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Dynamic equivalent modeling of two-staged photovoltaic power station clusters based on dynamic affinity propagation clustering algorithm

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ABSTRACT

This paper presents a novel dynamic clustering equivalent modeling method for a two-staged photovoltaic (PV) station cluster, which is a key tool to analyze the dynamic responses of the distribution network with high PV penetration. In this paper, a dynamic affinity propagation (DAP) clustering algorithm is proposed after studying the indexes that can describe the dynamic characteristics of two-staged PV power station. Then this algorithm is used to group the PV stations in the PV cluster according to their dynamic characteristics. Finally, the dynamic equivalent model of PV cluster is obtained by parameters aggregation of PV stations in the same group and simplification equivalent of the network. The proposed method is verified by a PV cluster distribution network with 20 two-staged PV stations and the simulation results show that the proposed dynamic equivalent model can accurately reflect the dynamic response characteristics of the PV cluster. At the same time, the simplified PV cluster model would reduce the computational complexity and the simulation time significantly.

1. Introduction

Compared with traditional fossil energy, photovoltaic (PV) power generation is resourceful, renewable and environmentally-friendly [1]. Therefore, in recent years, the PV industry has been developing rapidly. According to the data released by the International Energy Agency (IEA), the global cumulative installed capacity is about 230 GW [2]. It is expected that PV generation will account for 16% of the world's total electricity consumption by 2050 [3,4].

Due to the advantages of PV itself and the support of government policies, the small and medium-sized PV power stations with the two-staged structure are constructed in the application environments, such as the roof of industrial park and the wasteland of rural area, intensively and massively. So the PV station clusters are formed in the local distribution networks. With the increase of the PV penetration of the power system, dozens or even hundreds of small and medium-sized PV stations could be contained in a PV station cluster [5]. The power system issues caused by high PV penetration are gradually increasing, such as power quality [6,7], stability, etc.[8,9]. Therefore, it is necessary to establish a precise model to characterize the dynamic responses of the overall PV cluster in the normal and fault operating statuses at the point of common coupling (PCC). However, if modeling each station in the PV cluster in detail, not only the model complexity is increased, but also a lot of time and efforts is required in the data preparation and simulation computation. These disadvantages undoubtedly limit the detailed modeling method's application in practical engineering. Therefore, it is necessary to study the dynamic equivalent modeling of PV cluster to simplify the model complexity, and reduce the time of simulation computation.

At present, there are many literatures on the modeling of PV station and its components [10–13], but there is no literature on the modeling of PV clusters. In addition, in the field of renewable energy, the wind power modeling is more mature than PV modeling. The traditional single-machine equivalent method is to model the entire wind farm with an equivalent wind turbine [14,15]. However, the wind velocity in a wind farm is usually not uniform for the sake of wake effect. Therefore, the multi-machine equivalent method based on the principle that sorting the similar operating status wind turbines into the same group has become a research focus [16–19]. Unlike the wind farm, the solar irradiance in a PV station could generally be approximated as uniform, and the current PV stations usually operate at the mode of MPPT and unit power factor, except for few large PV stations where the parameters of internal PV units are different [20], the PV units of

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a PV station generally work in the same state. Therefore, each PV station can be modeled with a single equivalent PV unit, but the system parameters of different stations in the PV cluster vary widely due to the differences of manufacturers and designs. It is difficult to comprehensively reflect the dynamic features of the whole PV cluster by using a single equivalent PV station. Hence, this paper introduces the multi-machine equivalent concept of wind farm into the PV cluster modeling, and establishes a new dynamic equivalent modeling method of two-staged PV station cluster based on a proposed clustering algorithm, which can determine the equivalent number and parameters of PV stations. In this paper, simulation cases in the normal and fault operating statuses of a PV cluster system are used to verify the effectiveness of the proposed method.

The contributions of this paper to the research field are:

(1) The dynamic equivalent modeling method of PV cluster in distribution network is studied and proposed for the first time.
(2) The waveform clustering indexes based on dynamic features of two-staged PV station are proposed.
(3) A dynamic affinity propagation (DAP) clustering algorithm for dynamic modeling of PV cluster is proposed to track the similar dynamic features between PV stations and can be further applied to other large data problems in renewable energy.
(4) The methods of PV station parameters aggregation and network simplification equivalent are proposed.

The rest of the paper is arranged as follows. First, the math model of the two-staged PV system is built (Section 2). Second, the influence factors of the dynamic features of PV system are analyzed and then the clustering indexes and clustering algorithm is proposed (Section 3). Next, the method of PV parameters aggregation and simplification network equivalent are proposed (Section 4). Finally, the equivalent model of a PV cluster is built to verify the validity and accuracy of the proposed modeling method (Section 5).

2. Mathematical models of two-staged PV system

The two-staged PV system consists of four sub-modules: a PV array as a DC source; a DC-DC boost converter for maximum power tracking (MPPT) and voltage step up; an inverter for DC voltage control and reactive power control and a filter for harmonic suppression [21,22], which is shown in Fig. 1. The following subsections would describe the dynamic model of each sub-module.

2.1. PV array modeling

The study of PV array modeling is fairly mature [23,12]. An engineering mathematical model was chose here to describe it's nonlinear output characteristics [24]. Except for solar irradiance and temperature, this model only requires several measured values, which are provided directly by the manufacturer, to calculate the output characteristics $i_{pv} - u_{pv}$ of the PV modules. These values include: u'_{oc}, i'_{sc}, u'_m and i'_m, which are the open-circuit voltage, short-circuit current, maximum power voltage and maximum power current of the PV module under standard test conditions (STC) [25], respectively, where the superscript " ′ " means the measured value under STC. The output characteristic is calculated as shown in Eq. (1), and the specific meaning of each parameter is shown in Appendix A.

$$i_{pv} = i_{sc}\left[1 - C_1\left(e^{\frac{u_{pv}}{C_2 u_{oc}}} - 1\right)\right] \tag{1}$$

One can obtain the output characteristics of the array by simply multiplying u_{oc} and u_m by N_p and dividing i_{sc} and i_m by N_s in Eq. (1), where N_s and N_p are the series and parallel numbers of the modules in the array. The array is connected to the DC-DC boost converter through the array capacitance C_{pv}, which can suppress the ripple of the output voltage of the array. The dynamic characteristics of this connection link can be given in the Laplace domain by:

$$i_{pv} = C_{pv} s u_{pv} + i_L \tag{2}$$

where i_L is the inductance current of the boost converter.

2.2. DC-DC boost converter modeling

The dynamic characteristics of DC-DC boost converter can be described by the switching cycle average model. The average inductance current equation and the average capacitance voltage equation in the Laplace domain are [9]:

$$L_{dc} s i_L = u_{pv} - (1 - D) u_{dc} \tag{3}$$

$$C_{dc} s u_{dc} = i_{dc} - (1 - D) i_L \tag{4}$$

where L_{dc} and C_{dc} are the inductance and capacitance of the boost converter, respectively, D is the duty ratio of the switch, i_{dc} and u_{dc} are the output current and output voltage of the boost converter, respectively.

The task of the controller of the boost converter is to control the switch on and off so that the array output voltage tracks the maximum voltage of the array to achieve maximum power tracking. The model of the controller is given by:

$$D = \left(k_p + \frac{k_i}{s}\right)(u_m - u_{pv}) \tag{5}$$

where k_p and k_i are the proportional and integral control gains of the controller, respectively.

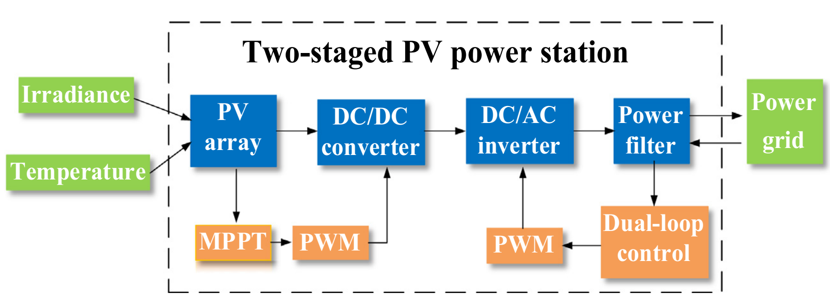

Fig. 1. The block diagram of two-staged PV power station model.