

Equivalent Modeling Method for Regional Decentralized Photovoltaic Clusters Based on Cluster Analysis

Hongbin Wu, Zhongqian Liu, Yu Chen, Bin Xu, and Xianjun Qi

Abstract—A large number of photovoltaic (PV) systems are decentralized and connected to distribution networks, leading to challenges in model simulation. This paper presents an equivalent modeling method for regional decentralized PV clusters based on cluster analysis. The proposed method is based on the grouping principle that PV systems have similar dynamic response characteristics, and grouping results are obtained using a fuzzy C-mean (FCM) clustering algorithm. Based on the clustering evaluation index, the optimal grouping number can then be determined and PV systems in the same group are combined into an equivalent PV system. The method to acquire equivalent parameters for PV arrays, transformers, and lines is also presented. A multi-machine equivalent model of regional decentralized PV clusters is established, and the precision and efficiency of the proposed method is demonstrated using an actual distribution network.

Index Terms—Distribution network, equivalent modeling, fuzzy C-mean clustering, photovoltaic cluster, regional decentralization.

I. INTRODUCTION

SOLAR energy is a clean, renewable energy that has undergone rapid development and large-scale application, with photovoltaic (PV) grid-connected systems being the most important solar energy application [1]–[3]. In China, with the implementation of PV power generation poverty reduction policies, many PV power stations are decentralized and connected to distribution networks, forming regional decentralized PV clusters [4]. This increases the complexity of the distribution network model and leads to challenges such as long simulation times, huge memory usages, and difficulty updating models. Therefore, it is necessary to establish a simplified equivalent model of regional decentralized PV clusters.

In recent years, equivalent modeling of PV system research has concentrated primarily on regional centralized PV systems or large-scale PV power stations. In [5], the authors propose an online clustering modeling method for large-scale PV power

plants, using the control parameters of inverter as the clustering index. In [6], two equivalent modeling methods for PV system are proposed for partially shielded and unshielded PV cells. To study the transient characteristics of large-scale PV power stations and avoid constructing detailed models for every type of inverter, Mukherjee *et al.* [7] analyzed the effectiveness of the model reference adaptive control (MRAC) approach for modeling a grid connected inverter system. In [8], the equivalent dynamic model of an actual PV power station with virtual synchronous characteristics was studied, and a method was proposed to obtain the dynamic equivalent model of a group of PV converters based on the synchronous power controller.

The study of equivalent modeling of regional decentralized PV system is in its infancy. In the coherent-based equivalent method of large-scale power grids, the coherent generator group is equivalent to corresponding aggregates, and only key transmission lines and nodes are retained. Therefore, the power system scale can be reduced and the main dynamic characteristics can be preserved [9]–[11]. However, the PV power generation is different from conventional power generation, so the criterion for PV system coherency must be defined to benefit from a coherency-based equivalent method. PV systems with similar dynamic responses under the same disturbance are considered coherent, and they should be combined into an equivalent PV system to ensure the dynamic characteristics of the original system remain unchanged.

This paper proposes an equivalent modeling method for regional decentralized PV clusters. The clustering index is selected from the response curves of PV systems during a disturbance. Then, a fuzzy C-mean (FCM) clustering algorithm is used to obtain dynamic grouping results, and PV systems in the same group are combined into an equivalent PV system, establishing a multi-machine equivalent model of regional decentralized PV clusters. Finally, simulation analysis is performed using an actual distribution network in Anhui province.

II. CLUSTERING INDEX

A. Model of Regional Decentralized PV Cluster

A PV cluster is a collection of PV systems that are near each other with only small differences in solar radiation, and the same point of interconnection (PCC). Taking the city of Jinzhai, Anhui province as an example, a total of 295 small village PV systems have been built and connected to a distribution net-

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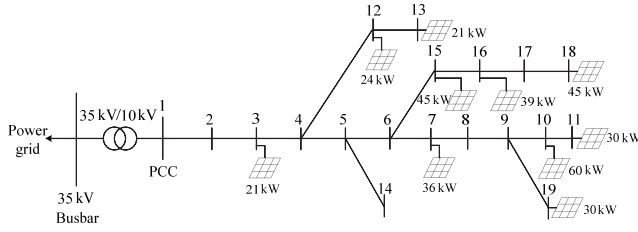


Fig. 1. Regional decentralized PV clusters.

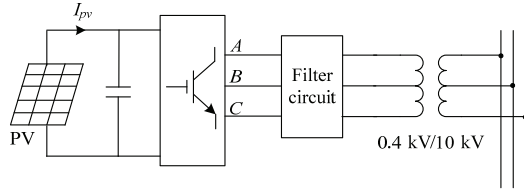


Fig. 2. The structure of a single PV system.

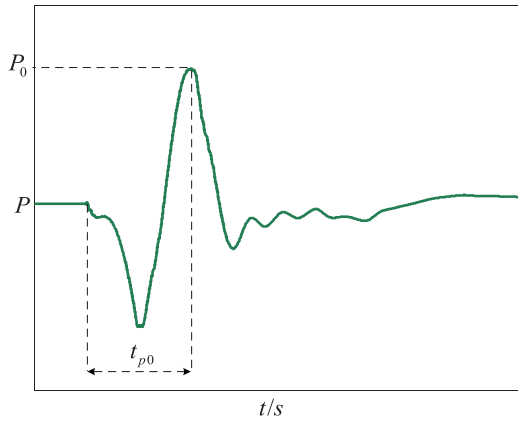


Fig. 3. Sketch of active power disturbance curve extraction.

work, forming several regional decentralized PV clusters. A typical PV cluster under a 35 kV substation is shown in Fig. 1, there are 10 PV systems in all, which is called the detailed model.

The common model of a single PV system is shown in Fig. 2, which contains a PV array, a grid-connected inverter, a filter, and other devices. The specific characteristic equation can be referred to in [12], but is not described in detail in this article.

B. Clustering Index of PV System

The basic idea of a regional decentralized PV cluster is to combine PV systems that have similar dynamic responses into an equivalent PV system. However, dynamic features of PV systems are influenced by many factors, including inverter controller parameters, the location and capacity of PV systems, and other parameters. Therefore, it is difficult to propose a reasonable clustering index from inherent parameters of a system model [13]. In this paper, the feature points extracted from the response curve of a PV system are taken as the clustering index. The active power response curve of a PV system under typical disturbance is shown in Fig. 3.

In Fig. 3, P_0 is the first peak and t_{p0} is the time from the start

of the dynamic process to the first peak. For the reactive power response curve, extraction of feature points is the same as for active power, with the two feature points being recorded as Q_0 and t_{q0} , respectively.

Considering that under a three-phase short-circuit disturbance, the dynamic response of a PV system is generally the most obvious, when a three-phase short-circuit fault occurs at the PCC point, the vector $[P_0, t_{p0}, Q_0, t_{q0}]$ of each PV system is taken as the clustering index. Note that parameters must be normalized due to differences in dimensions and orders of magnitude of parameters.

III. MULTI-MACHINE EQUIVALENCE OF REGIONAL DECENTRALIZED PV CLUSTERS

A. Clustering Method of PV Systems Based on the FCM Algorithm

The clustering algorithm is an iterative optimization process, where the similarity between the clustering index which are in the same group is greater, and the similarity between clustering index of different groups is smaller[14]-[18]. On the basis of general clustering, the concept of fuzzy clustering is proposed. Through the FCM algorithm, n clustering indexes x_j ($j = 1, 2, \dots, n$) that corresponding to n PV systems are divided into c groups, it is determined which group each clustering index belongs to by the membership between $[0, 1]$, and the clustering centers of each group are calculated v_i ($i = 1, 2, \dots, c$) to get the minimal value of the objective function. The objective function is as follows:

$$J_m(U, c) = \sum_{i=1}^c \sum_{j=1}^n \mu_{ij}^m \|v_i - x_j\|_2 \quad (1)$$

where $\|v_i - x_j\|_2$ is the Euclidean distance between the i^{th} cluster center v_i and the clustering index of the j^{th} PV system x_j , m is the weighting exponent, $m \in [1, \infty)$, usually m is 2, $c \in [2, \sqrt{n}]$, u_{ij} is the membership value that the j^{th} PV system belongs to the i^{th} cluster center, which satisfies normalization:

$$\begin{cases} \sum_{i=1}^c \mu_{ij} = 1, & 1 \leq j \leq n \\ \mu_{ij} \in [0, 1], & 1 \leq j \leq n, \quad 1 \leq i \leq c \\ n > \sum_{j=1}^n \mu_{ij} > 0, & 1 \leq i \leq c \end{cases} \quad (2)$$

In order for (1) to achieve the minimum value, the following functions are constructed:

$$\bar{J}_m(U, c, \lambda) = J_m(U, c) + \sum_{j=1}^n \lambda_j \left(\sum_{i=1}^c \mu_{ij} - 1 \right) \quad (3)$$

where λ_j is the Lagrange multiplier of (2). By taking the derivative of all input parameters, we can get the necessary condition for (1) to get the minimum value, which is as follows:

$$v_i = \sum_{j=1}^n \mu_{ij}^m x_j / \sum_{j=1}^n \mu_{ij}^m \quad (4)$$

$$\mu_{ij} = \frac{1}{\sum_{k=1}^c \left(\frac{\|x_j - v_i\|_2}{\|x_j - v_k\|_2} \right)^{\frac{2}{m-1}}} \quad (5)$$

Thus, the output of the FCM algorithm includes two parts: the first part is c clustering centers, and each clustering center represents the average characteristics of the clustering index of the PV systems, the second part is a $c \times n$ -order membership matrix, which represents the membership that each PV system belongs to each group. Generally, the rule of maximum membership determines which group the PV systems belong to.

To evaluate the clustering effect and determine the optimal grouping number, two evaluation indices, the partition coefficient (PC) and the classification entropy (CE), are defined as follows:

$$PC = \frac{1}{n} \sum_{i=1}^c \sum_{j=1}^n (\mu_{ij})^2 \quad (6)$$

$$CE = -\frac{1}{n} \sum_{i=1}^c \sum_{j=1}^n \mu_{ij} \log(\mu_{ij}) \quad (7)$$

where PC is used to evaluate the degree of separation of different PV groups, the larger the better, and CE is used to evaluate the degree of fuzziness of different PV groups, the smaller the better.

B. Multi-Machine Equivalent Model

Using the FCM algorithm to group PV systems in Fig. 1, the detailed steps are shown as follows:

Step1: The clustering index $[P_0, t_{p0}, Q_0, t_{q0}]$ are constructed for all PV systems.

Step2: A membership matrix is generated randomly, which satisfy (2).

Step3: Updating the clustering centers through the membership matrix according to (4).

Step 4: Updating the membership matrix through the clustering centers according to (5).

Step5: Repeating steps 3 and 4 until the change of the value of the objective function calculated by (1) is less than the permissible value.

Step 6: Calculating the clustering evaluation indices and according to (6) and (7).

Step 7: Changing the number of groups c , and come back to step 2 to group the PV systems again. The best number of groups is determined by comparing the values of PC and CE under different number of groups, and the final grouping results of PV system are determined by the membership matrix at this time.

The n PV systems are divided into c groups through the above steps, then PV systems that are in the same group are merged into an equivalent PV system, all equivalent PV systems are then connected to the PCC. The equivalent model is shown in Fig. 4.

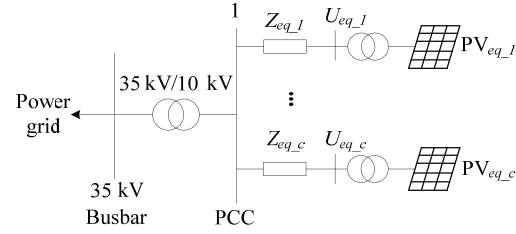


Fig. 4. Equivalent model of regional decentralized PV cluster.

The equivalent model of regional decentralized PV clusters is required to have the same external characteristics as the detailed model. That is to say, the two models should have similar dynamic response curves at the PCC point, including power, frequency, current, voltage, and so on.

IV. EQUIVALENT PARAMETERS CALCULATION

In Fig. 4, taking the x^{th} ($1 \leq x \leq c$) equivalent PV system as an example, and supposing that the x^{th} equivalent PV system is merged by M PV systems, the calculation method of the equivalent parameters is as follows.

A. Equivalence of PV Array

In the actual operation, it is difficult to ensure the power generation of PV systems due to partial shading and passing clouds, at this point, we can adopt parameter identification method to get the equivalent number of PV modules under ideal condition according to reference [19], thus the actual power generation of each PV array can be obtained, denoted as P_k ($k = 1, 2, \dots, M$). The power generation of the x^{th} equivalent PV array is as follows:

$$P_{eq_x} = \sum_{k=1}^M P_k \quad (8)$$

B. Equivalence of Line Parameters

Before equivalence, the voltage difference between the M PV systems and the PCC can be obtained by the power flow calculation, which is denoted as ΔU_k ($k = 1, 2, \dots, M$). Then we can calculate the weighted average voltage difference of the M PV systems (the power of a PV system is used for weighting) as:

$$\Delta \bar{U}_x = \sum_{k=1}^M (\Delta U_k P_k) / \sum_{k=1}^M P_k \quad (9)$$

After equivalence, according to Fig. 4, the voltage difference between the x^{th} equivalent PV system and the PCC is calculated as follows:

$$\Delta \bar{U}_{eq_x} = \frac{Z_{eq_x} P_{eq_x}}{\sqrt{3} U_{PCC}} \quad (10)$$

where U_{PCC} is the voltage of at the PCC point.

Solving the equation $\Delta \bar{U}_x = \Delta \bar{U}_{eq_x}$, the impedance of the equivalent line is as follows:

$$Z_{eq_x} = \frac{\sqrt{3}U_{pcc} \sum_{k=1}^M (\Delta U_k P_k)}{\left(\sum_{k=1}^M P_k \right)^2} \quad (11)$$

The above is the equivalent method of line impedance. Because the length of the line is short and the voltage is low, the influence of line capacitance can be ignored.

C. Equivalence of Transformer Parameters

According to Fig. 2, the equivalent impedance circuit of a single PV system can be simplified as shown in Fig. 5. where Z_{tr_k} is the impedance of the k^{th} PV transformer. Therefore, before equivalence, the total loss of the M transformers can be calculated by:

$$S_x = \sum_{k=1}^M I_k^2 Z_{tr_k} \quad (12)$$

After equivalence, the loss of the transformer in the x^{th} equivalent PV system is:

$$S_{eq_x} = I_{eq_x}^2 Z_{tr_eq_x} \quad (13)$$

At the same voltage level, it is thought that $I \propto P$. Therefore, by solving the equation $S_x = S_{eq_x}$, the impedance of the x^{th} equivalent transformer can be obtained:

$$Z_{tr_eq_x} = \frac{\sum_{k=1}^M (P_k^2 Z_{tr_k})}{\left(\sum_{k=1}^M P_k \right)^2} \quad (14)$$

Due to the low voltage level, the loss of the transformer excitation branch is small and can be ignored.

D. Equivalence of Inverter Parameters

The equivalent PI controller parameter of grid-connected inverters can be calculated using the capacity weighted method [20] as follows:

$$X_{eq_x} = \sum_{k=1}^M (X_k P_k) / \sum_{k=1}^M P_k \quad X = k_{pu}, k_{iu}, k_{pi}, k_{ii} \quad (15)$$

where k_{pu} and k_{iu} are the proportional and integral coefficients of the voltage outer loop, respectively, and k_{pi} and k_{ii} are the proportional and integral coefficients of the current inner loop, respectively.

To ensure the filtering effect of equivalent inverters, and that reactive power consumption remains unchanged before and after the equivalence, the equivalent filter inductance can be acquired by:

$$L_{eq_x} = \sum_{k=1}^M L_k / M^2 \quad (16)$$

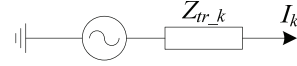


Fig. 5. Equivalent impedance circuit of a single PV system.

E. Error Analysis of Equivalent Model

In order to analyze the error of equivalent model proposed in this paper, the simulation results of the detailed model of PV cluster are taken as the reference, the error evaluation index of equivalent model is calculated as follows:

$$E = \int_{t_1}^{t_2} \left| \frac{Y_d - Y_e}{Y_d} \right| dt \quad (17)$$

where t_1 and t_2 are the start time and end time of simulation, respectively, Y_d and Y_e are the electrical quantity of the detailed model and the equivalent model at PCC, respectively, the electrical quantity here can be active power, reactive power, frequency and so on.

V. NUMERICAL EXAMPLES

A. Example of the System

The simulation system is the same as shown in Fig. 1. A typical double-loop controller is used as the inverter controller model, which contains a power outer loop and a current inner loop. The reference value of reactive power is set to zero, making the power factor unity. The main parameters of the system are shown in TABLE I and TABLE II. The line model is LGJ-35.

B. Clustering Result Analysis

The FCM algorithm is used to group the above regional decentralized PV cluster, when the grouping number is different, the evaluation indices of PC and CE are shown in Fig. 6.

As can be seen in Fig. 6, when the regional decentralized PV cluster is divided into two groups, the evaluation index PC is at a maximum and CE is at a minimum. Therefore, the optimal grouping number is $c = 2$. Results are shown in TABLE III.

The equivalent model of the regional decentralized PV cluster was calculated based on the method presented in Section III and is given in TABLE III.

C. Equivalence Effect Verification

In order to verify the effect of the equivalent model, the following four cases are simulated:

1) Three-Phase Short Circuit Fault

This simulation will compare the proposed equivalent method with the traditional single-machine equivalent method to verify the method in this paper. A three-phase short circuit fault occurs at the PCC point at 0.3 s and the fault clears at 0.38 s. The response curves of the detailed model, the proposed equivalent model, and the traditional single-machine equivalent model at PCC are shown in Fig. 7, the error calculation results are shown

TABLE I
LINE PARAMETERS

Line	Length (m)	Line	Length (m)
1-2	1839	10-11	435
2-3	1266	4-12	241
3-4	1679	12-13	1180
4-5	583	5-14	146
5-6	115	6-15	1610
6-7	386	15-16	1528
7-8	1298	16-17	985
8-9	90	17-18	708
9-10	172	9-19	2319

TABLE II
PV NODE PARAMETERS

Node Number	Power (kW)	k_{pu}	Inverter Parameters	L_k (mH)	Transformer Type
			k_{iu} k_{pi} k_{ii}		
3	21	0.51	0.86 150 10	0.125	S11-100/10
7	36	0.80	2.55 100 5	0.125	S11-125/10
10	60	0.62	1.23 400 1	0.125	S11-M-200/10
11	30	0.45	3.24 200 8	0.125	S11-M-200/10
12	24	0.75	1.05 300 2	0.125	S11-160/10
13	21	0.50	1.56 350 6	0.125	S11-100/10
15	45	0.42	0.65 250 1	0.125	S9-100/10
16	39	0.35	2.20 100 10	0.125	S11-M-100/10
18	45	0.62	1.64 400 4	0.125	S9-100/10
19	30	0.80	2.76 150 5	0.125	S11-M-100/10

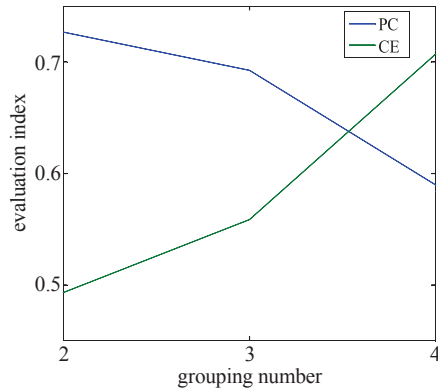


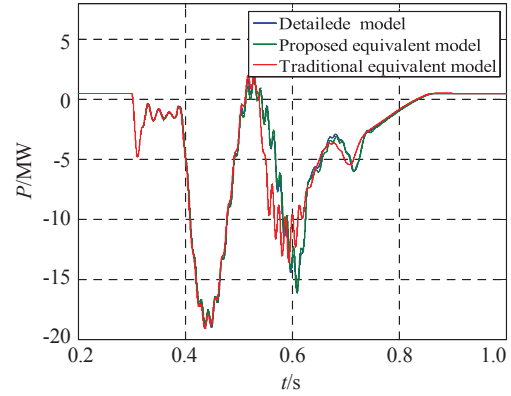
Fig. 6. Evaluation index of the clustering effect.

in TABLE IV, the actual time spent in the simulation process of the three models are shown in TABLE V.

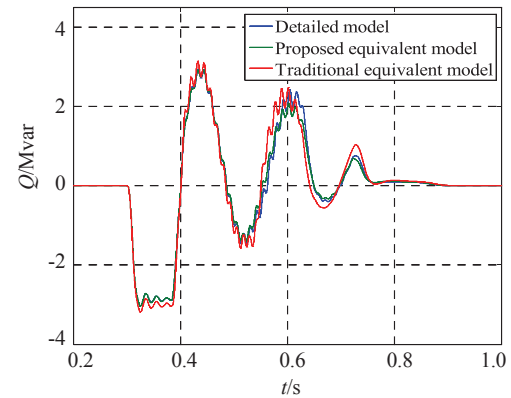
As shown in Fig. 7 and TABLE IV, the equivalent model in this paper has higher precision than the traditional single-machine model. TABLE V shows that the simulation time of the equivalent model in this paper is much lower than that of the detailed model, and is close to that of the traditional single-machine equivalent model. Therefore, the proposed equivalent model in this paper balances precision and simplification. However, this method also has some limitations, when the structure of distribution network or the capacity of PV systems changes,

TABLE III
BEST GROUPING RESULTS

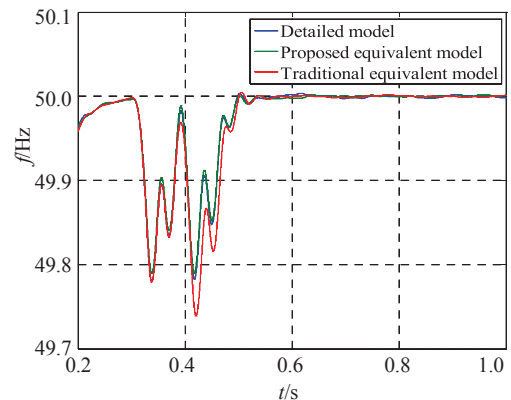
PV System Node Number	
Group 1	3, 7, 11, 12, 13, 19
Group 2	10, 15, 16, 18



(a) Active power response curve.



(b) Reactive power response curve.



(c) Frequency response curve.

Fig. 7. Response curves for three-phase short circuit.

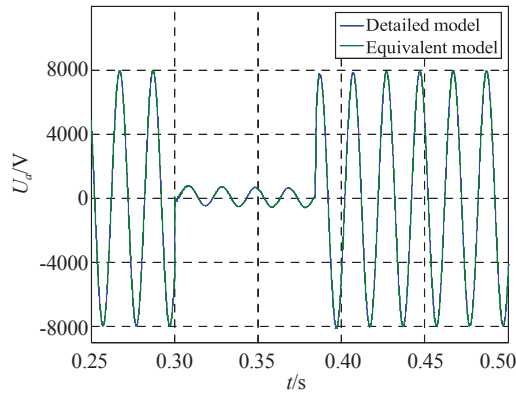
the power response curve under typical disturbance shown in Fig. 3 will also change, which leads to the change of clustering index, therefore we need to rebuild the clustering index for each PV system, it will increase much calculation burden.

TABLE IV
ERROR CALCULATION RESULTS

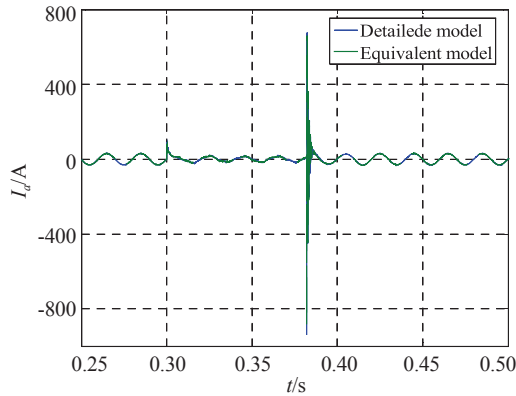
	Proposed equivalent model	Traditional equivalent model
Active power error	0.0041	0.0115
Reactive power error	0.0095	0.0340
Frequency error	0.0018	0.0044

TABLE V
MODEL SIMULATION TIME

	Detailed model	Proposed equivalent model	Traditional equivalent model
Time spent	25 s	7 s	5 s



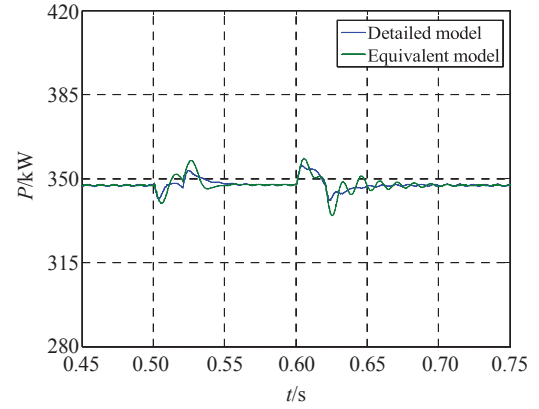
(a) Phase A voltage.



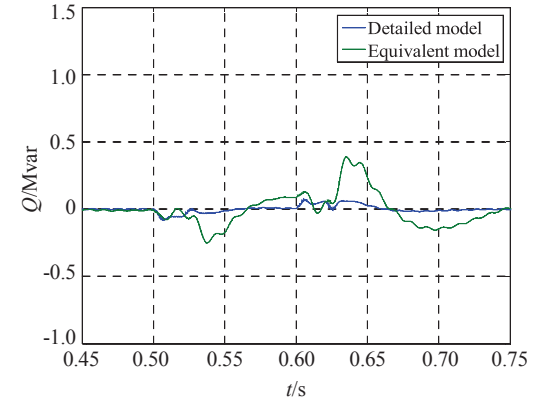
(b) Phase A current.

Fig. 8. Voltage and current response curves for single-phase short circuit.

As a final note, the equivalent model in this paper is a two-machine equivalent model based on TABLE III, but it does not mean that this equivalent model has the highest precision. In general, the more grouping number, the higher precision of the established equivalent model, but the model will be more complex correspondingly. In this paper, the best grouping number is chosen by the calculation of PC and CE, so the established equivalent model can best balance precision and simplification in theory.



(a) Active power response curve.



(b) Reactive power response curve.

Fig. 9. Response curves for voltage disturbance from power grid.

2) Single-Phase Short Circuit Fault

The clustering index of the PV system is constructed under the condition of a three-phase short circuit fault as shown in section II. To verify the application of the equivalent model to another fault situation, a single-phase ground fault occurs at PCC point at 0.3 s and the fault clears at 0.38 s. Voltage and current curves of the detailed model and the equivalent model at the PCC point are shown in Fig. 8.

Fig. 8 shows that the external characteristics of the equivalent model are in agreement with that of the detailed model. Therefore, the clustering index presented in this paper is reasonable, and a PV system with similar dynamic characteristics can be divided into the same group by the clustering algorithm.

3) Voltage Disturbance From Power Grid

Three-phase short circuit fault and single-phase short circuit fault are both large disturbance, in order to verify the accuracy of the equivalent model under small disturbance, small disturbance of power grid voltage is set in this simulation: the power grid voltage change from 1.0 p.u to 0.9 p.u at 0.5 s, and the voltage is restored to 1.0 p.u at 0.6 s. The active and reactive power curves of the detailed model and the equivalent model at PCC are shown in Fig. 9.

As seen in Fig. 9, the response curve of equivalent model is still agreement with the detailed mode under small voltage disturbance from power grid, this comparison shows the effective-

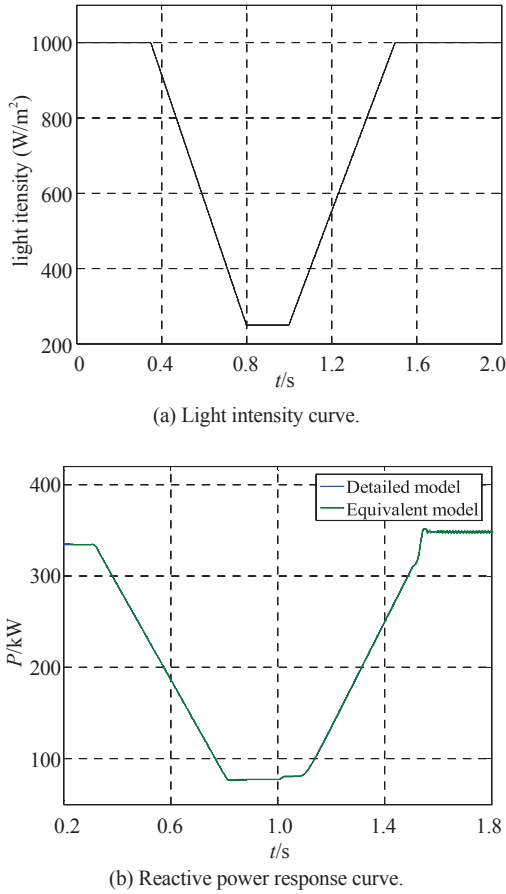


Fig. 10. Response curves for light intensity disturbance.

ness of the proposed clustering modeling method again.

4) Light Intensity Disturbance

In this section, a comparison is shown when the external environment changes. In the simulation, the light intensity of the system is shown in Fig. 10(a). The active power response curves of the detailed model and the equivalent model at the PCC point are shown in Fig. 10(b).

As seen in Fig. 10, the duration of interruption in light intensity is long, and the system response is not severe. Therefore, by using maximum power point tracking (MPPT), the active power of the PV cluster can effectively track the change in light intensity and the active power response curves of the two models are very similar.

VI. CONCLUSION

This paper presents an equivalent modeling method for regional decentralized PV clusters. By extracting feature points of response curves, the clustering index of a PV system is given. The PV systems are then divided into groups by a FCM clustering algorithm. PV systems that are in the same group are merged into an equivalent PV system by calculation of equivalent parameters, establishing an equivalent model of the regional decentralized PV cluster.

Simulation results and error analysis shows the effectiveness

of the proposed method. The optimal grouping number is determined by the evaluation indices PC and CE, and the established equivalent PV system has a similar response to disturbances such as short-circuit faults, grid voltage fluctuation and external environment changes as the detailed model. Whether this method can be extended to other types of distributed generator cluster is a topic for further research.

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