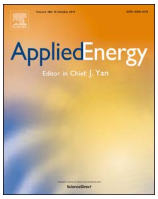
Applied Energy 211 (2018) 568–581

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy



Sparse voltage amplitude measurement based fault location in large-scale photovoltaic power plants

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HIGHLIGHTS

- A sparse measurement based fault location is proposed for large-scale photovoltaic (PV) power plant.
- The improved compressive sensing (CS) technique is empoyed in the negative sequence network.
- Data from the world's largest PV power plant is used to prove the proposed method.
- The improved method offers accurate fault location considering all the possible influence factors.

ARTICLE INFO

Keywords:
Fault location
Bayesian compressive sensing
Large-scale PV power plant
Sparse voltage measurement

ABSTRACT

Large-scale photovoltaic (PV) power plants contain numerous transmission line branches and laterals inside. When a fault occurs conventional fault location methods face challenges due to the complex system structure and the diversity of PV inverter controls. Most of the published fault location methods cannot be directly used in the PV power plant due to the following issues: (1) Most of the fault location methods consider the PV inverter as a constant voltage source while the actual inverters have varied controls during faults. Without analysis of the unique fault transients of the PV, the fault location will suffer from errors. (2) In a complicated large-scale PV power plant with massive quantity of nodes, the synchronised measurements from all the nodes are almost impossible. A method with sparse un-synchronized measurements is required. Therefore, a new negative-sequence voltage amplitude sparse measurement based fault location method is proposed for unbalanced faults. The improved Bayesian compressive sensing algorithm is used to recover the sparse fault current vector and then determine the faulted node. Both the field testing and the simulation results indicate that the proposed method can locate the faulted nodes accurately and effectively without synchronizing measurement requirements from all the nodes. This method also presents a good performance for various unbalanced fault types, fault resistances, inverter controls and signal noise. All these factors make the propose method feasible for industrial applications.

1. Introduction

To mitigate fossil energy demand and solve the ecological crisis, solar energy, as one of the major renewable sources, is fast developing for electricity generation. Benefiting from the advanced manufacture and reduced cost, large-scale photovoltaic (PV) power plants are being deployed worldwide with a capacity of hundreds to thousands of megawatts [1,2]. Such a PV power plant covers a total area of thousands of hectares. In the plant, power from the PV units (minimum generation units) is collected using numerous underground cables which make up a radial collection network. The cables may be broken accidentally by the bite of rodents or excavation by construction personnel. That will lead to a cable-to-ground fault in the network and then cause the faulted cable to be disconnected via protection devices. Looking for the actual failure position is difficult and time-consuming. The disconnected PV units cannot be restored before the failure position is identified. In the worse situation, an override trip occurs because of circuit breaker failure or protection incoordination. That will enlarge the interrupted zone and make failure checking more difficult. More PV units will remain disconnected longer. Hence, it is significant to locate the fault inside the PV power plant as quickly as possible to minimize the impact of a fault and maximize the power generation efficiency.

Inside a large-scale PV plant there is a radial collection network that is similar to medium-voltage distribution systems. Fault location

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https://doi.org/10.1016/j.apenergy.2017.11.075
Received 27 June 2017; Received in revised form 3 November 2017; Accepted 14 November 2017

Nomenclature

i_m^{r*}	the sequence reference current
e_m^r	the sequence voltage at the point of common coupling (PCC)
P_0^*, Q_0^*	the reference active power and reactive power
K	the control factor K denoting the used control strategy
$\mathbf{I}_{dq}^{p(n)}$, $\mathbf{E}_{dq}^{p(n)}$	the current and voltage amplitudes
γ	the factor describing the positive-sequence voltage sag
E_a	the pre-fault voltage amplitude at PCC
δ	a measure of the voltage unbalance
P_0', Q_0'	average values of the active the reactive powers supplied by PV during the fault
$\theta^{p(n)}$	the phase shift of the positive(negative)-sequence current
V_k^{neg}	the negative-sequence voltage at node k
I_k^{neg}	the negative-sequence current injected at the faulted node k
Z_{ii}^{neg}	the self-impedance of node i
Z_{ij}^{neg}	the mutual impedance between node i and node j
$\mathbf{V}^{neg}$, $\mathbf{I}^{neg}$	the node voltage vector and the node current injection vector
$\mathbf{Z}^{neg}$	the impedance matrix
$\mathbf{y}$	the measured signal
$\mathbf{\Phi}$	the sensing matrix
$\mathbf{e}$	the measurement noise
σ^2	the variance of the noise signal
$\boldsymbol{\theta}$	the unknown signal

techniques within a large-scale PV power plant have been rarely reported, whereas in distribution systems with distributed generators (DGs), fault location strategies have been under development for years [3]. Impedance based methods estimate the line impedance between the fault point and the relay installation point to locate the fault [4,5]. When a complex system such as a PV plant contains many branches and laterals, impedance based methods may give the same location for faults on different branches or laterals [6]. Travelling wave methods in [7,8] capture the transient wave reflected from a fault location and their performance is sensitive to laterals and short lines. Furthermore, fault transients generated by DGs will influence travelling wave recognition and cause errors or complete failure to locate the fault. The above conventional methods are vulnerable for numerous laterals and the fault characteristics of DGs and these methods are not directly applicable for fault location in a PV power plant.

To overcome the impact of laterals, many efforts have been performed on fault location techniques using smart meters and phasor measurement units (PMUs) [9–17]. The multi-terminal based method distinguishes the faulted section from the non-fault sections using voltage and/or current phasors and even switching state information from multiple measurements. Voltage sags at different nodes caused by the fault have been used for fault locating [9–13]. Voltage sag based methods need simulate overall fault scenarios and then select the optimal match by comparing the simulated results with measured voltages for a fault location, which is sensitive to the measurement accuracy and time-consuming for large systems. Among those multi-measurement based algorithms, some use PMUs further to measure synchronous phasors for improved performance [14–17]. However, PMUs are usually only equipped on important buses and this might cause fault location errors in distribution systems due to a lack of measurements.

In the context of the multi-measurement methods, artificial intelligent techniques such as Artificial Neural Network [18] and Support Vector Machine [19], have been introduced to simplify the diagnostic procedure and improve the fault location performance. But learning-based methods highly depend on the amount and quality of the training data and the performance may be unacceptable with limited information from insufficient monitoring devices. A comparison of the advantages and disadvantages of artificial intelligent techniques for fault location in distribution systems can be found in [3]. The compressive sensing (CS) technique in signal processing is used in [20–22] to locate distribution network faults without a training database required by most artificial intelligent algorithms. The CS based methods solve undetermined node voltage equations to obtain a sparse fault current vector to locate faults by regarding the fault as a current injection. However, directly applying the CS algorithms used in [20–22] might not work well for fault location in a PV power plant inside which the unique network topology and fault behaviours can influence the performance of those CS algorithms. But the CS technique has potential in fault location because of the extremely sparse measurements required, which means the low modification cost in existing systems.

Generally, a fault location method in a renewable power plant has not been reported yet and the common issues of the existing fault location methods in a distribution system are: (1) The DGs are mostly seen as a constant power sources or controllable current sources. However, PV units in a centralized plant have different behaviours from other DGs due to the method of control in both positive- and negative-sequence frames [22]. Considering the detailed DG models [23], the existing fault location methods applied in distribution systems with DGs will suffer from errors when they are used in a PV power plant with 100% renewable generation. (2) In large-scale power plants, the branches and nodes are massive in quantity. In this case, using PMUs or other synchronized measurements from all the nodes to locate the fault is a big challenge for industrial applications.

Based on the above two major issues, this paper proposes a new negative-sequence voltage amplitude sparse measurement based fault location method for large-scale PV power plants. The fault characteristics of PV units in a real PV power plant are studied considering the inverter fault current limitation control during the fault location procedure. Based on the fault performance of the PV inverters and integrated with negative sequence measurement, the effect of variable PV fault transients caused by different inverter controls can be eliminated. After employment with an improved Bayesian compressive sensing technique, accurate fault location can be achieved using only non-synchronized sparse voltage measurements. Both the field testing and the simulation results shows the proposed method offers accurate and fast fault locations under various fault scenarios and different influencing factors as fault types, fault resistances and measurement errors.

2. Fault current characteristics within the PV power plant

The centralized PV system is briefly illustrated in Fig. 1. For such a PV system, the combined DC voltage from multiple PV panels is able to meet the inverter requirement without a voltage boost circuit. The PV inverter usually chosen is the voltage source converter (VSC).

Inside the VSC, the outer-loop voltage control is used to realize the maximum power point tracking (MPPT), and the inner-loop current control regulates both positive- and negative-sequence currents for better fault-ride-through (FRT) ability under unbalanced faults. For the

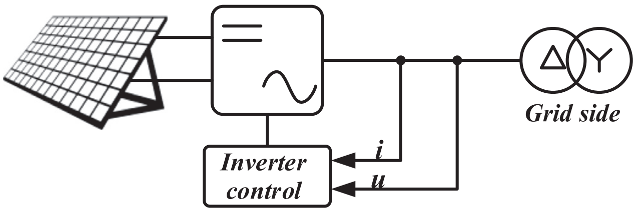

Fig. 1. Diagram of the centralized PV system.