and degradation processes are characterized by the spectroscopy measurement results. However, this scheme is complex and costly due to the need to measure impedance spectroscopy. The traditional approaches for the capacity predication of ultracapacitors can basically be divided into two categories: data-driven or physical models. The data-driven modelling approach uses historical data to build the lifetime prediction model of the ultracapacitor. Once the model is created, the historical data does not play a role anymore. The physical modelling approach has the demerits of complicated measurement equipment and calibration process.

With the development of sensor technology and data analysis methods, digital twin technology provides a new idea to solve the above problems. Digital twin uses virtual simulation technology to explore and predict the operation state of physical assets, which provides an essential theoretical basis for the simulation to reality connection and real-time interaction between virtual space and physical space. Its main advantage is the ability to map the real-time state of a product to the virtual space, which is a natural fit with the product's life and reliability needs. Digital twin technology has been applied to the state-of-charge estimation of both lithium-ion and lead-acid batteries [4]. In [5], the lithium-ion battery degradation in dynamic operating conditions is evaluated by a digital twin model. Inspired by these methods, we propose a digital twin-based method for lifetime prediction and reliability assessment of ultracapacitors in this paper. To the best of our knowledge, it is the first time that digital twin technology has been used to build a lifetime and degradation model to express the state of ultracapacitors. Besides, the proposed model accurately represents ultracapacitors' dispersion and uncertainty characteristics.

The following sections are organized as follows: the methodology of the proposed digital twin based capacityprediction model is discussed in Section II. The experimental findings are discussed in Section III. Section IV concludes this paper.

## II. Methodology

This section introduces an artificial neural network (ANN) based ultracapacitor's life prediction method. Based on this, selected variables are used to predict the electrical capacity of this ultracapacitor. After that, a digital twin model eliminates the error between the simulation model and the actual capacity.

### A. *Digital twin model*

The proposed digital twin model can be seen as an ANN that optimizes a predictive model by learning the gaps between a mathematical model and actual experimental data. The digital twin allows us to get feedback on the gap between what is predicted through mathematical models and actual experimental data. The real-time estimation through ANN feedback makes the digital twin model better than the ordinary mathematical model. This way, the consistency between mathematical and experimental results is guaranteed throughout the prediction process. Before that, we need to build a mathematical model named $cf$ to roughly describe the relationship between the number of battery charging and discharging cycles and the electrical capacity. With the two-term exponential model, we can approximately predict the capacity value with any number of charge/discharge iterations as the independent variable.

After the mathematical model is built, the digital twin model sets the output as the difference between the real experimental data and the mathematical prediction model as shown in Eq. (1), unlike the conventional way which sets the input as the number of iterations and the output as the experimentally derived electric capacity of the ultracapacitor of the ANN.

$$output = data.capacity - f(time) \tag{1}$$

where $output$ denotes the output variables of the digital twin model, $data.capacity$ is the actual capacity data, $f(time)$ is a capacity prediction model in digital space with the number of charge/discharge cycles as the input variables.

Fig. 1 shows the schematic diagram of the digital twin model. We first construct the database by the electrical capacity. At the same time, we construct the mathematical model to predict the capacity content in digital space and get the predicted value of capacity after several iterations. There is a gap between the real experimental data and the results obtained from the mathematical model. Therefore, an ANN eliminates the difference so that the gap between the digital space and the real world can be bridged.

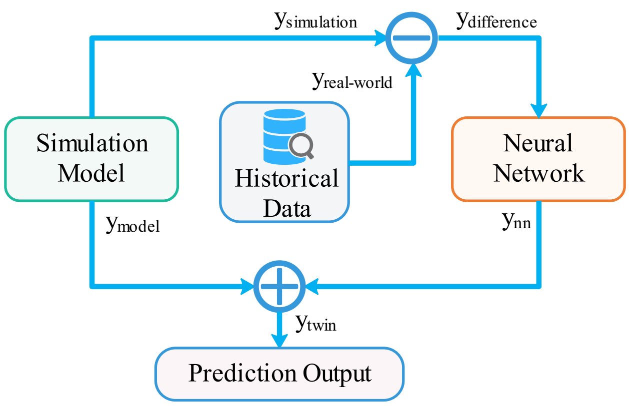



Fig. 1. Schematic diagram of the digital twin model.

## III. Experimental Validation

### A. Test Platform

The experiments were carried out on ultracapacitors from Maxwell Technologies Inc. with the nominal capacitance of 5F and 2F. The nominal operating voltage is 2.7V. As per the datasheet, the maximum charge voltage is set to 2.5V, and the minimum discharge voltage is set to 0.1V. The charge current is set to 1.6A and 1.2A for the 5F and 2F ultracapacitors. The loads are three 2.7Ohm/5W resistors in parallel. The charge and discharge currents are within the maximum range allowed by the datasheet. The test platform, shown in Fig. 2, consists of a power supply to charge the single ultracapacitor and a data acquisition board to record the charging and discharging energy.

TABLE I
Comparison among ANN and DT

| Capacitance | Model | SSE | MAE | MSE | RMSE | R2 |
|---|---|---|---|---|---|---|
| **5F** | **ANN** | 3.4436 | 0.0112 | 0.0002 | 0.0148 | 0.9954 |
| | **DT** | 1.9905 | 0.0089 | 0.0001 | 0.0112 | 0.9974 |
| **2F** | **ANN** | 3.4547 | 0.0113 | 0.0002 | 0.0148 | 0.9952 |
| | **DT** | 2.0206 | 0.0090 | 0.0001 | 0.0113 | 0.9973 |

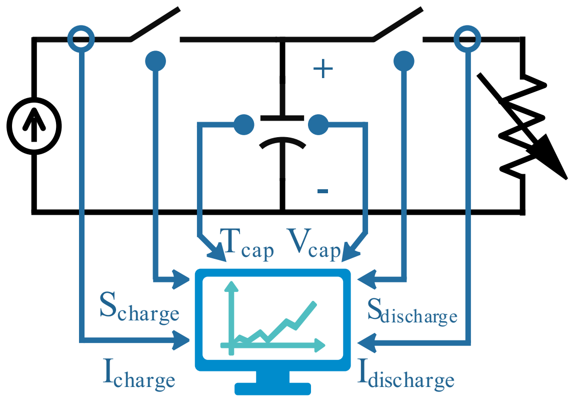



Fig. 2. Schematic diagram of the test platform.

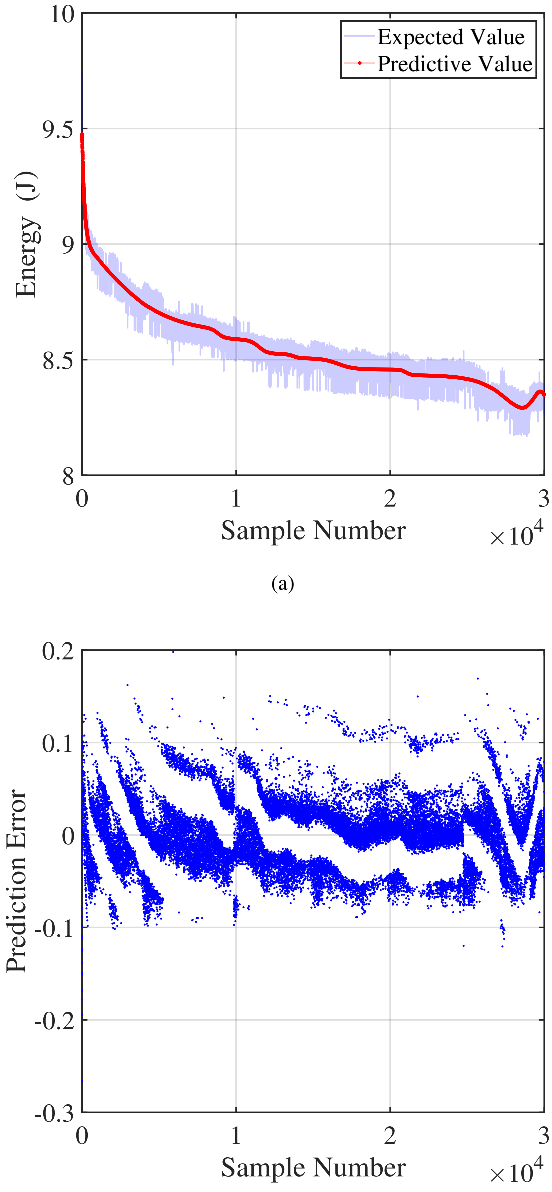
### B. Experimental results and analysis

The experimental results that show the performance of the digital twin model are demonstrated in Fig. 3. The experimental results of the predicted capacity in terms of energy stored are shown in Fig. 3(a) . The horizontal axis represents the number of iterations of ultracapacitor charging and discharging in the experiment. The ultracapacitor capacity prediction model of the digital twin has a good fit with the actual value. In Fig. 3(b), the vertical axis represents the error between the predicted value and the actual data, which is the output of the digital twin model. The distribution of the error is within the range of $\pm 0.1J$.

The error sum of squares (SSE), mean absolute error (MAE), mean squared error (MSE), root mean squared error (RMSE), and decision coefficient ($R^2$) are used to evaluate the performance of the proposed lifetime prediction model for ultracapacitors. The experimental results are shown in Table. I. The results show that the digital twin prediction method can achieve higher accuracy than the traditional ANN approach.

## IV. Conclusions

This paper proposes an ANN-based digital twin model capable of bridging the "simulation to reality" gap. Compared with traditional methods, digital twins can achieve more accuracy




(a)

(b)

Fig. 3. Experimental validation: (a) Capacity degradation, (b) Error of capacity degradation.

in predicting realistic simulated objects and better adaptation to the real world.

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