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Photovoltaic generator model for power system dynamic studies

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ABSTRACT

Photovoltaic (PV) power generation has developed very rapidly worldwide in the recent years. There is a possibility that the PV power generation will switch from an auxiliary power supply, as of today, to a main power source in many power grids in the future. Naturally, dynamic studies on power grids with a high penetration of PV generators have become increasingly important, and thus have attracted major attentions from both the power industry and the academia. Consequently, dynamic modeling of PV generators has been investigated widely. However, among various proposed models, there is a confusion on the model applicability and a lack of the clarification on the required level of details on the modeling work, which severely limit the real industrial applications of the developed models. This paper reviews the state-of-the-art PV generator dynamic modeling work, with a focus on the modeling principles of PV generator for the power system dynamic studies. The paper presents the detailed modeling process for the recommended PV generator dynamic model, and clarifies the assumptions and simplifications made in the modeling process, thus raises the discussion on the model applicability. Studies that require further attentions on developing the dynamic models of PV generators for power system dynamic studies are identified and presented in the paper. However, this work does not intend to conclude the research work in this important field, instead, it aims to provoke more discussions on developing guidelines on building or selecting the appropriate models to fit into the purpose of the targeted dynamic studies.

1. Introduction

Solar energy is one of the major renewable energy resources, which contributes significantly to the sustainable future of our earth especially for guaranteeing the energy security and protecting the environment. Among various renewable generation technologies, solar energy systems are relatively mature. Its fast cost reduction has also been accelerating the wide applications of solar energy for power generation in power grids. Photovoltaic (PV) power generation is one main form of utilizing the solar energy and has developed very rapidly around the world in the past decade (Domínguez et al., 2015; Pinson et al., 2017; Zappa et al., 2019). According to the International Energy Agency (IEA) report, renewable power capacity is set to expand by 50% between 2019 and 2024, led by solar PV. Solar PV is thought to account for ~60% of the expected growth (International Energy Agency, 2020). China is among those countries with the fastest deployment of PV systems. Indeed, the installed capacity of grid-connected PV generators in China has ranked the first in the world since the end of 2015, and still shows a strong growing trend (Ding et al., 2016; Kang and Yao, 2017; National Energy Administration of the People's Republic of China, 2019).

The increasing penetration of PV may impose significant impacts on the operation and control of the existing power grid. The strong fluctuation and intermittency of the PV power generation with varying spatio-temporal distribution of solar resources make the high penetration of PV generation into a power grid a major challenge, particularly in terms of the power system stability (Cheng et al., 2016; Kawabe and Tanaka, 2015; Shah et al., 2015; Wang et al., 2016). The problem becomes aggravated when the PV power generation is affected by extreme weather, for instance, the solar eclipse in Germany in 2015 (Wikipedia, 2015). In Tibet of China, in situ data at Yangbajing PV power plant shows that the power outputs can drop to 30% or 50% of its rated value in 3s, due to the rapid cloud transient (Huo and Lu, 2012; Wang et al., 2015), which is far more serious than scenarios where the solar outputs dropped by 70% in 5–10 min (Mills and Wiser, 2011; NERC, 2009; Rahmann et al., 2016). For countries with special geographical

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characteristics, such as China, where solar resources and the electricity loads are distributed unevenly, the PV penetration into the grid poses even bigger threats to system stability. In these countries the developments of PV power stations are characterized by the (often large-scale) developments, the weak grid integration, and the long-distance transmission. All these factors can easily lead to serious system stability problems (Xia et al., 2019; Zhao et al., 2019).

By and large, PV generation belongs to the big family of inverter-based generation technologies. There have been reported contingencies in the operation of real power systems with a high penetration of inverter based renewable energies including both wind power and solar power, such as the 2016 South Australia blackout (AEMO, 2017; Yan et al., 2018), the 2019 Great Britain blackout (National Grid ESO, 2019a, 2019b), the 2016 and 2017 California faults in southwestern United States (NERC/WECC, 2018; NERC/WECC Inverter Task Force, 2017). Therefore it is critical to understand the possible impacts of inverter-based generators on power system dynamics, so that a power system with a high PV penetration can be better operated and controlled. To achieve such goals, it is essential to build credible simulation models for PV generators (Villegas Pico and Johnson, 2019). Like all the other dynamic components, such as generators or motors, a PV generator needs to be modeled dynamically for the purpose of power system dynamic simulation. However, according to a survey completed by CIGRE (The International Council on Large Electric Systems)/CIRED (International conference on Electricity Distribution) joint workgroup on modeling of inverter-based generation for power system dynamic studies, there has been a high percentage of using negative load as the model for PV generators among the transmission system operators (TSO) and distribution system operators (DSO) (CIGRE C4/C6.35/CIRED joint working group, 2018). One of the key obstacles identified through this survey in applying the dynamic model for PV generators rather than a static model is the lack of clarity on the modeling principle, model applicability and model selection guidance for TSO and DSO, which is one major focus of this paper.

To date, the research on PV generator modeling mostly focuses on the modeling of PV arrays, the PV inverter, and all other relevant components of a PV generator. Among many academic and industrial efforts in PV generator modeling, the General Electric (GE) (Clark et al., 2010), the Western Electricity Coordinating Council (WECC) (Pourbeik et al., 2017; WECC Renewable Energy Modeling Task Force, 2012; WECC Renewable Energy Modeling Task Force, 2014; WECC White-paper, 2015), the International Electrotechnical Commission (IEC) (Ackermann et al., 2013), the China Standards Committee (Standardization Administration of the People's Republic of China, 2016a; Standardization Administration of the People's Republic of China, 2016b) and CIGRE (CIGRE C4/C6.35/CIRED joint working group, 2018; Yamashita et al., 2018) all have released dynamic models of PV generators with various granularity. Meanwhile, some international commercial power system simulation software has also started to include their recommended dynamic models for PV generators (DIgSILENT GmbH, 2011; General Electric Company, 2009; Manitoba Hydro International Ltd., 2012; Power Technology Inc., 2013; The MathWorks Inc., 2014). In China, the China Electric Power Research Institute (CEPRI) also developed the PV system model in Power System Analysis Software Package (PSASP) and Power System Department-Bonneville Power Administration (PSD-BPA) software (China Electric Power Research Institute, 2010; China Electric Power Research Institute, 2018). With the potential role change of PV power generation from an auxiliary generating resource to a main, or even dominant, generating resource, its dynamic characteristic plays an increasingly important role in power system dynamic studies. Consequently, developing and applying the PV generator dynamic models are of vital importance.

However, different from the conventional dynamic components in a power system (NERC, 2010), such as fuel/hydro generators or induction motors, PV generators are built with power electronics technologies. Considering the scales of both the applications of grid-tied PV generators and the power system of interest, a delicate balance between the modeling details and computation complexity needs to be sought. Stated differently, there is no need to add the complexity to the model if it can be deemed sufficient for an application of interest. On the other hand, it could be misleading to use an over-simplified model that undermines the credibility of the power system simulation (Belikov and Levron, 2018). Although there has been a large amount of PV generator models proposed in the literature, it raises the question on which model is appropriate for power system dynamic studies. The overwhelmingly collection of different PV models can cause major confusions among researchers and engineers, when choosing an appropriate model for their applications. And also what are the caveats and should be paid attention to in using a PV generator model for power system dynamic studies? This paper reviews the state-of-the-art PV generator modeling, with an intention to answer those critical questions raised above. From both the industrial and academic viewpoints, we believe a clarification on the model sufficiency for power system dynamic studies is important and will benefit both the industry and the research community. The directions that need to be further pursued on PV generator modeling for power system dynamic studies are also identified and highlighted in this paper.

The remainder of the paper is organized as follows: Section 2 gives an overview on the structure of typical PV generators. Section 3 reviews the modeling work on PV generators for dynamic studies. A detailed discussion on the modeling principle and the model development process are presented in Section 4, where the insights on developing appropriate dynamic simulation models are revealed. Section 5 discusses the research directions that needs further attentions on this topic and Section 6 concludes the whole paper.

2. PV generator and its modeling overview

A PV generator converts solar energy into electrical energy, either for local consumption or injected into a power grid. Thus, all of its components can be, at the top level, separated into two subsystems: (1) the PV array consisting of the PV cells, which completes the task of electrical energy generation from the Sun; and (2) the power-electronics-based energy conversion system, which converts the generated raw electric energy into the form suitable for consumption, e.g., high-quality AC electricity. Based on where the generated electric energy is used, a PV generator also can be categorized into a stand-alone PV system or a grid-tied PV generator. A PV generator can also be classified into a single-phase system or a three-phase system. A single-phase PV generator (Calais and Hinz, 1998; Hassaine et al., 2009) is used at low voltage levels, such as the household rooftop PV generator. Three-phase PV generators, such as the utility-scale solar power plants, are often connected to the high voltage sub-transmission or transmission networks. This paper focuses on the dynamic models of the PV generator for power system dynamic studies, thus will concentrate on the three-phase grid-tied PV generator.

There are two typical configurations of PV generator in power system applications, namely, single-stage and two-stage as shown in Figs. 1a and 1b. A single-stage PV generator uses only one converter to complete both the maximum power point tracking (MPPT) and the power grid connection. The DC link capacitor decouples the AC energy and the DC energy, and is constantly charged or discharged due to the imbalance between these two forms of energies. The advantage of the single-stage PV generator lies in its low cost, since only one converter is used. However, it lacks control flexibility. It also might need more PV cells in series or parallel to form the solar panel (Jose, 2012). A two-stage PV generator often uses a boost converter first to boost up the DC voltage level, followed by a DC/AC converter to transform the DC energy captured from PV cells into AC energy, which can then be utilized in AC networks (Nanou et al., 2015). The two-stage PV generator has increased the controllability as compared to the single-stage PV

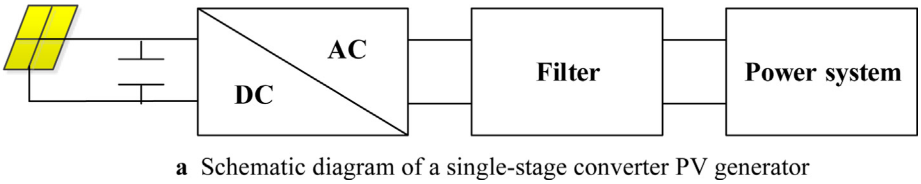

Fig. 1a. Schematic diagram of a single-stage converter PV generator.

generator. To further increase controllability, some PV generators also install energy storage systems that can store the excessive solar energy in the daytime and supply the load when there is not enough sunshine (Beltran et al., 2019).

A straightforward idea for developing a dynamic model for any power system dynamic component is to divide the dynamic component into its subsystems, then build a dynamic model for each subsystem, and finally put them all together to form the complete model of the whole dynamic component. This can also be applied to modelling a PV generator. As a PV generator can be naturally decomposed into an electrical power generation subsystem and an electrical power conversion subsystem, efforts have been made to model them separately.

Fig. 2 shows the block diagram of a PV generator. The electric power generation system is represented by the "Solar Power" block in the figure. Each PV cell is a basic element of this block, which is modeled by its current and voltage characteristics (Jedari and Hamid Fathi, 2017). The main functionality of this block is to capture the maximum possible power output, unless it is dispatched not to do so. Thus the core algorithm relevant to the "Solar Power" block is the aforementioned MPPT. The "Inverter" block converts the DC voltage output from the "Solar Power" block back to the AC form, so that the PV generator can be connected to the main grid. In order to synchronize the output AC waveform of a PV generator with the AC voltage in the network and tune the angle differences between them at the specified values, the AC voltage in the network needs to be measured and used as the reference. Thus a "Phasor Lock Loop (PLL)" is needed as shown in Fig. 2. Unlike a conventional generator that is often modeled as a PV node (set the generator's terminal voltage and its active power output constant), a photovoltaic generator is operated as a PQ node (set the photovoltaic generator's active power and reactive power outputs constant). Although a photovoltaic generator can be controlled as a flexible reactive power source to control the voltage, the variation of its reactive power outputs will affect the active power outputs of this PV generator due to the fixed total capacity of the inverter, namely $\sqrt{P_{Gen}^2 + Q_{Gen}^2}$, where P_{Gen} and Q_{Gen} represent the active power and the reactive power output of the PV generator, respectively. To reduce the curtailment on solar energy, a PV generator is often operated at its maximum capable active power output with a unit power factor. Thus, at the steady state, most PV generators only output the active power although they have the capability to generate the reactive power. When a PV generator senses a fault in the external grid, which is often reflected through the low voltage of its point of interconnection (POI), the PV generator is often switched into the low voltage ride through (LVRT) mode activated by the "Protection" block in the figure. During the LVRT, the PV generator will significantly reduce its active power output while increasing its reactive power output to the power system for the purpose of supporting the voltage in the system. The PV generator also might experience high voltages and need to keep itself connected to the power grid within the allowed temporary high voltage limits, which is often noted as high voltage ride through (HVRT) capability. The flexibility of controlling the active power and the reactive power in a PV generator is achieved through decoupling these two controls, which is crucial in modeling a PV generator for power system dynamic studies, and will be elaborated more in Section 4. To decouple the active power control and the reactive power control, a coordinate transformation is required, which is shown in Fig. 2 as the "abc/dq" block, indicating the three-phase variables need to be transformed to equivalent variables in direct-quadrature (dq) coordinates through Park Transformation, which will also be discussed in Section 4.

3. State-of-the-art PV generator modeling

3.1. Overview

Table 1 shows various practices related to works on PV generator modeling. Among the modeling and application practices, the modeling validation should be given special attention since most of the literature uses only digital simulations to validate the model and the algorithm. Laboratory tests have been reported in some works on modeling the electric power generation system, such as PV panel control. However, validation works on the electric power conversion system, such as the inverter models or their controls through the real power system practices, are far less.

3.2. Modeling dynamics of PV generator

Strictly speaking, a PV generator is always operated under dynamics. The basic and the fundamental dynamics is caused by the change of the ambient environment. The outputs of a solar generator are affected by the incident solar radiation, the solar incidence angle, the cell temperature and the load resistance (Desoto et al. 2006). The data from the manufacturer are available on rated conditions, which, therefore, are insufficient to model the solar power outputs under various operational conditions. To capture the dynamics of generation, which is of interest of power system economic dispatch and the power system frequency control, modeling two components of a PV generator is crucial. One is the model of the current–voltage (I-V) curves while the other is the control algorithms to extract the maximum power from the PV panels. The current–voltage curves of a PV module is often modelled by a circuit with one or more diodes and the most widely used is the 5-paramter model: the photocurrent, the diode reverse saturation current, the ideality factor, the series resistance and the parallel resistance. These 5-parameters can be identified from the data provided by the manufacturer (Desoto et al. 2006). To improve the model accuracy under different operational scenarios, more complex models with more parameters were developed, such as modeling the parameter dependence on the temperature (El-Saadawi et al., 2011). Since the real operational situation may be quite different from the rated operation condition, curve fitting techniques were developed to match the model with the real test data for a large range of ambient environment changes

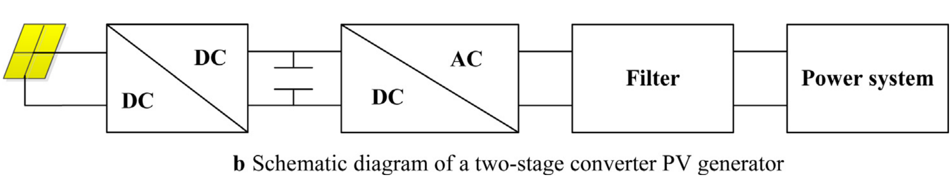

Fig. 1b. Schematic diagram of a two-stage converter PV generator.

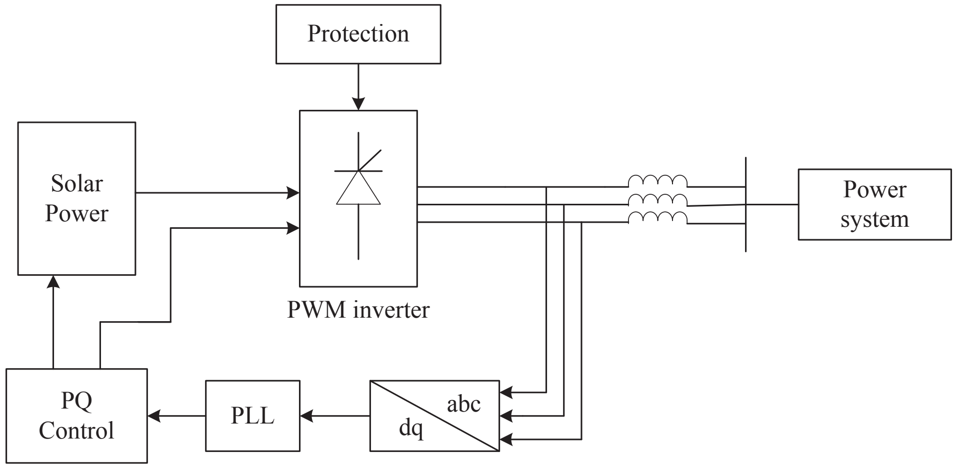

Fig. 2. Structure of a PV generator.

(Hansen and King, 2019; Lim et al., 2015; Rampinelli et al., 2014; Villalva et al., 2009). It is also interesting to note in Hansen and King (2019), five published methods for determining the series resistance from I-V curves are compared using the simulated I-V curve and the results from these five techniques are quite different from the true value of the series resistance. Another highly related but even more challenging modeling work is to accurately estimate the solar energy received by the plane-of-array, which includes considering the non-uniform irradiation on different parts of a PV field (Petrone et al., 2007) and converting the global horizontal irradiance (GHI) and direct normal irradiance (DNI) to plane-of-array irradiance (Xie et al., 2018).

Regarding to the MPPT, the algorithms can be generally categorized into the model-based methods and the non-model based method (Jedari and Hamid Fathi, 2017; Rajesh and Carolin Mabel, 2015). The commonly used method is Perturb and Observe (P&O) and Hill Climbing (HC). Although they can cause oscillations around the maximum power point and also are not robust to sudden changing environments, they are easy to be implemented in real world. The tracking speed and the oscillation need to be balanced, which hinges on the choice of the perturbation size. To make a fast tracking, the perturbation size needs to be bigger, however, the oscillation is also bigger. A smaller step size makes the oscillation smaller, but it takes longer time to track the maximum power. Efforts have been made to improve the performance of P&O especially under various changing operational situations (Tan et al., 2004). Another commonly used MPPT algorithm is Incremental Conductance (IC) algorithm. The idea of IC to track the maximum power lies in the necessary condition of the maximum value of a continuous function, i.e., at the maximum the slope of the P-V curve varnishes. The Artificial intelligence (AI) and the heuristic methods are also applied in developing MPPT algorithms (Rajesh and Carolin Mabel, 2015), however, the algorithms of this type often rely on training the data and there are no explicit rules to balance the model complexity and its generalization capability. Furthermore, these algorithms are often too complex for the real applications and sensitive to the training data. All these factors, therefore, limit their real applications. Compared to the non-model based methods, the model based MPPT methods rely on the aforementioned modeling practices on I-V curves, thus their fast tacking speed and improved dynamic performance depend on the modeling accuracy of PV characteristics under various operational situations. By approximating the PV characteristics by polynomials, the maximum power point voltage can be solved directly from the model rather than through tracking (Jedari and Hamid Fathi, 2017). Although the PV generation under various environments is a typical dynamic process, it is seldom researched via the standard dynamic control routine. Almost all the published work uses the implicit algebraic equations to model the process and requires the iteration to find the solution. The dynamic equations of MPPT have not been found in the literature except in Batzelis et al. (2018) where a state space PV generation model driven by irradiance variation was developed and the MPPT is represented by a set of difference equations. The state space equation offers the foundation for further applications of the control theory into this research domain. Another important topic related to the PV generation is its efficiency. Efforts have been made to investigate the efficiency of MPPT and DC to AC conversion and their dependency on the parameters (Rampinelli et al., 2014), which is out of scope of this paper.

In addition to the generation dynamics related to the operational environments, the other category of dynamics of a PV generator is the dynamics related to the electric power conversion system. Section 4 will discuss the different time scales of these dynamics and highlight the modelling requirements for the power system dynamic studies. This category of dynamics of PV generators is directly caused by converters/inverters and their respective controls. Therefore, research on modeling the electric power conversion system has been focusing on developing a generic model for converters/inverters. In addition to modeling the converter/inverter itself, the auxiliary control models, such as the voltage control or the frequency control, were also proposed in some literature. There are two types of inverters proposed to complete the electrical energy conversion from DC to AC, namely, the Voltage-Source Inverter (VSI) and the Current-Source Inverter (CSI). The VSI uses a capacitor to regulate the DC side voltage while the CSI uses an inductor at DC side to regulate the DC side current. The VSI is most widely used in grid-tie inverter for PV generators. For a typical two-stage PV generator as shown in Fig. 1b, both the DC/DC converter and the DC/AC inverter are controlled by a double loop structure. The inner loop of the DC/DC converter controls the PV array voltage to the voltage reference value set by the outer loop control based on the MPPT algorithm or the

Table 1
Practices on PV generator modeling.

Modeling in academia	Electric power generation subsystems
	Electric power conversion system
Modeling in industries and organizations	GE, WECC, EPRI, IEEE, CIGRE, IEC, etc.
Modeling validations	Simulation, laboratory test, field test
Commercial software	GE PSLF, DIgSILENT PowerFactory, PSCAD/EMTDC, PSS/E, MATLAB/Simulink, PSASP, PSD-BPA, etc.

active power control requirements. The inner loop of the inverter regulates the currents to the reference values while the outer loop sets up the current references based on the active power and reactive power references (Clark et al., 2010; Clark et al., 2011; Nanou et al., 2015). Both the inner loop and the outer loop often use the proportional-integral (PI) controller to achieve the control targets. The PI controller is chosen because its outputs have no static errors regarding to the references. The CSI uses the similar double loop PI control structure. However, it regulates both the DC side current and the AC side current. The inner loop regulates the AC side current injected into the grid, thus controls the active power and the reactive power injected to the grid, while the outer loop controls the DC current (Dash and Kazerani, 2011). An interesting and also very important discussion on modelling the converter/inverter is the level of details of modelling work, which will be discussed in Section 4 specifically for power system dynamic studies. There are two types of models, namely, the instantaneous model which is often called detailed model and the average model which is an approximation to the detailed model but it neglects the fast transients. A straightforward idea to discuss the modelling sufficiency is to build both models and compare their simulation results as shown by Yonezawa et al. (2016). However, it should be noted that the detailed model requires very small simulation time steps in order to accurately emulate the switching events, which is computationally expensive. Based on a piecewise state-space averaging method (Xu et al., 2016), a model of PV converter has been proposed in (Wang et al., 2019) to improve the computing efficiency compared to the detailed model while giving a higher accuracy than the average model.

The controller design on PV generators initially focused only on maximizing the utilization of the solar energy. With the increased integration of PV generators into the grid, the system operators start to require PV generators have capabilities to stay online during the fault, and provide the active power and the reactive power supports when being required to do so. These additional control and protection facilities of a PV generator provide ancillary services to increase the security of a power system. To adjust the active power output from a PV generator, the PV generator can also provide the inertia to the system. Modeling these auxiliary control facilities is often completed through adding a specific control logic to change the active power and reactive power reference values (Batzelis et al., 2019; Nanou et al., 2015) to mimic the active power and reactive power output changes, such as the Low Voltage Ride Through performance (Nanou and Papathanassiou, 2014). In addition to the state-space based model, the input–output (I-O) model can also be developed using the transfer function (Patsalides et al., 2016). Since the I-O based model is built from the input signals and the output signals, it is more suitable for us identifying the parameters of the model using the test data, which makes it more flexible on choice of parameters to fit the real measurements. The downside of the input–output model is that it can hide the important physical information and also due to its nature as an equivalent black-box model to the real PV generator, there can be multiple parameter values that all fit the measurements.

Because the auxiliary controls and protections of grid-tie PV generators to provide the ancillary services are required from the system operators, these facilities cannot be separated from the grid requirements that are explicitly stipulated in the grid codes on PV connection. On the other hand, when PV generators are connected to the grid, they interact with all the other dynamic components in the power grid and will impact the stability of the power system (Shah et al., 2015). This bidirection interaction should be considered in the PV generator modelling work especially with the increased regulations from the system operation centers all over the world on the PV generators' performances during the transients. For example, a state-space dynamic model that considered ancillary services required by European Network of Transmission System Operators for Electricity (ENTSO-E) grid code was developed by Batzelis et al. (2019). Most recently, the stability issues for a weak power grid with high penetration of PV generators raise great interests. Under this type of operational condition, the impedance model of a PV inverter was widely used. Cespedes and Sun (2014) modeled the inverter by a positive-sequence and a negative-sequence impedance directly in the phase domain. For practical conditions with small voltage unbalance, the coupling of the two sequence subsystems can be neglected and they can be investigated independently from each other. Wen et al. (2016) presented that a small increase of PLL bandwidth could make the system become unstable using the small-signal impedance model. Xia et al. (2019) found that the grid impedance has different influences on the system stability depending on the frequency range when the complete model of a PV generator is taken into consideration. The dynamics of PV panels, power loop and so on were all included in the complete model, so that the interactions among all loops of the PV system can be carefully investigated, which can enhance the accuracy and completeness of the stability analysis.

In addition to the above mentioned dynamics at two different time scales, it should be noted that there is a third type of dynamics of PV generation at even longer time scales as far as the renewable energy integration to the grid is concerned. It relates to the spatio-temporal variability of renewables and is the interest for future power grid planning. The interested readers can refer to Ringkjøb et al. (2018).

3.3. Practices in PV generator modeling

In parallel with the academic research, the industries and relevant organizations also have made significant contributions on developing PV generator models for the power system dynamic studies. The GE company puts forward a model for stability analysis of PV generator around 2010 (Clark et al., 2010; Clark et al., 2011; General Electric Company, 2009), which uses the controlled current source as the grid-connected interface. The IEEE Task force (Task force on modeling and analysis of electronically-coupled distributed resources, 2011) proposed modeling guidelines and a benchmark system for power system simulation studies of single-stage, three-phase, grid-connected PV systems. It is pointed out that for simulation of power system transients, the PV inverter can be modeled in different ways, including the detailed "switched" or "topological" model, and the average-value model. The Renewable Energy Modeling Task Force of WECC has developed two general positive-sequence dynamic models for PV generators (Pourbeik et al., 2017; WECC Renewable Energy Modeling Task Force, 2012; WECC Renewable Energy Modeling Task Force, 2014; WECC White-paper, 2015). The first one is for large PV power plants (larger than 10 MW) connected with the transmission power grid through centralized POI, while the second one is for distributed PV generators. Application of the WECC PV power plant models in power system dynamic studies under PV penetration are also reported (Lammert et al., 2016; Pourbeik et al., 2017; WECC Renewable Energy Modeling Task Force, 2014). In close collaboration with WECC, NERC, IEEE and IEC, EPRI has been contributing to the industry wide efforts for the development of generic dynamic simulation models for wind and PV generation and energy storage for stability studies (EPRI, 2013; EPRI, 2014). With an objective to form a more uniformed framework on renewable energy modeling for power system dynamic studies, the CIGRE C4/C6.35/CIRED joint working group (JWG) summarizes all factors that should be considered in dynamic modeling the inverter interfaced renewable energy generators including the PV generator (CIGRE C4/C6.35/CIRED JWG, 2018; Yamashita et al., 2018).

As a catch-up in the solar energy utilization, China has also carried out intensive research activities on developing dynamic models for PV generators. The national standard for grid connected PV power generation in China (Standardization Administration of the People's Republic of China, 2012) clearly specifies the modeling requirements on PV generators for the planning and operation. Moreover, the national standard demands "the changes with models and parameters of PV power plants should be tracked, and the latest information should be updated to the power system dispatching centers at any time," which highlights the importance of the veracity of the model and parameters.

Although modeling PV generator is widely reported in the literature, the validation work on various models so far, however, is still limited. Most of the reported modeling work uses the digital simulation to validate the developed model while only a few report the field test results. Soni (2014) performed validation of the WECC PV plant model against the field measured data, however, the power plant controller's active power control loop as well as some electrical controller settings had not been validated against the field measurements. In (Ma et al., 2017), the WECC PV model was validated by the measured data of a typical commercial PV inverter developed and widely used in China. The active power output of the WECC PV model shows a large overshoot with its peak over 54% of the rated value during the voltage recovery process, which does not conform to the real measurements. The improvements on modeling the control system thus had been made to tackle the problem. Pourbeik et al. (2017) validated the WECC generic PV model by comparing the simulation curves with the field responses at both the PV-inverter level and the PV power plant. In (Chao et al., 2019), the responses of the complete LVRT process for a PV generator were formulated, and an adjustable factor was proposed to describe possible LVRT behaviors under unbalanced voltage dips. This modeling method was validated by electromagnetic simulation using field test data in that paper.

Commercial software GE PSLF (Clark et al., 2011; General Electric Company, 2009), DIgSILENT PowerFactory (DIgSILENT GmbH, 2011), PSCAD/EMTDC (Manitoba Hydro International Ltd., 2012), PSS/E (Power Technology Inc., 2013) etc. all have their inbuilt dynamic simulation model for PV generators. For power system electromechanical dynamic studies, the PV generator is often represented by a controlled current source, as in GE PSLF (Clark et al., 2011). In DIgSILENT PowerFactory, a model called the static generator was developed as the standard interface of renewable energies with a power grid, which includes not only PV generator, but also wind power, fuel cell etc (DIgSILENT GmbH, 2011). Lammert et al. (2019) investigated the impact of LVRT and dynamic voltage support capability, the active current recovery rate as well as local and plant-level voltage control of a PV generator on short-term voltage stability and frequency dynamics. The WECC generic PV generator model was used and the simulation analysis was conducted in DIgSILENT PowerFactory. Kim et al. (2009) modeled a PV generator using user-defined function of PSCAD/EMTDC, which used a simple circuit model to simulate the PV array with detailed power and protection control systems as well as electrical circuits of the PV inverter. Moursi et al. (2013) proposed a control scheme to enhance the fault ride through (FRT) performance of a PV power plant. A comprehensive simulation was conducted in PSCAD/EMTDC to verify the control effects under severe balanced and unbalanced voltage conditions. Fazeli et al. (2014) presented a small-signal model to investigate the stability of a PV inverter exchanging reactive power with the grid. The grid-connected PV generator model and proposed voltage control method were validated in PSCAD/EMTDC using measured solar irradiation. Al-Shetwi et al. (2018) modeled a single-stage PV power plant in MATLAB/Simulink to investigate the LVRT capability control. The model includes the PV array, MPPT control, three-phase inverter and its controllers, RL filter, the step-up transformer and power grid. For satisfactorily simulating the transient behavior of a PV converter at the same time reducing the computation burden of electromagnetic simulations, Villegas Pico and Johnson (2019) proposed a PV plant model which is compatible with the positive-sequence simulation because of the voltage-behind-reactance representation. This model contained the PLL, AC- and DC-side dynamics, and closed-loop controllers, and was established in MATLAB/Simulink. In China, PSASP (CEPRI, 2010) and PSD-BPA (CEPRI, 2018) both developed by CEPRI are most widely used power system simulation software in the power industry. The PV generator model built in these two softwares and the respective comparison with the GE model were reported in (CEPRI, 2010) and (CEPRI, 2018).

As long as the PV generator model is implemented in the software, it is often then straightforward to further add the ancillary service model (Batzelis et al., 2019; Duckwitz and Fischer, 2017; Fazeli et al., 2014; You et al., 2019) on top of the PV generator model such as the frequency regulation participation and the voltage/reactive power control. Most of commercial software leaves modeling these extra control facilities to the users through the user-defined modeling functionality, while some software does have some control utilities integrated in the PV generator's model for power grid operators, for example, the primary frequency regulation functionality of the PV generator is also implemented in PSD-BPA software (CEPRI, 2018).

4. What modeling details of PV generator are sufficient for power system dynamic studies?

This section examines the dynamic modeling process for PV generator, especially the key steps and related assumptions. The purpose is to clarify what modeling details of PV generator are sufficient for power system dynamic studies since choosing the appropriate models has become a major concern in the industrial applications.

4.1. Fast dynamics and slow dynamics of power system

Power system studies can be broadly classified into steady state studies and dynamic studies that are also known as transient studies. Steady state studies focus on the power system operation when there are no disturbances that could change the system operation status significantly. Thus, all generators' outputs and loads across the network can be viewed as constants. A PV generator is modeled as a constant active power and reactive power source in power system steady state studies. When PV generation changes due to the ambient environment, the power system steady state studies do not investigate the transients of the power system caused by the change in PV generation. Instead they consider each possible PV output as an operation scenario of a steady state, and then find out in that scenario how the generation can be dispatched to supply loads and whether all technical constraints, such as line capacity, minimum and maximum output limits of a generator and voltage, are all satisfied.

In contrast to power system steady state studies, power system dynamic studies focus on the characteristics of a power system experiencing disturbances. The core in power system dynamic studies is transients because the original steady operational state of the concerned power system is broken by disturbances, and the system has to go through a series of events, such as cascading faults, line switching, or generation control actions. Power system steady state studies and dynamic studies are related to each other. In that, power system steady state studies provide the initial operational state for power system dynamic studies. Surely, different initial operational states affect the power system dynamics differently. If the system is operated with a large security margin, the system is more robust to external disturbances and less inclined to lose its stability compared to the situation of an initial operational state with a small security margin. Meanwhile, the power system steady state studies search for the post-fault steady state of the power system. A secure post-fault operational state is the necessary condition that a dynamic process of a power system triggered by faults or disturbances can possibly end.

The fundamental cause of a dynamic process lies in the energy stored in a power system. There are many energy storage devices in a power system. An inductance in the network stores the magnetic field energy when there is a current flowing through it. A capacitor in the network stores the electric field energy as long as there is a voltage across its two terminals. A generator and a motor have their rotor storing kinetic energy and potential energy when they are in operation. Each steady state of a power system corresponds to a balanced energy state. When a fault happens, the initial balanced energy state is broken, but the energy cannot change instantly. The changes of the energy evolve into the dynamic process. However, each energy storage device has a different rate of change for its stored energy. The energy stored in inductances and capacitors often changes at a much faster speed than that stored in rotating components of a power system. Thus the power system dynamic studies include electromagnetic transient studies that are centered on the changes of the electric filed energy and the magnetic field energy; and electromechanical transient studies that focus on the changes of mechanic energies. CIGRE C4/C6.35/CIRED JWG (2018) has given a good summary on the application scenarios for electromagnetic transient studies, as well as electromechanical transient studies.

The different rates of change on the energy stored in a power system lead to different timescales in power system dynamic studies. It is crucial to understand such different timescales and their respective dynamics for modeling power system dynamic components. This is especially true for PV generator modeling in power system dynamic studies. On one hand, the PV generator is controlled with power electronics. The control usually has very high frequency, which means a very small timescale in its control transients and falls into the domain of electromagnetic transient studies. On the other hand, the outputs of a PV generator interact with the power outputs from all the other generators, including conventional generators, which happens at a much slower timescale and falls into the domain of electromechanical transient studies. The specific application of the studies determines which type of models should be chosen. The model based on instantaneous variables is needed for electromagnetic transient studies due to the fast dynamics involved; while the phasor model, also known as the root mean square (RMS) model, is developed for electromechanical transient studies, because of its much slower dynamics compared with the electromagnetic transients.

As discussed earlier, there are no operational state changes in the power system steady states. Thus all the power system components for power system steady state studies are modeled via the algebraic equations. On the contrary since during the power system dynamics, all the states change with respect to time, they can be only modeled by the differential equations (Here we only consider the time continuous dynamics. If the time discrete dynamics are considered, the difference equations need to be used.) Therefore, a complete dynamic model of a power system takes the form as follows:

$$\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{u}), \tag{1a}$$

$$\dot{\boldsymbol{y}} = \boldsymbol{g}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{u}), \tag{1b}$$

where $\boldsymbol{x}$ represent the state variables related to the slow dynamics, especially the energy transition in the electromechanical transients, whereas $\boldsymbol{y}$ denote the state variables related to the fast dynamics, especially the energy transition in the electromagnetic transients. To better capture the time characteristics of the dynamics, Eq. (1) is often written as:

$$\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{u}), \tag{2a}$$

$$\varepsilon\dot{\boldsymbol{y}} = \boldsymbol{g}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{u}), \tag{2b}$$

where ε represent very small positive numbers reflecting the small time constants of the fast dynamics. Eqs. (2a) and (2b) takes the form of standard singular perturbation model (Khalil, 2002), however, the focus here is not about the discontinuity of the dynamics depending on the parameter ε, but on the contrast of the timescales where the dynamics of different state variables happen. Due to the different timescales of the dynamics, the complete models (1) and (2) can be extremely complex and raise serious challenges on the numerical integration stability and the computing burden when they are solved using computers.

To preserve the major dynamics to be investigated while making a balance between the model complexity and the solution tractability, the complete dynamic model (1) and (2) is reduced to the following two differential–algebraic equations:

$$0 = \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{u}), \tag{3a}$$

$$\dot{\boldsymbol{y}} = \boldsymbol{g}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{u}), \tag{3b}$$

and

$$\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{u}), \tag{4a}$$

$$0 = \boldsymbol{g}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{u}). \tag{4b}$$

The model (3) reflects the fast dynamics, namely the electromagnetic transients of a power system, since the dynamics of $\boldsymbol{y}$ is so fast that during the changes of $\boldsymbol{y}$, the slow dynamic of $\boldsymbol{x}$ has not got a chance to change resulting to their derivatives equal to zero. On the contrary, the model (4) represents the slow dynamics, namely the electromechanical transients of a power system, since the dynamics of $\boldsymbol{x}$ is so slow that when $\boldsymbol{x}$ starts to change, the fast dynamic variables $\boldsymbol{y}$ have come to their steady states leading to their derivatives becoming zero.

The key point to review the generic dynamic modeling principle of the fast dynamics and the slow dynamics in power system here is to stress the importance of distinguishing the fast dynamic variables and the slow dynamic variables when modeling the power system dynamic components. Actually this distinction is crucial for judging the sufficiency of the model details regarding to the dynamic problem to be studied. The basic principle in choosing the appropriate dynamic models is that the fast and the slow timescales reflected through the dynamic variables (represented by their non-zero derivatives) and the steady-state variables (represented by their zero derivatives) should match the timescale of the dynamic problem under the investigation. This principle is especially crucial to inverter-based generation system modeling since inverter-based generation system is controlled by power electronics technologies taking place at a much higher frequency than the frequency of many power system dynamic problems. Thus there is a natural requirement in distinguishing the fast dynamics and the slow dynamics as far as the inverter-based generator modeling is concerned including modeling PV generator. Since the power system dynamic problems vary depending on all the dynamic components involved and the system configuration, there cannot be a universal dynamic model of a PV generator suiting all the applications. It is more important to understand the timescales (frequency band) of the dynamic problems that requires dynamic modeling a PV generator before developing the appropriate model. Thus it is never enough to discuss the timescale of the investigated dynamic problem and clarify the time-scales of the dynamic variables' transients. However, such clarification on each specific dynamic problem has rarely been seen in the current literature on developing dynamic models for PV.

4.2. Fast and slow dynamics of PV generator

The dynamics of the PV components happen at different timescales. The major dynamics include the change of the weather, the control on MPPT and on the energy stored in the capacitor, the inverter control, the changes on the magnetic field energy stored in the inductances. The dynamics related to the electric energy generation system is much slower than the dynamics related to the inverter and the inductance in the PV generation system. The voltage of the DC capacitor at the DC side of the inverter has a much slower dynamics than the controls on the DC/AC inverter due to much slower changes in solar irradiance and temperature compared with the fast power electronics control. From the principle of simplifying the dynamics based on different timescales presented in the previous subsection, assuming the DC voltage constant (Cespedes and Sun, 2014; Golestan et al., 2011; Patsalides et al., 2016; Roshan et al., 2007) does not compromise the model accuracy for the power system electromagnetic and electromechanical transient studies.

Meanwhile one fundamental principle when developing a dynamic model of a PV generator is that the details of the model should be compatible with the details of the other dynamic components' models in a power system. For electromagnetic transient studies of a power system, since the transients of the inductances and the capacitors in the power grid are considered, the dynamics of the magnetic field stored in the inductances of PV generator should also be modeled for power system electromagnetic transient studies, which include the transients related to the grid interfacing inductance and the filter. The filter is a passive circuit. Here we focus only on reviewing the modeling process on grid interfacing inductances since they are crucial in developing the PV model for power system dynamic studies.

The inverter is controlled using pulse width modulation (PWM) with high frequency. Therefore, the dynamics of PWM happens on a very fast timescale. For a grid connected PV, the inverter is crucial as it takes the role of the interface between the power system and the PV generator. On one hand, the inverter receives the control commands on its active power and reactive power outputs from the solar farm dispatch center, which happens at a timescale of power system electromechanical transients under the emergency and the steady state timescales in normal operations; On the other hand, the inverter converts the commands from the control center into the PV's power outputs to the grid, which happens at a much faster timescale than the timescale of the power system electromechanical transients. Thus, for the power system electromechanical studies, the inverter control can be seen as being completed instantly, which significantly reduce the modeling complexity for power system electromechanical transient studies and will be further discussed in the next subsection.

4.3. Generic PV generator model for power system dynamic studies

Based on the principle of decoupling fast and slow dynamics, this subsection reviews developing the generic PV generator model for power system dynamic studies. The exposition demonstrates what factors need to be considered and what kind of models are good enough for the electromagnetic transient studies and the electromechanical transient studies. Furthermore, although there are various dynamic models for a PV generator reported in the literature, and their forms may look different, they all share the same essentials discussed in this subsection.

A generic model of a PV generator for power system dynamic studies refers to the type of model that is independent of any specific product of a PV generator in the market but could preserve all the dynamic characteristics related to the power system dynamic problems to be investigated (Ackermann et al., 2013). As being argued in the preceding subsections, the applicable dynamic model of a PV generator is related to the specific dynamic problem and the whole power system composition. Therefore, here we can only review the generic principles when developing a dynamic model of a PV generator.

The three-phase grid inductances are shown in Fig. 3 below, where v_a, v_b and v_c are the three-phase voltage outputs from the inverter while v_A, v_B and v_C are the three-phase voltages at the grid side; i_a, i_b and i_c are the three-phase currents flowing through the grid interfacing inductances. By controlling the instantaneous three-phase inverter output voltages v_a, v_b and v_c, the PV generator controls the active power output and the reactive power interchanges with the external grid. Such active power and reactive power control models can be developed through building the phase model followed by the coordinate transformation (Machowski et al., 2008). However, vector analysis gives a better and more convenient approach for modeling three-phase dynamic components (Quang and Dittrich, 2008). It compiles the instantaneous values into the corresponding vectors, thus the active power and the reactive power defined on the phasor can be extended to the instantaneous values.

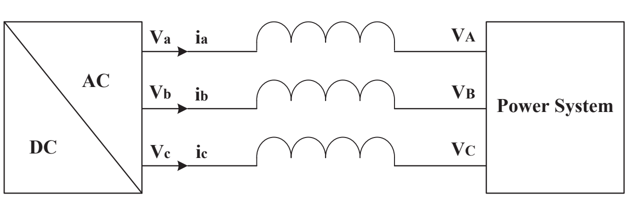

Fig. 3. Grid interfacing inductances.

Any three-phase instantaneous values, such as the three-phase instantaneous voltages and currents, can be written into a vector in R^3 as $\vec{F} = [f_a, f_b, f_c]^T$ where f can be the voltage v, the current i, the flux ψ etc. If $f_a + f_b + f_c = 0$, rewriting it into the form of the inner product of two vectors as

$$[1, 1, 1]\begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} = 0. \tag{5}$$

Eq. (5) indicates that all such $\vec{F}$ vectors form a plane in R^3 with $[1, 1, 1]^T$ as the normal vector of this plane. The zero vector $[0, 0, 0]^T$ also lies on this plane. Thus in mathematic terms, the formed plane is a subspace of R^3 and its orthogonal complement space is the vector space formed by $[1, 1, 1]^T$. If $f_a + f_b + f_c = 3f_0$, but f_0, called the zero component, is not zero, the $\vec{F}$ vectors themselves do not lie in a plane, but the vector $(\vec{F} - [f_0, f_0, f_0]^T)$ still lies on a plane in R^3 with $[1, 1, 1]^T$ as its normal vector, which is due to

$$[1, 1, 1]\begin{bmatrix} f_a - f_0 \\ f_b - f_0 \\ f_c - f_0 \end{bmatrix} = 0. \tag{6}$$

The plane passes the vector $[f_0, f_0, f_0]^T$, but it does not pass the zero vector $[0, 0, 0]^T$. Figs. 4a and 4b shows the vector F and the plane in R^3 formed by the corresponding $(\vec{F} - [f_0, f_0, f_0]^T)$.

Since in either case, where there are no zero components, the remained vectors from $\vec{F}$ lie in the plane, we have the flexibility to choose any coordinate systems in the plane to represent the vectors in this plane noted as $\vec{F}$ here.

A vector in a plane therefore can be represented by two coordinate systems, namely, the polar coordinate system and the rectangular coordinate system. To use the polar coordinate system, a reference vector needs to be defined first, so the phase angle of any vector in that plane could have a reference. We define a stationary vector $\vec{A}_0$ as the reference vector of the polar coordinate system. The entries of the vector $\vec{F}$ are the 3-phase instantaneous values of the physical variable under consideration, such as the voltage of each phase. Since the values change all the time, the vector $\vec{\mathbf{F}} = [f_a, f_b, f_c]$ changes its position in the plane all the time. Consequently, in addition to the stationary reference vector$\vec{A}_0$, we also define a moving vector $\vec{A}_k$ which rotates at an

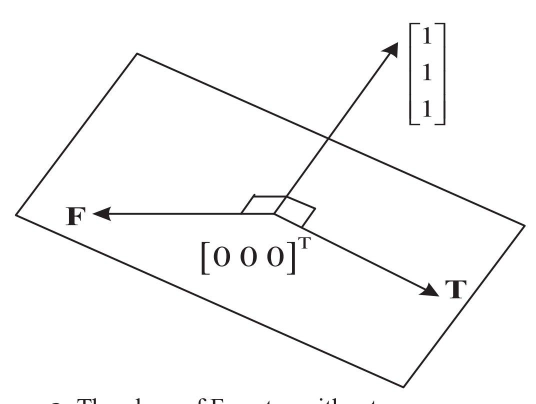

Fig. 4a. The plane of F vector without zero component.

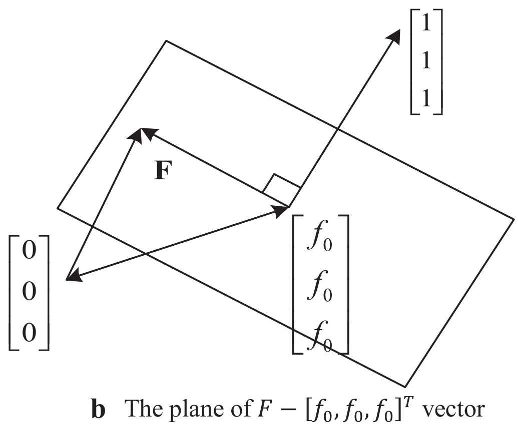

Fig. 4b. The plane of $\vec{F} - [f_0, f_0, f_0]^T$ vector.

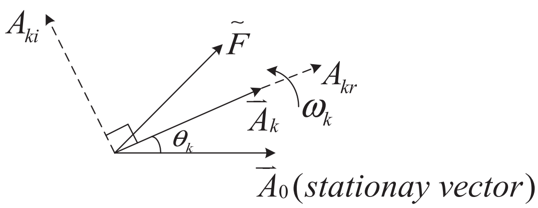

Fig. 5. Coordinate system in a plane.

angular speed ω_k. The angle between $\vec{A}_k$and $\vec{A}_0$ is denoted as θ_k, which also changes with respect to the time as $\theta_k = \omega_k t + \theta_{k0}$. θ_{k0} is the initial angle between $\vec{A}_k$and $\vec{A}_0$at t = 0 s. Fig. 5 shows the chosen polar coordinate systems and the vector $\vec{F}$.

Clearly $\vec{A}_k = e^{j\theta_k}\vec{A}_0$, now assign $\vec{F}$ with specific physical meaning, we have $U_{I\vec{A}_0}$ denote the vector formed by $[u_a, u_b, u_c]^T$ of the inductance at the inverter side and $U_{G\vec{A}_0}$ as the vector formed by $[u_A, u_B, u_C]^T$ of the inductance at the grid side; $I_{\vec{A}_0}$ as the vector formed by $[i_a, i_b, i_c]^T$ flowing into the grid. The subscript $\vec{A}_0$ indicates all these vectors use $\vec{A}_0$ as the reference. Then the dynamics of the inductance can be described by the following equation:

$$U_{I\vec{A}_0}\vec{A}_0 - U_{G\vec{A}_0}\vec{A}_0 = RI_{\vec{A}_0}\vec{A}_0 + L\frac{dI_{\vec{A}_0}\vec{A}_0}{dt}. \tag{7}$$

R and L are the resistance and inductance respectively, note Eq. (7) is formulated in the polar coordinate system defined by $\vec{A}_0$, which is marked by multiplying each vector referred to $\vec{A}_0$ by $\vec{A}_0$ in the equation. Eq. (7) can be transformed into the coordinate system referenced by the rotating vector $\vec{A}_k$ by simply replacing $\vec{A}_0$ by $\vec{A}_k e^{-j\theta_k}$, which gives

$$U_{I\vec{A}_0} e^{-j\theta_k}\vec{A}_k - U_{G\vec{A}_0} e^{-j\theta_k}\vec{A}_k = RI_{\vec{A}_0} e^{-j\theta_k}\vec{A}_k + L\frac{dI_{\vec{A}_0} e^{-j\theta_k}\vec{A}_k}{dt}. \tag{8}$$

Denote, $U_{I\vec{A}_k} = U_{I\vec{A}_0}e^{-j\theta_k}$, $U_{G\vec{A}_k} = U_{G\vec{A}_0}e^{-j\theta_k}$, $I_{\vec{A}_k} = I_{\vec{A}_0}e^{-j\theta_k}$. Therefore, $U_{I\vec{A}_k}$, $U_{G\vec{A}_k}$ and $I_{\vec{A}_k}$ are the respective vectors in the polar coordinate system defined by the reference vector $\vec{A}_k$. Eq. (8) can be rewritten as:

$$U_{I\vec{A}_k}\vec{A}_k - U_{G\vec{A}_k}\vec{A}_k = RI_{\vec{A}_k}\vec{A}_k + L\frac{dI_{\vec{A}_k}\vec{A}_k}{dt}. \tag{9}$$

Since

$$\frac{dI_{\vec{A}_k}\vec{A}_k}{dt} = \frac{dI_{\vec{A}_k}}{dt}\vec{A}_k + I_{\vec{A}_k}\frac{d\vec{A}_k}{dt} = \frac{dI_{\vec{A}_k}}{dt}\vec{A}_k + I_{\vec{A}_k}\frac{de^{j\theta_k}\vec{A}_0}{dt}$$

$$= \frac{dI_{\vec{A}_k}}{dt}\vec{A}_k + I_{\vec{A}_k}e^{j\theta_k}.j\frac{d\theta_k}{dt}\vec{A}_0 = \frac{dI_{\vec{A}_k}}{dt}\vec{A}_k + j\omega_k I_{\vec{A}_k}(e^{j\theta_k}\vec{A}_0)$$

$$= \frac{dI_{\vec{A}_k}}{dt}\vec{A}_k + j\omega_k I_{\vec{A}_k}\vec{A}_k, \tag{10}$$

we have

$$U_{I\vec{A}_k}\vec{A}_k - U_{G\vec{A}_k}\vec{A}_k = RI_{\vec{A}_k}\vec{A}_k + L\frac{dI_{\vec{A}_k}}{dt}\vec{A}_k + j\omega_k \mathrm{L} I_{\vec{A}_k}\vec{A}_k. \tag{11}$$

Eq. (11) is the inductance dynamics under the generic coordinate system since the position of $\vec{A}_k$ and its rotating speed are not confined and can be chosen freely. Eq. (11) can be alternatively written in the rectangular coordinate system. Choose the direction of $\vec{A}_k$ as the real axis A_{kr} and the direction of the vector orthogonal to $\vec{A}_k$ as the imaginary axis A_{ki} as being indicated by the dash line in Fig. 5, we immediately have

$$(U_{I\vec{A}_{kr}} + jU_{I\vec{A}_{ki}}) - (U_{G\vec{A}_{kr}} + jU_{G\vec{A}_{ki}})$$

$$= \mathrm{R}(I_{\vec{A}_{kr}} + jI_{\vec{A}_{ki}}) + \mathrm{L}\frac{d(I_{\vec{A}_{kr}} + jI_{\vec{A}_{ki}})}{dt} + \mathrm{j}\omega_k L(I_{\vec{A}_{kr}} + jI_{\vec{A}_{ki}}), \tag{12}$$

which gives

$$U_{I\vec{A}_{kr}} - U_{G\vec{A}_{kr}} = RI_{\vec{A}_{kr}} + L\frac{dI_{\vec{A}_{kr}}}{dt} - \omega_k \mathrm{L} I_{\vec{A}_{ki}}, \tag{13}$$

$$U_{I\vec{A}_{ki}} - U_{G\vec{A}_{ki}} = RI_{\vec{A}_{ki}} + L\frac{dI_{\vec{A}_{ki}}}{dt} + \omega_k \mathrm{L} I_{\vec{A}_{kr}}. \tag{14}$$

The commonly used d-q coordinate system through Park transformation is just a special case of the generic coordinate system defined by $\vec{A}_k$ by choosing the rotational speed of $\vec{A}_k$ as ω_0, i.e., the synchronous speed; and consequently A_{kr} as d-axis and A_{ki} as q-axis. Naturally, Eqs. (13) and (14) become the dynamics of the inductance under the d-q coordinate system, which is:

$$U_{Id} - U_{Gd} = RI_d + L\frac{dI_d}{dt} - \omega_o \mathrm{L} I_q, \tag{15}$$

$$U_{Iq} - U_{Gq} = RI_q + L\frac{dI_q}{dt} + \omega_o \mathrm{L} I_d. \tag{16}$$

In the PV generator control, a strategy to choose the coordinate system is to choose the vector $(U_{G\vec{A}_0}\vec{A}_0)$ formed by $[u_A, u_B, u_C]^T$ at the grid side as the reference vector $\vec{A}_k$, which means $\vec{A}_k$ needs to lock to $U_{G\vec{A}_0}\vec{A}_0$ at any instant. The direct consequence of this selection of the coordinate system is that: $\mathrm{U_{Gq}} = 0$, which simplifies Eq. (16). However, the real benefit by choosing such coordinate system lies in decoupling the active power and the reactive power injected into the power grid by the PV generator, which can be solved as:

$$P_G + jQ_G = (U_{Gd} + jU_{Gq})(I_d + jI_q)^* = (U_{Gd}I_d + U_{Gq}I_q) + j(U_{Gq}I_d - U_{Gd}I_q), \tag{17}$$

with $\mathrm{U_{Gq}}$ always being equal to zero, the active power $\mathrm{P_G}$ and the reactive power $\mathrm{Q_G}$ can be reduced to:

$$P_G = U_{Gd}I_d, \tag{18}$$

$$Q_G = -U_{Gd}I_q, \tag{19}$$

which means by controlling the d-axis current and the q-axis current separately, the active power and the reactive power injected to the grid by the PV generator can be controlled in a decoupled manner. Therefore, Eqs. (15) and (16) actually set up the most important component of the PV generator model for electromagnetic transient studies since they decide the d-axis current and the q-axis current, where $\mathrm{U_{Id}}$ and $\mathrm{U_{Iq}}$ are control variables, while $\mathrm{I_d}$ and $\mathrm{I_q}$ are variables to be controlled representing the active power and the reactive power injected into the grid by this PV generator.

From the above analysis, it can be seen that there are another two critical components in modeling a PV generator for electromagnetic transient studies. One is the phasor lock loop (PLL) and the other is the current control block. The PLL is used to lock the vector reference $\vec{A}_k$ to the grid side voltage vector ($U_{GA_0}\vec{A}_0$) while the current control block is used to trace the desired current references on the d-axis and q-axis. Since various control methods can be applied to achieve these two goals and further considering the fact that the real controller from the manufacturer is proprietary and unknown to the general public, theoretically any controller that could accomplish these two goals can be used as an initial control model to generate the control signals for the inverter. We call them initial models because these control models need to be revised or tuned in order to mimic the real controllers hidden under the hood. This effort is very important in terms of making the developed generic model practical to the real industrial applications, however, experiences and research results on this side are hardly seen in the published work, which is identified as one important work to be further pursued.

The simplest controller to achieve the just mentioned two control objectives is to use a PI controller for PLL and a double-loop control to control the current where the outer loop generates the d-axis and q-axis reference current from the references of the active and reactive power according to Eqs. (18) and (19) while the inner loop traces the d-axis and the q-axis currents to the generated references. These also can be achieved using PI controller. Thus the whole dynamic model of PV generator can be schematically shown in Fig. 6.

As being noted earlier, the forms of the current controller design and the PLL controller design are not unique, for example, in (Schauder and Mehta, 1993), a compensator was designed first before applying the current double-loop control for type-II inverter in order to completely decouple the d-axis and q-axis in Eqs. (15) and (16). Out of this reason, again it does not make sense to assert which generic model is superior to the other generic models. The crucial point is to revise the structure and the parameters of these control blocks to make their dynamic performance conform to the real performance of the device.

It should also be noted that so far all the derivation in building the model is based on the three-phase instantaneous values, thus the model developed can be used for the unbalanced network operational scenarios. The filter connected to the PV generator needs to be modeled for harmonic analysis, which will not be expanded here.

For power system electromechanical transient studies, the model derived so far can be simplified based on the modeling principles discussed in earlier sections. First, the electromechanical dynamics is often measured at a timescale of millisecond (ms). The production-grade simulation software uses usually 10 ms as the simulation time step. Thus the electromechanical dynamics happens at a much slower timescale compared to the transients of the power electronics control which is measured by microsecond (μs). Thus for a stable power electronics control system, the changes of I_d and I_q to their reference values almost happen instantly if we focus on the timescale of the electromechanical dynamics. For example, even if the grid side voltage changes dramatically, which constitutes a serious challenge to the PLL control to lock the grid side voltage vector, for a stable and well-designed controller, however, the transients to lock the voltage happens much faster than the electromechanical transients of the voltage. The results are the PV generator could generate the active power and the reactive power to the values set by their references as long as the protection circuits are not activated by the fault. Secondly, the fast transients of the inductances in the power grid, such as the transformers, the transmission lines, et al, are all neglected in electromechanical transient studies of a network even without PV generators, therefore there is no need to model the transients of the grid connecting inductance of a PV generator for the electromechanical transient studies of a power system with PV generators. Consequently, Eqs. (15) and (16) become the algebraic equations with $\frac{dI_d}{dt} = 0$ and $\frac{dI_q}{dt} = 0$ as shown below:

$$U_{Id} - U_{Gd} = RI_d - \omega_o LI_q, \quad (20)$$

$$U_{Iq} - U_{Gq} = RI_q + \omega_o LI_d. \quad (21)$$

This fact combines the prior arguments that i_d and i_q can change almost instantly at the timescale of electromechanical transients, it is reasonable to model the PV generator as the current source when it is looked from the POI since the currents on the d-axis and q-axis are almost the real-time proxy of the active power and the reactive power injected at POI from PV. If the PV generator is seen from the left side of the inductance in Fig. 2, based on Eqs. (20) and (21), it can be modeled as a controlled voltage source as U_{Id} and U_{Iq} are controlled by I_{dref} and I_{qref}, which is the nature of the model presented in Ramasubramanian et al. 2017. The reason of not modeling the PV generator as an active power and reactive power source even though the outer loop control tries to trace the active power and reactive power to their reference values is because the protection block might be activated to override the active power and reactive power control. Therefore, the focus on developing the dynamic PV generator model lies on modeling the protection modules, which is equally important for the electromagnetic

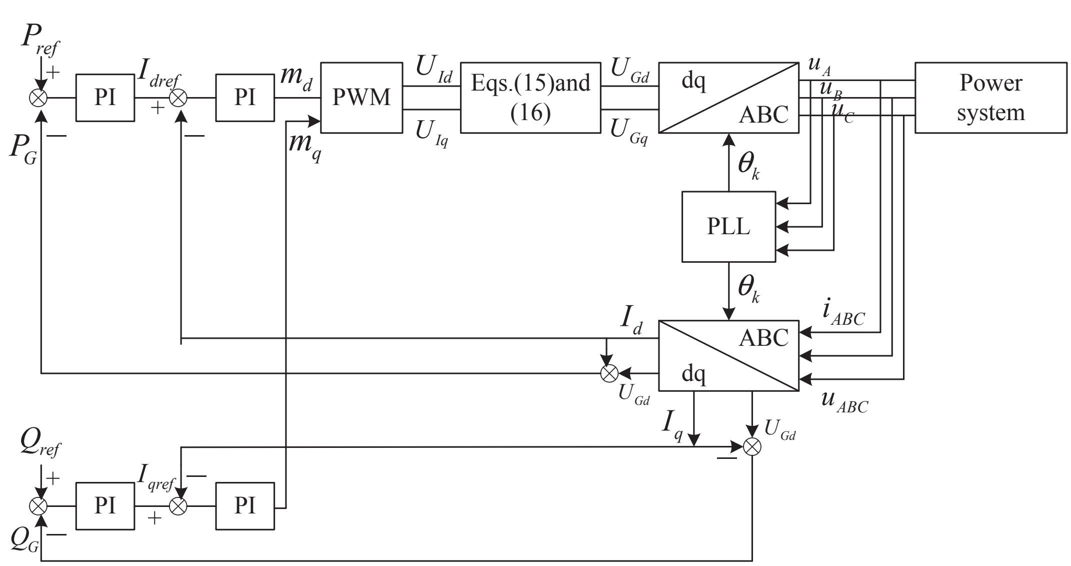

Fig. 6. Schematic diagram of dynamic model of PV generator.

transient studies, and the control logic on setting up the references for the active power and the reactive power.

The controller performance might have serious impacts on the electromechanical dynamics even though it is much faster because it might be unstable under certain operational scenarios, or in certain power systems, such as a weak power system with a low short circuit ratio (SCR) at the far end of a big power system. However, since the controller design is proprietary to the manufacturer and unknown to the modeler, a generic PV generator dynamic model even with the control transients does not necessarily mean it can represent the real behavior of the interaction between the controller and the external power system dynamics, which, therefore, leads to very limited applicable values of the model. The solution, we recommend, is to check the conformance of the real device to the grid connection codes on the faults. If the PV generator could meet the grid code requirements, then the dynamic performance of the PV generator can be modeled based on the current source model plus modeling its protection modules. If any unexpected dynamics is captured through the tests on the real device, specific control block needs to be designed to simulate that observed dynamics. Again, although modeling tested dynamics through added control block is very important, there are scant research reported in the literature. Regarding to the protection functionalities to be modeled, CIGRE C4/C6.35/CIRED JWG (2018) gives a detailed exposition, which will not be repeated here.

5. Outlook for further research

With the fast developments of PV generation facilities in the power grids, there are urgent needs to develop reliable and computationally efficient PV generator dynamic model for the PV integration analysis. Based on the review so far, there is an unavoidable difficulty when trying to achieve such purpose, i.e., the proprietary controller design of the manufacturers. To make the problem even more challenging, the controllers designs have a huge diversity. As discussed earlier, however, the dynamic characteristics of PV generator rely heavily on the controller dynamics. To push the developed PV generator model to be practical in the real power industry applications, the research on adapting the generic control model described above to the real PV generator needs to be carried out. Although much dynamic modeling work on the PV generator has been reported in the literature, research on how to revise the generic model including to tune the parameters to match the input–output characteristics between the model and the real device is far less satisfactory. Specifically, the following studies need further attention:

(1) Based on the information of typical model structure and parameters provided by the PV manufacturers, through the measurement and parameter identification technologies, the generic model recommended in the last section needs to be evaluated through the physical tests against the real device outputs. Especially, the protection modules need to be modeled (Singh and Agrawal, 2019), which, typically, include the over-voltage ride through protection, low-voltage ride-through protection, over-current protection etc. The input–output control characteristics between the model and the real device needs to be compared and extra control blocks need to be added or the parameters need to be tuned to make the model outputs conform to the real measurements, as in (Ma et al., 2017) a differential controller needs to be added to the generic model to capture the dynamics observed in the measurements. Various system configurations with the different electrical strength and fault scenarios should be designed since they have great influences on the validity of the dynamic characteristics of the model. For instance, as being discussed in the previous section, the dynamic characteristics of PLL play a crucial role in the actual dynamic behavior of PV generators during the transient process caused by the disturbances. Since the PLL design is one core technic in PV generator design and is not disclosed by the manufacturer, matching the input–output curves of the model and the real measurements from the device under the various fault scenarios and the system configurations becomes the only way to mimic the dynamic impacts of the real PLL of the PV generator on the power system dynamic studies. Studies of this type also align with the increased requests from the power industry on the validity of PV generator models, for example, at the end of 2019 China issued the mandatory national standard "Code on Security and Stability for Power Systems", which requires all the renewable power plants to provide measured models and parameters to the system operation center.

(2) The timescales of the dynamics for each dynamic problem to be investigated and each specific power system configuration and its components involved need to be analyzed and clarified before exploring the applicable PV generator model. What local control functionalities and the network control functionalities (offering the ancillary services such as the inertia emulation, the frequency control and the voltage control) need to be modeled and in what details rely on the purpose of that dynamic analysis/control and its respective timescales, through which the PV generator models covering multi-timescales such as transient, medium-term and long-term dynamics can be developed.

(3) In addition to the dynamic model of the PV generator, the dynamic models of the other active and reactive power control devices equipped with the PV power plant are also very important, which have visible impacts on the active power and the reactive power control of the PV generator (IEEE-PES Task Force on Voltage Control for Smart Grids, 2019). At present, there are many kinds of dynamic reactive power compensators (such as Static Var Compensator (SVC), Static Synchronous Compensator (STATCOM)) in PV power plants, and the actual performance of these dynamic reactive power compensators varies greatly (Cui et al., 2015). There is a strong need for the accurate simulation models of these reactive power compensators based on the measured data. Understanding the dynamics of a power grid with the PV generators requires strengthening the establishment of the model for these in-plant dynamic reactive power compensation devices (Pourbeik et al., 2012). It is also interesting to note condensers and battery storages might also be installed in solar farms. The condensers could dynamically adjust the reactive power outputs continuously in a wide range. The battery storage is installed to maximize the utilization of the solar energy, thus it will have impacts on the active power management of PV generators. On the other hand, the battery storage is interfaced with the solar farm through power electronics, thus it could also generate and absorb the reactive power as long as the total MVA capacity is within its capacity limits. Therefore, modeling condensers and battery storage is also important for solar farms where they are installed.

(4) There are many types of a PV inverter (Huang et al., 2006; Ravi et al., 2011; Yu et al., 2019), and with the continuous development of power electronics conversion technologies, new types are still emerging, such as inverters with higher voltage level and larger capacity. Meanwhile, some inverter types that appeared many years ago might also show increased importance along with their wide applications due to the technology progresses, for instance, the string inverter (Yu et al., 2019) has been widely used in many areas of China and some other countries. As the topology and control strategies of these types of inverters are quite different from the conventional centralized inverters, with their increasing share in the power system, it is necessary to validate the already established controller models on various types of inverters in use for the stability analysis of a bulk power system. Furthermore, as being pointed out in Section 3.2, the interactions between PV generators and a weak power system where they are connected are raising great interests in both the academy and the industry. The typical characteristic of a weak power system is its low short-circuit-ratio

(SCR). The voltage source based inverter of a PV generator is developed in such a power system instead of the current source based inverter. This voltage-based inverter is often called grid-forming inverter. Its control and modeling has just started and needs further investigation.

(5) Since many of these future works involve model validation, the scenario generation and the data analysis become important. There has been an increased interest in the past a few years in applying the artificial intelligence (Jin et al., 2016; Kontis et al., 2019) and the big data theory (Kang et al., 2018; Viscondi and Alves-Souza, 2019; Zhang et al., 2019) into the renewable energy integration research as well as modeling complex systems (Bacha et al., 2019; Liu et al., 2018). Although their applications in the PV generator have not been reported, using the data analytics to develop, revise and update the dynamic model of a PV generator is certainly worth further exploring.

On top of modeling a PV generator for the power system dynamic studies, the research on PV power plant equivalence and aggregation modeling methods (Han et al., 2018; Han et al., 2019; Li et al., 2019; Remon et al., 2016; Soni et al., 2014) is also important since the individual PV generators are connected and often formed into a solar power plant to be connected into the bulk transmission network. Another important application of the aggregation techniques on PV generator modeling for bulk power system dynamic studies is to develop an equivalent aggregated PV generator model for the small PV generators that spatially distribute across low-voltage distribution networks. Although the research on the PV generator aggregation methods is important, with this paper's focus on modelling single PV generators, aggregation techniques will not be elaborated here.

6. Conclusion

Developing computationally efficient and reliable models of PV generators for power system dynamic studies has been an important focus for both the industry and academia. This paper reviews the state-of-the-art PV generator modeling works, and examines the rationale behind the modeling methods. Through the exposition of the process in developing a generic model for a PV generator, the assumptions made, and thus the conditions in applying the developed model, are clarified, which in turn gives important guidance on choosing the appropriate PV generator models for power system dynamic studies. Another conclusion based on the analysis is that to match the timescale of the electromechanic transient studies, and be compatible with the other components in the power system for these studies, the focus on the PV generator dynamic modeling should be on its active power and reactive power controller. However, since the controllers are proprietary to the manufacturer, the field test results and the corresponding validation and model amendments are critical, which have not been reported sufficiently in the existing works.

The paper also identifies topics that need future attention. Although due to the pressing requests on PV generator integration studies, there is a trend from transmission system operators to require models on all or most components of a PV generator. For example, in the recent published Power System Model Guidelines from the Australian Energy Market Operator (AEMO), both the RMS and electromagnetic transient (EMT) models are required for DC-DC converter, DC link, unit transformer and internal filters for power system transient stability studies (AEMO, 2018). Identifying the timescales of specific transient stability events and then choosing only the necessary component models will speed up the simulation analysis, especially for large-scale power systems, and also will avoid the confusion on whether or not EMT model or RMS model should be used. Therefore, it is crucial to investigate how the timescale of the specific dynamic problem and the timescale of the dynamic component in PV match each other. This work has been very scarce so far, in clear contrast to the overwhelming literature on setting up the mathematical form of the PV generator components. Furthermore, the importance of research on clarifying the applicable scopes of the developed generic models and the validation of modeled controller performances with the real PV generator is highlighted in this work, which is critical for the successful applications of developed models into the real industrial projects on power system dynamic studies. In addition to developing the dynamic model of a PV generator, from our own industrial experiences on dynamic studies of PV integrated power systems, the paper also points out the importance in modeling the dynamic reactive power compensators in PV generation systems for power system dynamic studies. The paper also tries to stimulate more interactions among the TSOs, the manufacturers, and the researchers on dynamic modeling PV generators, since the dynamic problem itself, the proprietary controller design and the applicability of the developed generic model are inseparable, as repeatedly emphasized in this paper.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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