A Comparative Study of Deep Neural Network and Meta-Model Techniques in Behavior Learning of Microgrids

HAO XIAO1,2, (Member, IEEE), WEI PEI1,2, (Member, IEEE), WEI DENG1,2, (Member, IEEE), LI KONG1,2, HONGJIAN SUN3, (Senior Member, IEEE), AND CHENGHONG TANG4, (Senior Member, IEEE)

1Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing 100190, China
2School of Electronic, Electrical, and Communication Engineering, University of Chinese Academy of Sciences, Beijing 100049, China
3Department of Engineering, Durham University, Durham DH1 3LE, U.K.
4NARI Group Corporation, Nanjing 211106, China
Corresponding author: Wei Pei (peiwei@mail.iee.ac.cn)

This work was supported in part by the National Natural Science Foundation of China under Grant 51607170 and Grant 51777202, and in part by the National Key Research and Development Program of China under Grant 2017YFE0112600.

ABSTRACT Behavior learning of microgrids (MGs) is a necessary and challenging task for multi-MGs cooperation and energy pricing of distribution energy market. With the increasing demand for user privacy, this problem becomes more severe because of much less limited access to device parameters and models behind the Point of Common Coupling (PCC), which hinders conventional model-based power management methods. In this paper, to address this problem, some novel model-free data-driven methods including Deep Neural Network (DNN) and Meta-model techniques, such as Radial Basis Function (RBF), Response Surface Methods (RSM), and Kriging methods are introduced. These methods can predict the behavior of MGs through continuous iterative learning by accessing merely the historical active power measurements at the PCCs as well as public electricity price and weather information behind the PCCs, without full system identification and no prior knowledge on the system. A comparative study has been fully carried out by comparing with the conventional model-based model to better understand their advantages, drawbacks and limitations. The validity and applicability of the proposed methods is verified by numerical experiments. This paper can provide some references for future MGs interactive operation under incomplete information.

INDEX TERMS Data-driven method, artificial neural network, meta-model techniques, micro-grids behavior learning.

I. NOMENCLATURE

SETS AND INDICES

\( P_{S} \) set of solar irradiance data
\( P_{WS} \) set of wind speed data
\( P_{T} \) set of temperature data
\( \gamma_{P} \) set of electricity price data
\( K \) set of random variables for sampling
\( M \) set of PCC power data

ACRONYMS

MG Microgrid
PCC Point of Common Coupling

DNN Deep Neural Network
RSM Response Surface Methods
RBF Radial Basis Function
DG Distributed Generator
DR Demand Response
ESS Energy Storage System
ANN Artificial Neural Network
DSO Distribution System Operator
KDE kernel density estimation
PDF probability density function
CDF cumulative probability distribution function
LHS Latin Hypercube Sampling
RMSE root mean squared error
LSTM Long Short-Term Memory
RL Reinforcement learning

The associate editor coordinating the review of this manuscript and approving it for publication was Salvatore Favuzza.

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CONSTANTS

- \( h \): window size for kernel density estimation
- \( \alpha \): Learning rate for RL
- \( \gamma \): Discount factor for RL

VARIABLES

- \( \hat{f}_h(x) \): estimated density function of variable \( x \)
- \( p_{ij} \): correlation between the row \( i \) and row \( j \) of matrix
- \( P^k_{meta} \): Predictive power by weighting sum of RSM, RBF and Kriging surrogated models.
- \( M^k_{RSM} \): Predictive power by RSM model.
- \( M^k_{RBF} \): Predictive power by RBF model.
- \( M^k_{Kriging} \): Predictive power by kriging model.
- \( A_{s,k+iws24} \): Data at the \( k \)-th time interval for the \( i \)-th day.
- \( s_t \): Current state at time \( t \) for RL
- \( a_t \): Current action at time \( t \) for RL

II. INTRODUCTION

Microgrids (MGs) as an aggregate of Distributed Generators (DG), Renewable Energy Resources (RES), Demand Response Loads (DR) and Energy Storage Systems (ESS), has excellent potential and controllability to participate in energy market services through the optimal coordination of DG, RES, DR and ESS [1]. In order to realize effective interaction operation between MGs and the distribution network, and to achieve reasonable energy pricing, fast and accurate MG behavior prediction is the primary key. However, predicting the behavior of MGs is evolving into an increasingly challenging task for utilities in recent years. The main difficulty is that utilities generally have limited access to real-time asset behaviors and models behind the Point of Common Coupling (PCC) with MGs. This problem becomes more severe with the increasing demand for user privacy [2]. Hence, how to deal with this challenge is an urgent issue that needs to be taken in distributed network operation and energy market design.

Traditionally, the behavior prediction of MGs are formulated by the model-based power management methods [3], [4], there have been substantial efforts to investigate the optimal calculating of PCC power in the literature, including heuristic techniques [5], [6], nonlinear programming methods [7], [8], and distributed optimization methods [9], [10]. However, these power management methods all highly depend on the full system operator’s knowledge of MG operation behind the PCC and customers’ private data, which compromise the data ownership of MGs. Moreover, they have much of disadvantages. Such as: (1) Depending on ideal physical model and experience, the timeliness is poor. (2) Rules are formulated based on fixed model and typical operation mode, their inability to adapt to constantly-changing system conditions when the amount of measurement data is limited. (3) Energy model and control mode need to be greatly simplified and approximated to ensure calculation efficiency. Moreover, the random power prediction error of renewable energy and loads will be further influencing the accuracy and reliability of the model.

On the contract, model-free data-driven methods, such as Artificial Neural Network (ANN), Meta-model techniques, are new effective solutions for MGs behavior predicting, which can predict the behavior of MGs through function approximation or continuous iterative learning by accessing merely the active power measurements at the PCCs as well as public weather information and public electricity price information behind the PCCs, without full system identification and no prior knowledge on the system. There have been some useful preliminary exploration on the prediction of renewable energy generation, or on stability evaluation of power system, etc. Such as the utilization of ANN to forecast short-term load demand for MGs [11], prediction of uncertain factors [12], [13], utilization of RSM to approximate the critical damping ratio of MGs [14]. However, for the behavior learning of MGs, there are strong uncertainties included in both power source side and load demand side, also, there exists complex energy management strategies in MGs. Moreover, due to the existence of energy storage and transferable loads, complex time-coupling relationship will be existed for MGs participates in demand response, thus the behavior characteristic of MGs will be more complex and difficult to predict than DGs.

To the best of authors knowledge, the behavior predicting of MGs with strong uncertainties and incomplete information under complex energy management strategies have not yet been fully studied. In addition, a comparative study in testing various model-free data-driven methods to better understand their scope of applications are also not properly addressed.

Based on the above challenges and motivations, In this paper, several recently introduced model-free data-driven methods, including DNN, RL, RBF, RSM, and Kriging in predicting the real-time behavior of MGs under incomplete information are carried out, the validity of the proposed method is verified by numerical experiments, especially, based on the above challenges and motivations, a comparative study is comprehensively implemented by compared with conventional model-based optimal methods, the main contributions of this paper can be listed as follows:

1) A series of novel model-free method for predicting the real-time behavior of MGs are developed with access only to the historical active power measurements at the PCCs as well as public electricity price and weather information behind the PCCs, thus can handle the current limitations raised from data privacy and data ownership.

2) A comparative study has been firstly carried out to compare novel DNN, RL and Meta-model techniques with the conventional model-based model in behavior learning of MGs under incomplete information, provided a better understanding of their advantages, drawbacks and limitations for future MGs interactive operation.

The remainder of this paper is organized as follows. Section II presents the proposed data-driven based prediction mechanism for MGs behavior learning, which consists of the
behavior predicting architecture and the data preprocessing method. Behavior learning method for MGs using DNN, RL, RBF, RSM, and Kriging are discussed in Section III. Two cases are tested and different data-driven methods are compared comprehensively in Section IV, followed by the conclusions in Section V.

III. NOVEL DATA-DRIVEN BASED PREDICTION MECHANISM FOR MG BEHAVIOR LEARNING

A. DATA-DRIVEN BASED MG BEHAVIOR PREDICTING ARCHITECTURE

Considering the future MGs interactive operation under incomplete information, model-based solutions will be difficult to apply for their requirement of completely observable and controllable information, thus in this paper, a novel data-driven based MG behavior predicting architecture is proposed, as shown in Fig. 1.

In the upper level is the operation management layer, the distribution system operator (DSO) takes the role to optimize the pricing, realize market clearing and overall optimal operation only by observing the response of MGs to external signals at their PCCs, in our novel data-driven based prediction mechanism, DSO or MG will train a black box meta-model or neural network that describing the interactive behavior of the other MGs merely through the available active power measurements at the PCCs and the public historical data information, such as the statistical electricity price, local solar irradiance, wind speed and temperature information that independent of the MGs. Therefore, it is possible to predict the tie-line power of MG without knowing the internal units and parameters, and it is possible to better implement the interactive operation between multi micro-grid (MMG) or between MG and DSO under incomplete information. Moreover, by avoiding explicit MG modeling, the data-driven model becomes highly adaptable against changes in MG parameters which are excluded from MG’s state set.

In the bottom level is the multi-MGs physical layer, the MGs receive the external price information from the upper layer DSO, and then carried out optimal power management to maximum its own interest with internal energy management system (EMS).

B. DATA CHARACTERISTICS ANALYSIS BASED ON MACHINE LEARNING

Data characteristics analysis is the first key point for data-driven behavior learning, probability distributions with fixed parameters are often used to describe the stochastic characteristics of weather information, such as weibull distribution for wind speed, beta distribution for solar irradiance and so on. However, these methods are merely approximate fitting of the actual probability histogram, the fitting errors are large especially at the edges [15], meanwhile, the parameters of these probability distributions are difficult to obtain.

On this basis, this paper intends to introduce non-parametric kernel density estimation (KDE), an effective machine learning technique to mine the depth characteristics of weather data. Based on the sample data directly without any prior knowledge, KDE can achieve high-precision fitting on the basis of selecting the appropriate sliding window. The main principle is to estimate the distribution through the kernel function of each discrete interval (red dashed line in Fig. 2). The color dashed line (Blue Solid line in Fig. 2) is accumulated to approximate the equivalent histogram distribution interval. The calculation is shown in (1).

\[
\hat{f}_h(x) = \frac{1}{2h} \sum_{i=1}^{N} \begin{cases} \frac{1}{N} & x \in [x_i - h, x_i + h] \\ 0 & \text{otherwise} \end{cases} \\
= \frac{1}{2Nh} \sum_{i=1}^{N} I(x - h \leq x_i \leq x + h) \\
= \frac{1}{Nh} \sum_{i=1}^{N} \frac{1}{2} I\left(\frac{x - x_i}{h} \leq 1\right) 
\] (1)
where, $\#x_i \in [x-h, x+h]$ represents the number of samples falling on the interval $[x-h, x+h]$. Let $K \left( \frac{x-X_D}{h} \right) = l(\frac{x-X_D}{h} \leq 1)$, then (1) can be rewrite as

$$\tilde{f}_h(x) = \frac{1}{Nh} \sum_{i=1}^{N} K \left( \frac{X-X_D}{h} \right)$$

(2)

where, $K(\cdot)$ represents the kernel function, commonly used kernels function include Gauss kernels function, rectangular kernels function and so on.

Taking the annual data of local weather information as well as local electricity price information as an example, we can first preprocess the annual data by classifying them with time interval, as shown in (3), and then analyze the statistical characteristics of each time interval with KDE separately.

$$\begin{bmatrix}
A_{S,1} & A_{S,2} & \cdots & A_{S,24} \\
\vdots & \vdots & \ddots & \vdots \\
A_{S,1+i*24} & A_{S,2+i*24} & \cdots & A_{S,24+i*24} \\
\vdots & \vdots & \ddots & \vdots \\
A_{S,1+N*24} & A_{S,2+N*24} & \cdots & A_{S,24+N*24}
\end{bmatrix}
S \in [P_{si}, P_{ws}, P_T, \gamma_P]$$

(3)

where, $A_{S,k+i*24}$ represents the data at the $k$-th interval for the $i$th day, $S$ is the variable set, representing solar irradiance ($P_{si}$), or wind speed ($P_{ws}$), or temperature ($P_T$), or electricity price ($\gamma_P$).

Assume the annual data of solar irradiance and wind speed are shown in Fig. 3 and Fig. 4 respectively, the probability density function (PDF) and cumulative probability distribution (CDF) of typical time interval obtained by KDE is shown in Fig. 5 and Fig. 6.

From Fig. 5 and Fig. 6, we can find that the proposed KDE method described the probability distribution characteristics of each time interval well, different from the traditional single peak approximation fitting of normal distribution or Weibull distribution with fixed parameters, the distribution function calculated by KDE method has the characteristics of multi peak and multi valley, more coincides with its histogram and has better fitting accuracy.

C. DATA ENHANCEMENT BASED ON LATIN HYPERCUBE SAMPLE METHOD

Considering the acquired data are often hard to exhaust and cover all kinds of possible scenarios, in order to ensure the data completeness of behavior learning in MG, effective data enhancement is necessary.
Data enhancement can be achieved by sampling with the probability characteristics of the acquired data, however the traditional random sampling method usually needs a large number of repeated sampling, and it is difficult to cover the whole sampling space. On this base, an effectively Latin Hypercube Sampling (LHS) method with good uniformity and orthogonally is proposed. As shown in Fig. 7.

Its basic principle is to discretize the range of cumulative probability distribution into several equal intervals, and then stratified sampling is carried out among each interval [17], thus to ensure the integrity and accuracy of sampling data as calculated by (4).

\[
X_{kn} = F_k^{-1}\left(\frac{n-0.5}{N}\right) \quad n = 1, 2, \ldots, N
\]  

(4)

If the number of random variables is \( K \), then the sampling matrix can be formed by (5).

\[
X_{KN} = \begin{bmatrix}
X_{11} & X_{12} & \cdots & X_{1N} \\
X_{21} & X_{22} & \cdots & X_{2N} \\
\vdots & \vdots & \ddots & \vdots \\
X_{K1} & X_{N2} & \cdots & X_{KN}
\end{bmatrix}
\]  

(5)

For the directly sampled matrix \( X_{KN} \), there are usually strong correlation among its rows [18], which is not suitable for the generation of diversified samples. To address this problem, cholesky decomposition algorithm is introduced in this paper to reduce the correlation of samples and improve the diversity of samples [19]. The main procedures are shown in Fig. 8.

The detailed calculation steps are described as follows:

1) Initialize the ranking matrix \( L_{KN} \), each row consisting of random permutations of integers 1, 2, 3..., \( N \).

2) Calculate the correlation between the rows of \( L_{KN} \), and obtain the correlation matrix \( D_L \) as shown below.

\[
\rho_{ij} = \frac{\sum_{k=1}^{K} (V_{ik} - \bar{V}_i)(V_{jk} - \bar{V}_j)}{\sqrt{\sum_{k=1}^{K} (V_{ik} - \bar{V}_i)^2} \sqrt{\sum_{k=1}^{K} (V_{jk} - \bar{V}_j)^2}}
\]  

(6)

3) Use Cholesky decomposition method to calculate the nonsingular lower triangular matrix \( D \) for the correlation coefficient matrix \( D_L \), which satisfied \( DD^{-1} = D_L \).

4) Constructing matrix with less correlation \( G_{KN} = D^{-1}L_{KN} \).

5) Reorder elements in matrix \( L_{KN} \) based on the size and position of elements in \( G_{KN} \).

6) Judge whether the relativity of ranking matrix \( L_{KN} \) meets the requirements.

7) If it does not meet the requirement, go back to step 2) to recalculate. Otherwise, updating the position of each element in the original sampling matrix based on matrix \( L_{KN} \).

Based on the PDF and CDF of wind speed and solar irradiance obtained, 500 new scenarios are generated with the proposed LHS and cholesky decomposition algorithm, as shown in Fig. 9 and Fig. 10. The iterative convergence process of cholesky decomposition method to reduce the correlation of sampling scenarios is shown in Fig. 11.

It can be seen from Fig. 9 and Fig. 10 that the enhancement scenarios of solar irradiance and wind speed are diverse enough, and basically fill the whole sampling space. From Fig. 11 we can find that the cholesky decomposition algorithm has a very good convergence property, the correlation converges after approximately 5 iterations, proved to be effective.

D. SCENARIO CLUSTERING WITH PSO ASSISTED K-MEANS METHOD

Repetitive learning of similar scenarios may be existed by directly using the above generated scenarios for learning,
in order to improve the learning efficiency, the typical categories should be further determined for the generated scenarios in section C.

Common used classification methods include fuzzy clustering, K-means clustering and so on [20], but these methods all have difficulties in determining the number of clusters. To address this issue, this paper introduced a novel particle swarm optimization assisted k-means method (PSO-K-Means) to support quickly determination of optimal number of clusters. The flow chart of proposed PSO-K-Means algorithm is shown in Fig. 12, the PSO’s fast global search capability is fully utilized to help in finding the optimal number of cluster centers, through continuous iterative evaluation, ensure to find the best cluster center.

With the PSO-assisted K-means clustering algorithm, 500 wind speed and solar irradiance scenarios are clustered, the optimal clustering number determined by PSO-assisted K-means is 8. The clustering results for wind speed and solar irradiance are shown in Fig. 13 and Fig. 14 respectively. It can be seen from Fig. 13 and Fig. 14 that the proposed PSO-assisted K-means algorithm has good effect on scenario classification, and it can effectively identify cluster centers, providing guarantee for improving training and learning efficiency.
response surface approximating functions the second order polynomials in (7) is widely used as the using the least squares method on a series of points in the Response surface methods (RSM) approximates functions by 1) RESPONSE SURFACE METHOD scope. ing model and so on. Each meta-model has its own applicable Method (RSM), Radial Basis Functions (RBF) model, Krig- ming model and so on. Each meta-model has its own applicable scope.

1) RESPONSE SURFACE METHOD Response surface methods (RSM) approximates functions by using the least squares method on a series of points in the design variable space [21]. Low order polynomials, such as the second order polynomials in (7) is widely used as the response surface approximating functions

\[ \hat{y}(x) = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_i x_i^2 + \sum_{i} \sum_{j} \beta_{ij} x_i x_j \]  

(7)  where, \( \beta_0, \beta_i, \beta_{ij} \) are parameters computed using least squares regression by minimizing the sum of the squares of the deviations of predicted function values, \( \hat{y} \) is the predictive function values.

RSM can be easily constructed, and its smoothing capability allows quick convergence of noisy functions in the optimization. However, this over-simplification may be troublesome for modelling highly non-linear or irregular behavior

2) KRIGING META-MODELS

Kriging is a type of meta-model based on spatial correlation functions. It is a stochastic model used to treat the deterministi-c computer response as a realization of a random function, with respect to the actual system response [22]. A Kriging model postulates a combination of a polynomial model and the minor departure of the form:

\[ \hat{y}(x) = f(x)T \beta + Z(x) \]  

(8)  where, \( \hat{y}(x) \) is the unknown function of interest, \( f(x) \) is a known polynomial function often taken as constant, and \( Z(x) \) is the correlation function which represents a stochastic process with mean at 0, variance \( \sigma^2 \), and nonzero covariance. Due to the wide range of correlation functions available, Kriging methods can provide accurate predictions of highly non-linear or irregular behavior.

3) RADIAL BASIS FUNCTIONS

Radial basis function (RBF) meta-model is another surro-gated model formed by linear combinations of a radially symmetric function based on the Euclidean distance between the sampled data point and the point to be predicted [23]. RBF was presented as an effective analytical method for representing irregular surfaces, the model can be expressed as in (9) and (10).

\[ f(x) = c_0 + c_1 x + \sum_{i=1}^{n} \lambda_i \varphi(|x - x_i|) \]  

(9)  \[ \varphi(x) = \exp \left(-\frac{x^2}{2\sigma^2}\right) \]  

(10)  where, \( c_0, c_1 \) and \( \lambda_i \) are the parameters for radially symmetric function computed by minimizing the Euclidean distance between the sampled data point and the point to be predicted. \( \varphi(x) \) is the radially symmetric function. RBF prove to have good fits to arbitrary contours of both deterministic and stochastic response functions. It has been used successfully in many engineering applications, including ocean depth measurement, altitude measurement, rainfall interpolation, surveying, mapping, geographic and geology, image warping, and medical imaging [24].

B. ARTIFICIAL INTELLIGENCE BASED BEHAVIOR LEARNING

1) DEEP NEURAL NETWORK

Deep neural network (DNN) is a data-driven method that does not rely on any analytical equations, but it utilizes voluminous existing data to formulate the mathematical problem and to approximate the solutions. DNN proved to have strong non-linear fitting ability. The recent years have witnessed the rapid advancement of deep neural network in a variety of applications, e.g., computer vision, machine translation, and remote sensing [25]. Fig. 15 shows a basic DNN model. The multiple hidden layers and the large number of neurons within the DNN can automatically extract features for data analysis to achieve an accurate model regression or classification. Once the DNN is well trained, it will develop high generalization and can be directly applied to new instances without costly numerical computation. Compared to the conventional model-based method, the DNN is highly computational efficient while maintaining considerable accuracy.
2) REINFORCEMENT LEARNING

Reinforcement learning (RL) algorithm is another well-known model-free method for solving problems with hidden information. RL can obtain the optimal decisions within an unknown environment through continuous interactions between the agent and the environment. For the model-free RL algorithm, the principle evaluates possible actions in terms of the current state at time $t$, then finds the optimal action with max reward value by $\varepsilon$-greedy strategy to strike a balance between exploration and exploitation of decision space, and finally updates the action-value $Q(s_t, a_t)$ at each iteration based on the Bellman optimality equation [26], as follows:

$$Q(s_t, a_t) = Q(s_t, a_t) + \alpha(r(s_t, a_t) + \gamma \max Q(s_{t+1}, a_{t+1}) - Q(s_t, a_t))$$  \hspace{1cm} (11)

Based on the latest expected state-action value, the optimal policy can be estimated to maximize the agent’s accumulated reward, as follows:

$$a_{opt} = \arg \max Q(s_t, a_t)$$  \hspace{1cm} (12)

RL does not require any prior knowledge, the algorithm is versatile, and it can protect data privacy. The accuracy of action-state function for RL depends on learning experience, thus RL usually requires a lot of evaluation and iterations, and the calculation time is relatively long.

C. PROCEDURE OF PREDICTING BEHAVIOR FOR MICROGRIDS

Based on the proposed architecture, data preprocessing method and behavior prediction algorithm above, the overall procedure of predicting behavior for micro-grids is presented as algorithm 1, which is specifically described as follows:

1) Utilize KDE to analyze the probabilistic characteristics of local solar irradiance ($P_{si}$), wind speed ($P_{ws}$), temperature ($P_T$) and electricity price ($\lambda_p$) data.

2) Generate incremental sample data using LHS and Cholesky decomposition algorithm.

3) Cluster all sample data by PSO assisted K-means algorithm to find out typical scenario categories.

4) Take one scenario from each category in order, reorder all the sample scenarios.

5) Initialize the training data with previous $(i-1)^{th}$ days data set: input data: $S_I \rightarrow S_I + (i-1)^{th} \{P_{si}, P_{ws}, P_T, \lambda_p\}$, output data: $S_U \rightarrow S_U + (i-1)^{th}P_{pcc}$.

6) Construct Meta-models and DNN network or determine the optimal policy by RL using the training data.

7) Predict tie-line power of the next $i^{th}$ scenario with constructed Meta-models and DNN as well as RL algorithm.

8) Calculate actual tie-line power of MG in the $i^{th}$ scenario using the model based algorithm.

9) Calculate the mean square error ($\beta_E$) for Meta-models and DNN as well as RL algorithm.

10) Determine whether $\beta_E$ is less than the preset value $\varepsilon$. If it is satisfied, the calculation ends and output the corresponding predicted power. Otherwise, go to step 5 and enter the next iteration.

V. TEST CASE

A. CASE I–MICROGRID WITHOUT ENERGY STORAGE SYSTEM

The first test case is a grid-connected MG without energy storage system, the one-line diagram is shown in Fig. 16, and it composes by three types of DGs: solar PV, wind turbine, and Micro-turbine. We intend to train an interactive behavior model of this MG by using the active power measurements at the PCCs and the public historical data information outside of MG. we assume the spot price data are taken from American electricity price [27], the local solar irradiance, wind speed, temperature and electricity price in previous $N^{th}$ days are selected as the input of the training set, and the tie-line power of MG in previous $N^{th}$ days are taken as the expected output of the training set. Data-driven based methods proposed above are utilized for network training, and the trained networks are tested on the next $(N+1)^{th}$ day to verify their accuracy and applicability.

Since the energy storage is not included in MG, the operation periods of the MG can be decoupled from each other, thus the MG can be controlled independently in different time slots. Thereby, the input dimension and output dimension of the training network are selected as 4 and 1 respectively. The training parameters for DNN are shown in the Table 1. For RL, since we don’t know the internal parameters of MG,
so we make full use of DNN to predict its action-reward value, and then form a deep Q-network (DQN) to learn the tie-line power of MG. The training parameters of RL algorithm are shown in the Table 2.

Firstly, the predictive results of DNN is compared with that of meta-model method and model-based method (regard as theoretical results). Among them, the predictive value of meta-model method is calculated by weighting sum of RSM, RBF and Kriging surrogated models. The calculation is shown in (13)

\[
\begin{align*}
\omega_k^{\text{meta}} &= \omega_k^P \ast M_{\text{RSM}}^k + \omega_k^R \ast M_{\text{RBF}}^k + \omega_k^K \ast M_{\text{Kriging}}^k \\
\omega_k^P &= \frac{M_{\text{RSM}}^k}{M_{\text{RSM}}^k + M_{\text{RBF}}^k + M_{\text{Kriging}}^k} \\
\omega_k^R &= \frac{M_{\text{RBF}}^k}{M_{\text{RSM}}^k + M_{\text{RBF}}^k + M_{\text{Kriging}}^k} \\
\omega_k^K &= \frac{M_{\text{Kriging}}^k}{M_{\text{RSM}}^k + M_{\text{RBF}}^k + M_{\text{Kriging}}^k}
\end{align*}
\] (13)

The prediction results of DNN, surrogated model and conventional model-based method regarding with training days are shown in Fig. 17. For dimension reasons, only three-dimensional maps are given out, the electricity price and solar irradiance are selected as input variables and PCC power is selected as output variable. The predicted value of PCC output power by DNN is compared with that of theoretical results through model-based optimal method as shown in Fig. 18. We can find from Fig. 17 that with the training data gradually enriched, the PCC power prediction value of DNN, basically coincides with the theoretical calculation value driven by the model, which shows the strong fitting ability of DNN. Although meta-model method has aggregated advantages of
FIGURE 18. Comparison of DNN prediction results of tie-line power with theoretical values.

As can be seen from the Fig. 19, with the increase of days and training data, the three surrogated techniques, RSM, RBF, and Kriging show a downward trend in prediction errors. When there are insufficient samples in the early stage, the covariance function calculated from these few points result in large errors for Kriging, so the fitting effect of Kriging technique is not good and the prediction error is large. However, with the accumulation of samples, the fitting error between the covariance function and the actual model decreases gradually, thus the prediction error of Kriging decreases rapidly. The same phenomenon occurs in RBF, since the parameters of its basis function are difficult to match, so the RMSE error is large in the early stage, with the sample becomes more abundant, the basis function parameters are constantly modified, and the fitting accuracy is gradually improved. As for RSM, it uses low-order surface response function to fit the sample space, so it presents a better fitting effect in the early stage. However, because its basis function order is fixed in training process, the fitting improvement is hard to improve even in the later stage with high-dimensional samples, thereby the prediction error of RSM maintains a certain level, which also indicated that low-order basis function and surface fitting is relatively stable, but they are not suitable for accurate behavior prediction.

From the RMSE comparison of DNN, RSM, and RL in Fig. 20, we can find that the prediction error of DNN is large when there are insufficient samples in the early stage, this is because the scenarios learned at the beginning of training stage are difficult to cover all the various scenarios in wind speed, solar irradiance, temperature and electricity.

<table>
<thead>
<tr>
<th>Method</th>
<th>RMSE error</th>
<th>Training time(s)</th>
<th>Test time (s)</th>
<th>Accuracy (%)</th>
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<td>71.58</td>
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<td>DNN</td>
<td><strong>0.219</strong></td>
<td><strong>15.19</strong></td>
<td><strong>0.147</strong></td>
<td><strong>86.38</strong></td>
</tr>
</tbody>
</table>
**Algorithm 1** Procedure of Predicting Behavior for Microgrids

1: Utilize KDE to analyze the probabilistic characteristics of local solar irradiance ($P_{si}$), wind speed ($P_{ws}$), temperature ($P_{T}$) and electricity price ($\lambda_p$) data

2: Generate incremental sample data using LHS and Cholesky decomposition algorithm

3: Cluster all sample data by PSO assisted K-means algorithm to find out typical scenario categories

4: Take one scenario from each category in order, reorder all the sample scenarios, complete data preprocessing process

5: for $i$ in 1 to $N_D$ do

6: Initialize the training data with previous $(i-1)^{th}$ days data set,
   input data: $S_I \rightarrow S_I+(i-1)^{th}$ scenarios data
   output data: $S_U \rightarrow S_U+(i-1)^{th}$ $P_{pcc}$

7: Construct the Meta-models and DNN or determine the optimal policy by RL using the training data

8: Predicting behavior of the next $i^{th}$ scenario with constructed Meta-models and DNN as well as RL algorithm

9: Calculate actual $i^{th}$ scenario behavior of MG ($P_{pcc}$) using the model based algorithm

10: Calculate the mean square error ($\beta_E$) for Meta-models and DNN as well as RL algorithm

11: if $\beta_E < \varepsilon$ do

12: Break;

13: end if

14: End for

prices, however with the abundance of samples and more learning scenarios, the number of scenarios covered by DNN gradually increases, thus the accuracy of DNN increases continuously, and the accuracy of DNN is much higher than that of RSM in the later stage. On the other hand, from the comparison between DNN and RL, for the DQN reinforcement learning algorithm utilized in this paper relies heavily on the predictive ability of DNN to update its reward value, its overall accuracy is slightly lower than that of DNN, but it can constantly learn and approximate the DNN prediction model, so the overall prediction and decision-making effect is also high enough.

From the statistical results of the training time and accuracy of the various methods in Table 3, it can be further seen that DNN and RL do have better prediction accuracy, and their results are better than the meta-model method. From the convergence process of the RL algorithm in Fig. 21, it can roughly converge to the optimal results in about 200 epochs, however, the training time is the longest as seen from Table 3 for the number of policy evaluations required by RL is large. In summary, the above results indicated that DNN has best fitting ability of complex MG energy management functions and it is more suitable for the behavior learning of MGs.

**B. CASE II—MICROGRID WITH ENERGY STORAGE SYSTEM**

The second test case is a grid-connected MG equipped with battery energy storage system (BESS), the grid structure is shown in Fig. 22. After BESS is connected to MG,
FIGURE 22. Test Micro-grid with battery energy storage system.

TABLE 4. Training parameters of LSTM.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dim of LSTM layer</td>
<td>100</td>
</tr>
<tr>
<td>Max Epochs</td>
<td>100</td>
</tr>
<tr>
<td>Mini Batch Size</td>
<td>200</td>
</tr>
<tr>
<td>Loss function</td>
<td>Mean square error</td>
</tr>
<tr>
<td>Initial Learning rate</td>
<td>0.005</td>
</tr>
<tr>
<td>Gradient Threshold</td>
<td>1</td>
</tr>
<tr>
<td>No. of training samples</td>
<td>Previous 10000 days sequential data</td>
</tr>
<tr>
<td>No. of test samples</td>
<td>Next 10000 days sequential data</td>
</tr>
<tr>
<td>Learning Rate Drop Period</td>
<td>50</td>
</tr>
<tr>
<td>Learning Rate Drop Factor</td>
<td>0.2</td>
</tr>
<tr>
<td>Optimizer</td>
<td>Adam</td>
</tr>
</tbody>
</table>

The operation periods of the MG are strongly coupled with each other, therefore, the input data and output data for training are 4*24 sequential sample and 1*24 sequential sample respectively. For this reason, the long short-term memory (LSTM) deep network that can effectively deal with sequential data [28] is adopted here for behavior learning of MGs equipped with BESS, the training parameters of LSTM are shown in Table 4.

Based on 10000 sample data accumulated by model-based optimization, 9000 training samples and 1000 test samples are selected respectively, the behavior learning results of LSTM is comprehensively compared with that of meta-model technologies as well as the RL algorithm, the statistical results are presented in Table 5.

It can be seen from Table 5 that the surrogated techniques obtain large fitting errors for time-coupled and high-dimensional sequential data. The accuracy of the best performing RBF technique is only about 81.86%, this indicates that the low-order surface response function based RSM and basis function based RBF are powerless in fitting higher-dimensional and temporally coupled spatial variables, thus the fitting error is larger. From the comparison between RL and LSTM, we can find that the predicting accuracy of RL is slightly lower than that of LSTM, this is because that the calculation of the RL algorithm’s reward relies heavily on the predictive value of LSTM deep neural network, therefore, its predicted value approaches the LSTM infinitely, but is still slightly lower than that of LSTM. In addition, due to the need for a large number of evaluations and feedback to modify network parameters, training time of RL is usually long. The LSTM method shows the best prediction effect by processing the time sequential power data with memory gate, it is more suitable for predicting the sequential tie-line power of MG that contains timing coupling characteristics brought by energy storage, the prediction accuracy of it reaches 96.20%.

The predicted tie-line power by LSTM is further compared with the theoretical results on typical days, as shown in Fig. 23. The convergence process of the training RMSE and loss function of LSTM is shown in Fig. 24 and Fig. 25 respectively.

We can find that the convergence speed of the LSTM is fast, the convergence is achieved after about 300 iterations. At the same time, the prediction accuracy of the LSTM is relatively high, the power prediction values by LSTM are basically consistent with the theoretical results, which shows the effectiveness of LSTM deep network especially in behavior learning of MG equipped with BESS.
C. COMPARISON OF META-MODEL TECHNIQUES AND ARTIFICIAL INTELLIGENCE METHODS

Based on the analysis results of the above test cases, we can further summarize the advantages and disadvantages of the meta-model techniques and the artificial intelligence methods in MG behavior learning problem as shown in Table 6.

We can draw the conclusion from Table 1 that RSM and Kriging methods are more suitable for the fitting and prediction of low-order and low dimensional MG behavior learning problems. While RBF and DNN are more suitable for high-dimensional and large-scale variable fitting problems because of their network depths and free radicals combination features. Although RL is highly scalable and has good versatility for various decision-making and prediction problems, but the action-value function of it is difficult to model. Meanwhile, the policy training time of RL is long for its need for a large number of policy evaluations.

In summary, the predicting process for most meta-model techniques are fast, but the accuracy of them are not high, so they are more suitable for computational expensive design problems. The training time of DNN network and RL algorithm are relatively long, but the accuracy is much higher, so there are more suitable for behavior learning and decision-making problems in MG.

D. CONVERGENCE AND SENSITIVITY ANALYSIS

The sensitivity analysis of DNN (the best performance method) in behavior predicting is further carried out for test case I. The training process with three different hidden layer number are tested: \{20 10\}, \{30 20\}, \{30 10\} respectively, the convergence curves of three different cases are shown in Fig. 26.

It can be seen from Fig. 26 that the hidden layer number has great influence on the training convergence of DNN. Too few or too many hidden layers cannot achieve satisfactory
learning fitting effect and are prone to over-fitting or under-fitting. In practical application, the number of hidden layer should be decided by considering dimension of input variables, calculation time requirement, fitting effect and so on.

VI. CONCLUSION
A comparative study of several recently introduced model-free data-driven methods, including DNN, RL, RBF, RSM, and Kriging in predicting the real-time behavior of MGs under incomplete information is carried out in this paper. The validity of the proposed method is verified in numerical experiments by comprehensively compared with conventional model-based optimal methods. We can draw the conclusions that:

1) The proposed model-free behavior prediction methods can effectively protect the privacy requirements of the MG for they do not need to access the internal parameters of the MG.

2) The surrogate techniques is more suitable for the low-dimensional, temporally decoupled behavior prediction problem, and it is not suitable for behavior prediction problems with high-dimensional variables. While the DNN and RL has good adaptability to various MG behavior prediction problems such as high-dimensional, low-dimensional, and time-coupling problems.

REFERENCES


**HAO XIAO** (Member, IEEE) received the B.S. degree from the Huazhong University of Science and Technology, Wuhan, China, in 2009, and the Ph.D. degree in electrical engineering from the Chinese Academy of Sciences, Beijing, China, in 2015.

From 2015 to 2018, he was an Assistant Professor with the Institute of Electrical Engineering, Chinese Academy of Sciences, where he has been an Associate Professor, since 2019. He has also been an Associate Professor with the University of Chinese Academy of Sciences, since 2019. His research interests include optimal operation and planning of power systems and application of artificial intelligence in power systems.

Dr. Xiao serves as a member of the IEEE PES Energy Internet Committee. He received the IEEE Transportation Electrification Conference Best Paper Award, in 2014. He also serves as the Section Chair for the IEEE ICEMS2018 Conference and a Reviewer of several the IEEE and IET Journals, including the IEEE TRANSACTIONS ON SMART GRID, the IEEE TRANSACTIONS ON INDUSTRIAL INFORMATION, IEEE ACCESS, the IET Generation Transmission & Distribution, and IET Smart Grid.

**WEI PEI** (Member, IEEE) received the B.S. and M.S. degrees in electrical engineering from Tianjin University, Tianjin, China, in 2002 and 2005, respectively, and the Ph.D. degree from the Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing, China, in 2008.

He is currently working as a Professor with the Institute of Electrical Engineering, Chinese Academy of Sciences, and with the University of Chinese Academy of Sciences. He is also the Director of the Distributed Generation and Power System Research Group, Chinese Academy of Sciences. His research interests include integrated energy systems and AC/DC micro-grid. He is also an Editor of IET Smart Grid, IET Energy Systems Integration, and the CSEE Journal of Power and Energy Systems.

**WEI DENG** (Member, IEEE) received the B.S. degree in computer science and technology from North China Electric Power University, Beijing, China, in 2004, and the Ph.D. degree in electrical engineering from the Chinese Academy of Sciences, Beijing, in 2010. He is currently an Associate Professor with the Institute of Electrical Engineering, Chinese Academy of Sciences, and with the University of Chinese Academy of Sciences. His research interests include distributed generation, microgrid, active distribution networks, AC/DC hybrid grid, and the application of information technology (IT) in smart grids.

**LI KONG** received the B.S. degree from the Huazhong University of Science and Technology, Wuhan, China, in 1982, and the Ph.D. degree in electrical engineering from the National Institute of Technology, Paris, France, in 1994.

He is currently a Professor with the Institute of Electrical Engineering, Chinese Academy of Sciences, and with the University of Chinese Academy of Sciences. He is also the Chair of the Power Grid Technology Research Group, Chinese Academy of Sciences. His research interests include AC/DC hybrid distribution networks, renewable generation, and micro-grids. He is a Senior Member of the Chinese Electrical Society and the Deputy Secretary-General of the Solar Power Association of China.

**HONGJIAN SUN** (Senior Member, IEEE) received the Ph.D. degree from the University of Edinburgh, U.K., in 2011.

He took his postdoctoral positions at the King’s College London, U.K., and Princeton University, USA. Since April 2013, he has been with the Department of Engineering, Durham University, U.K., as an Associate Professor (Reader) in smart grid. He has published more than 100 articles in refereed journals and international conferences.

He has also published five book chapters and edited two books: IET book Smarter Energy: from Smart Metering to the Smart Grid and CRC book From Internet of Things to Smart Cities: Enabling Technologies. His research interests include demand side management, renewable energy sources integration, and artificial intelligence for energy systems. He is the Editor-in-Chief of IET Smart Grid Journal. He has served as a Guest Editor for the IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS for three Feature Topics on smart grid technologies. He has made contributions to and coauthored the IEEE 1900.6a-2014 Standard.

**CHENGHONG TANG** (Senior Member, IEEE) is currently the Deputy Chief Engineer of the Technology Research Center, NARI Research Institute. She has been mainly involved in Technical Research and Product Research and Development in the field of distribution networks, micro-grids, and integrated energy system. She has won 11 provincial, ministerial and state grid company-level awards, and six prefecture-level science and technology progress awards; which have been applied in many areas of the country, and achieved good economic and social benefits.