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Photovoltaic generator modelling to improve numerical robustness of EMT simulation

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ABSTRACT

Numerical simulation is an indispensable tool for studying photovoltaic (PV) systems, to derive component ratings, optimise protections, design controllers as well as to evaluate the impact of embedded generation on distribution system operation. In EMT simulation, the non-linear equations representing the PV generators are separated from the linear equations of the rest of the power system. This technique presents high computational efficiency but introduces a one-step delay, which can cause problems of numerical instability. These problems are particularly evident when the PV generator is represented by multiple single-diode equivalent circuits, such as in the cases of PV generators composed of different types of arrays or subject to partial shading or interfaced by multilevel inverters. To overcome such problems, in this paper a new approach is proposed to include the PV generator model into EMT simulation. A convergence analysis gives proof of the obtained improvements, which are also confirmed by numerical results. The robustness of the proposed technique is tested by simulation of an IEEE benchmark system in the cases of partial shading and of electric faults.

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1. Introduction

In recent years the growing concern for environment preservation has caused a wide spreading of photovoltaic (PV) systems in distribution networks. To derive component ratings, optimise protections, design controllers, evaluate the impact on the distribution system operation, detailed modelling of grid connected PV systems for power system simulation studies is needed.

Research has deeply analysed the models for the components of a grid connected PV system, including equivalent circuits of the PV generator [1–3], configuration and dynamic response of the inverter [4–6], behavior of the grid interface and performance of the control system [7–9]. Other important aspects have been addressed, related to the inclusion of the PV system into the distribution network [10].

In a PV system, the PV generator consists of electrically connected PV modules and it is modelled by physical-oriented equivalent circuits, including one or more diode. The single-diode equivalent circuit is the most commonly used model for large PV generators and it is adopted in this paper. This model introduces a non-linear dependency of the current injected by the PV generator on the voltage at its terminals, which in turn depends on the operating conditions of the whole power system which the PV generator is connected to.

When PV systems are included into the power system simulation, the non-linearities present in the PV generator models require special attention. On one side, they cannot be neglected because they affect the performance of the various components of the PV systems, in particular of the control systems and of the Maximum Power Point Tracker (MPPT) [10]. On the other side, the non-linearities can introduce numerical problems during the power system simulation [11].

From a strict mathematical point of view, in each step of the simulation, the set formed by the non-linear equations representing the PV generators and by the linear equations representing the rest of the power system must be solved, using an iterative numerical algorithm. This approach is adopted by some simulation tools, such as PSpice and Matlab; it is accurate but presents the drawback of a heavy computational burden when simulating large distribution networks including several PV systems. To guarantee computational efficiency, some authors have proposed equivalent circuits based on simplified or linearised equations, thus losing in terms of model accuracy [12–14].

An alternative approach consists of separating the non-linear equations of the PV generators from the linear equations of the rest of the power system. Then, the PV generator models are solved substituting in the non-linear equations the values of voltage and/or current available from the past simulation step [15,16]. This approach can be used in any simulation tool and, in particular, it is adopted by EMTP and EMTDC [17]. It keeps the accuracy of the PV generator model while presenting a computational burden which is comparable with the one of a linear system. Unfortunately,

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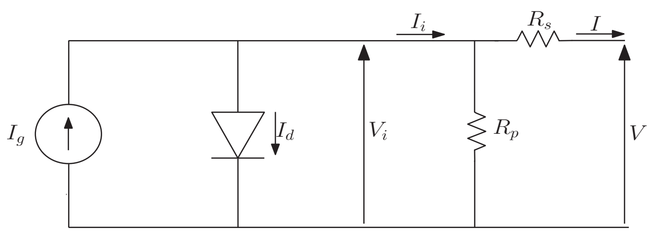

Fig. 1. Single-diode equivalent circuit of the real PV module.

the one-step delay introduced in the solution of the PV generator models can cause numerical instability problems. These problems arise especially when the PV generator is represented by multiple single-diode equivalent circuits, such as in the cases of PV generators composed of different types of arrays or subject to partial shading or interfaced by multilevel inverters [18,19]. In the following this approach is referred to as Basic Linear System Technique (BLST).

To overcome most numerical problems of the BLST simulation while keeping high computational efficiency, a new approach is proposed in this paper to include the PV generator model in EMT simulation. The basic idea is to extend the original approach of BLST by adding some information extracted from the non-linear equations of the PV generator models into the linear equations of the rest of the power system. This approach is referred to as Extended Linear System Technique (ELST).

In this paper, the inclusion of the PV generator model into EMT simulation of power systems is tackled. After briefly recalling the single-diode equivalent circuit, the BLST is described and the new ELST is presented. Then, a convergence analysis is performed to evidence the numerical instability problems of BLST and the improvements introduced by ELST. Using PSCAD/EMTDC tool, the theoretical results of the convergence analysis are verified by simulation of a simple system. Eventually, the robustness of the ELST is tested by simulation of an IEEE benchmark system in the cases of partial shading and of electric faults.

2. PV generator modelling for EMT simulation

2.1. PV generator modelling

A PV module can be modelled by the single-diode equivalent circuit shown in Fig. 1 [1]. The ideal PV module is composed of a current generator I_g connected in parallel to a diode and it can be described by the following equation

$$I_i(V_i) = I_g - I_d(V_i) = I_g - I_o(e^{\beta V_i/a} - 1) \quad (1)$$

where I_i and V_i are the terminal current and voltage of the ideal PV module, I_d is the current diverted through the diode, I_o is the diode reverse saturation current, a is the diode ideality factor and β is the inverse thermal voltage. For a PV module composed of M_s series-connected PV cells, β is defined as

$$\beta(T) = \frac{q}{M_s kT} \quad (2)$$

where k is the Boltzmann constant ($1.3806503e^{-23}$ J/K), q is the electron charge ($1.60217646e^{-19}$ C) and T is the p–n junction temperature. The real PV model is enriched by a series resistance R_s and a parallel resistance R_p and it can be described by the following equation

$$I(V) = I_g - I_o\,(e^{\beta(V+R_sI)/a} - 1) - \frac{V + R_sI}{R_p} \quad (3)$$

where I and V are the terminal current and voltage of the real PV module.

In general, the five circuit parameters a, I_g, I_o, R_s and R_p are functions of the type of PV device and of the environmental conditions, described by the solar irradiation G and the p–n junction temperature T [20]. In this paper, the dependency on the environmental conditions is accounted for only I_g and I_o, whereas it is neglected for a, R_s and R_p. Furthermore, the values of the five circuit parameters are evaluated by using analytical expressions reported in [21] on the basis of the data provided by manufacturers.

The single-diode equivalent circuit can also be used to represent a PV generator, equipped with N_p parallel arrays of N_s series-connected PV modules, which are assumed to be all of the same type and in the same environmental conditions. In this case, the five circuit parameters involved in (3) and the inverse thermal voltage in (2) are related to the PV generator and indicated with $a_{gen}, I_{g,gen}, I_{o,gen}, R_{s,gen}, R_{p,gen}$ and β_{gen} respectively. They can be evaluated from the PV module parameters as

$$a_{gen} = a, \quad I_{g,gen} = N_pI_g, \quad I_{o,gen} = N_pI_o, \quad R_{s,gen} = \frac{N_s}{N_p}R_s,$$
$$R_{p,gen} = \frac{N_s}{N_p}R_p, \quad \beta_{gen} = \frac{\beta}{N_s} \quad (4)$$

Anyway, the single-diode equivalent circuit can always be used to represent one or more arrays of the same type and in the same environmental conditions, and various circuits can be electrically connected to represent the whole PV generator.

In practice, the PV generator is modelled by a non-ideal current generator: it injects a current I whose value depends on the terminal voltage V, which, in turn, depends on the operating conditions of the whole power system which the PV generator is connected to. Moreover, the relationship (3) between I and V is non linear.

In the following, the problem of including the PV generator model into the EMT simulation is tackled by using BLST and ELST. For the sake of simplicity and clarity, but without any loss of generality, some hypotheses are assumed: the power system includes only a PV system; the power system is linear except for the presence of the PV generator; the PV generator is composed of modules of the same type and in the same environmental conditions.

2.2. BLST

The BLST is the simplest and most straightforward way to include the relationship (3) in the EMT simulation. It is based on the separation of the non-linear equation of the PV generator from the linear equations of the rest of the power system. In particular, the non-linear equations are solved by substituting the values of voltage and/or current available from the past simulation step [15,16].

Referring to EMT simulation, Fig. 2 shows the block diagram related to the kth step of the simulation. In detail, the value $I(k)$ is evaluated by (3), given the value $V(k-1)$ available from the previous step of the simulation. Then, the linear power system is solved, assuming a current injection equal to $I(k)$ in place of the PV generator. The resulting vector $\mathbf{V}(k)$ represents the values of all nodal voltages, which also includes the value $V(k)$ of the voltage at the PV generator terminal.

The BLST simulation presents a computational burden which is comparable to the one of linear power systems. However, using a one-step delayed value of V it can introduce numerical instability in the simulation. Such problems are particularly evident when it is necessary to represent the PV generator with multiple single-diode equivalent circuits. It is the case when arrays with different characteristics are present in the PV generator, as well as when the arrays are subject to different environmental conditions, such as in the case of partial shading. In these circumstances the performance of

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