Considerations on the Modeling of Photovoltaic Systems for Grid Impact Studies

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Abstract-- **Photovoltaic systems continue to be deployed at increasing levels and their impact on the electric grid needs to be evaluated more accurately. This includes the impact both in the local grid where they are connected and the impact on the operation of the whole system. As a consequence, adequate models of panels, inverters, and the rest of the grid are required. Models of photovoltaic systems need to characterize their dominant characteristics and effects on the electric grid for the different types of studies, i.e. load flow, harmonic distortion, voltage stability and electromagnetic transient studies. This paper gives an overview of models that are currently in use for different types of grid impact studies, and points to their applications and limitations.**

***Index Terms*—Photovoltaic, Grid impact, Model.**

I. Introduction

Grid connected photovoltaic (PV) systems have been used for several decades already. The number of systems installed and their rated power are growing, and they are connected from low to high voltage networks. Their influence on the overall electric grid is becoming more significant, and significant attention should be given to future scenarios and preventing possible problems, as well as to increasing efficiency and reliability.

Evolution of PV modules, inverters, and requirements for connecting PV systems to the grid is constantly asking for new grid impact studies. According to a report of IEA [1], the installed PV system capacity in 22 analyzed countries was 103 MW in 1992, 678 MW in 2000, and 34953 MW in 2010. These numbers clearly show that PV systems are quickly becoming an important part of the electrical power system, and should be taken into account in system studies.

The literature is offering a number of models for power flow, stability, short-circuit, transient, and harmonic load flow studies, with details added or neglected for each specific study type. However, there is still a need for a generalized modeling approach to initiate the modeling process with the selection of the appropriate model which would emphasize the dominant effect of PVs on the system. The objective of this paper is to give an overview of available models of PV systems for different types of studies, and to explain their applications and limitations. Attention is also given to the aggregation of multiple units and their summated effect on grid operation.

An overview of characteristics of different PV models and studies is given in Table I. Each type of studies is elaborated further in a separate section.

II. Model for Power Flow Calculation

In normal steady state operation the control system of the converter determines how the solar generator must be represented. In the most common case, the generator will be operated as a PQ node. In this mode, the generator is assumed to produce constant active and reactive power. The active power contribution in reality depends on the solar irradiation, which is assumed to be constant for the point in time under investigation. The converter control system is set up to achieve a constant reactive power contribution as well, as modern converter systems can operate freely within a certain reactive power range. Converter control system modes of constant power factor or constant reactive power only correspond to different data input modes for the generation asset as a PQ node.

Due to their ability to adjust their reactive power contribution within a certain range, converter-based power plants can also be used for voltage control. When used in this function, the solar power plant must be treated as a PU node in the power flow calculation. At the PU node active power and voltage magnitude are known values, and reactive power and voltage angle are determined by the power flow calculation. As with all generation assets, the maximum currents have to be taken into account – the calculation procedure must ensure that the reactive power limits of the voltage-controlling converter are not exceeded.

Software packages usually achieve this by internally converting nodes from PU to PQ where needed.

A third variant is that setpoints can be given for both

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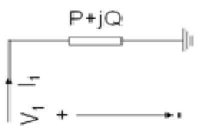
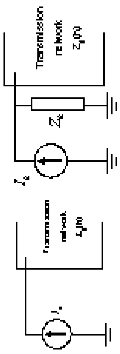
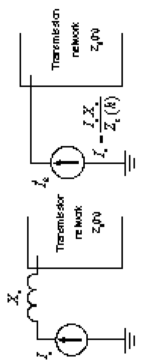
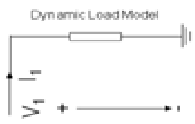
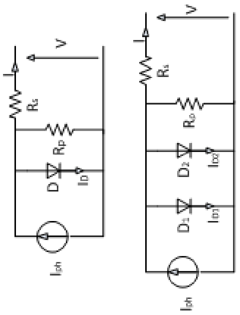
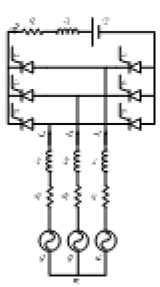
TABLE I
CHARACTERISTICS OF DIFFERENT TYPES OF MODELS AND STUDIES

Inverter model	**Type**	**Aggregated model considerations**	**General model considerations**
Load flow	PQ, PU, or DU node 	Arithmetic summation	Steady state
Harmonics	Ideal or non-ideal current source  Voltage source or current re-injection 	Summation coefficients $I_{SUM} = \sqrt[\beta]{\sum_i I_i^{\beta}}$	Frequency domain Frequency Scan of the point of connection is very important 
Electro-Mechanic stability	Dynamic profile – P and Q  PV Panel: 	No simplified models available	Weather conditions and cloud formations are or significant importance for voltage level fluctuations
Electro-magnetic transients	Detailed model of power electronics with controls 	No simplified models available, use actual circuit	Time-Frequency domain

voltage and reactive power at the same asset. Since it is impossible to perform voltage control and reactive power control at the same assets, the setpoint deviations of both are weighted against each other, using a weighting factor called droop. Higher droop settings shift the weight from a smaller voltage setpoint deviation towards a smaller reactive power setpoint deviation. This type of node is called a DU node, which references the resulting voltage setpoint deviation. Since neither voltage nor reactive power is known from the beginning, the power flow algorithm starts with the assumption of zero voltage setpoint deviation and then adjusts both voltage and reactive power in each iteration step. This works because the correlation between voltage and reactive power at the node is known from the droop setting. Of course, reactive power limits must be taken into account in the same way as for a PU node.

III. MODEL FOR SHORT CIRCUIT CALCULATION

In the past, converter-based generation assets did not contribute a significant share of active power generation to the power system. Since their reactive current contribution to short circuit currents is also limited in comparison to the traditional synchronous machine based power plants, it was common practice that they were immediately disconnected when a fault was detected. However, this practice is not feasible any longer with the increasing share of converter-based generation. Disconnecting large active power shares generated by such assets has a severe impact on system stability and can cause supra-regional blackouts.

New connection guidelines and regulations (grid codes) therefore require that new converter-based power generation assets of significant size be capable of “riding through faults”. They have to remain connected to the grid as long as the fault impact does not exceed certain specified limits. While they remain connected their control system has to respond to voltage changes by adjusting the reactive current contribution along a given characteristic, which mimics the contribution of a synchronous machine. The required control system response is fast enough to guarantee appropriate contribution to transient fault currents. As a result, short circuit calculations must include the contribution of converter-based assets for accurate results.

Short circuit calculations are carried out in network planning and network operation. In network planning, approximate solutions are acceptable, as there are often other factors that are not fully known yet, and the intention of the study is the appropriate dimensioning of circuit breakers. It is often acceptable to apply the synchronous machine model also for converter-based generators in this kind of study.

However, in network operation, more accurate results are required to determine whether the given equipment is capable of dealing with short circuit currents that can occur after switching the grid to a different configuration. The approach to use the synchronous machine model could be taken as well, but the results will not be very accurate. The problem is the limitation of the reactive current magnitude by the converter: power electronic converters are limited to produce current up to their rated current, which they produce at nominal apparent power. However, synchronous machines can provide transient short circuit contributions above their nominal current by a factor of up to eight. The representation of a converter by a synchronous machine model can therefore only be accurate to a certain degree (i.e., when certain conditions are met). When the synchronous machine model parameters are set correctly for a short circuit at the generator terminals, they will be incorrect for remote faults and vice versa. Due to the limitation of the converter contribution to the short circuit current, this contribution is in fact independent of the fault distance to some degree. Only if the voltage drop at the converter remains within certain limits, the fault current contribution will resemble a synchronous machine. This behavior is fundamentally non-linear, and cannot be represented in the traditional and standardized linear short circuit calculation methods.

An alternative approach is to run a dynamic simulation for each case. Unfortunately, this approach requires a much higher modeling effort and significantly more time for simulation and result evaluation. In fact the effort is so high that this approach must be considered infeasible for use in regular network operation.

A new approach has recently been developed by DIgSILENT GmbH [2]. The basic idea is to accept the non-linearity of the converter characteristic and use an iterative approach for the short circuit calculation in the transient time scale. In comparison to the traditional short circuit calculation methods, this leads to longer calculation times. However, sufficiently accurate results can be obtained while still avoiding the additional effort of time-domain modeling and simulation.

IV. MODELS OF PV PANELS AND MPP TRACKING

Describing solar array I-V characteristic according to irradiance and temperature is mainly analyzed by two lumped models in literature, namely single diode model (SDM) and double diode model (DDM). DDM considers more parameters and along with gives better precision particularly at low irradiation [3]. In SDM (Fig. 1), current-voltage characteristic function of the PV array is depicted as:

$$I = I_{ph} - I_0\left[\exp\left(\frac{V+R_S I}{AV_t}\right) - 1\right] - \frac{V+R_S I}{R_p} \qquad (1)$$

In (1), I_0 is the dark saturation current, R_S is the cell series resistance, R_p is the cell parallel resistance, A is the diode quality (ideality) factor and V_t is the junction thermal voltage which is described by $V_t = kT_{stc}/q$, where k is the Boltzmann’s constant, q is the charge of the electron and T_{stc} is the temperature at standard test condition (STC).

I_{ph} is the photo-generated current which is a linear function of irradiance and a function of temperature [4]. I_{ph}, in short circuit condition, can be approximated to:

$$I_{ph}(G,T) = I_{sc,STC}\frac{G}{G_{STC}}\left[1 + K_I(T - T_{ref})\right] \qquad (2)$$

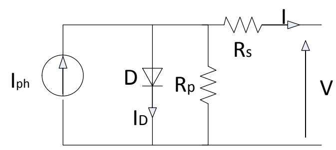


Fig. 1. Single diode scheme

where G is irradiation and G_{STC} is irradiation in STC(1000W/m^2), $I_{sc,STC}$ is the short circuit current at STC, T_{ref} is the reference temperature at STC(298°K) and K_I is the short-circuit current temperature coefficient(%/°K). Moreover, open circuit voltage can be expressed as a linear function of temperature [4].

$$V_{OC}(T) = V_{OC,STC} + K_V(T - T_{ref}) \qquad (3)$$

where $V_{OC,STC}$ is the open circuit voltage in STC and K_V is the open-circuit voltage temperature coefficient(V/°K).

For, DDM (Fig.2) V-I characteristic function is illustrated as [3]:

$$I=I_{ph}-I_{01}\left[\exp\left(\frac{V+R_S I}{V_t}\right)-1\right]-I_{02}\left[\exp\left(\frac{V+R_S I}{2V_t}\right)-1\right]-\frac{V+R_S I}{R_p} \qquad (4)$$

Finding unknown parameters requires iterative process, in [4] was shown how to derive solar array parameters through datasheet values. However, by reducing the complexity of model, for instance neglecting parallel resistance and assuming some approximations it would be possible to reach a four-parameter model based on the analytical expressions.

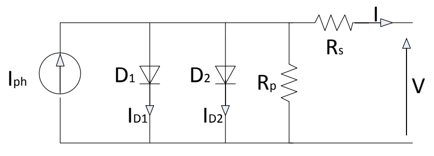


Fig. 2. Double diode scheme

The characteristic of PV array power-voltage for different irradiation levels has been illustrated in Fig. 3. As can be seen, by decreasing the irradiance level the output power decreases. Fig. 4 depicts that the output power of solar array is reduced when the temperature rises. It is desired that PV system operates at Maximum Power Point (MPP) then the desired operating point for each PV cell is I_{mp} and V_{mp}.

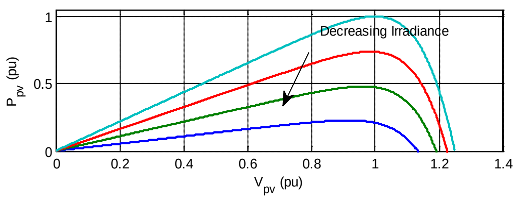


Fig. 3. Irradiance impact on power-voltage characteristic of a PV cell

Extracting maximum power from the PV array needs Maximum Power Point Tracking (MPPT), therefore MPPT is the essential part of PV system. MPPT function is to regulate output voltage and current of the PV system in such a fashion to get maximum power of the PV array according to weather conditions. Different MPPT algorithms have been proposed and implemented such as perturb and observe (P&O), incremental conductance (IncCond), fractional open-circuit voltage, fractional short-circuit current and etc. P&O method makes a perturbation in voltage and observes the consequent of this change on the output current and power of PV array, in doing so if the power increases, the perturbation is held in the same direction otherwise it is reversed [5], [6]. Once the MPP is reached, there would be an oscillation at output power of PV. Reducing perturbation step size decreases oscillation but in the meantime slows down the MPPT. Some methods have been proposed to get optimum perturbation step size by having variable step size [6]. Under fast environmental change within one MPPT perturbation, MPPT may fail to track the correct MPP and getting diverged. Some techniques like employing three-point weight comparison or optimizing sampling rate have been introduced to overcome this drawback [5]. Incremental conductance performance is based on this fact that the slope of power curve is zero at MPP. Via comparing instantaneous conductance (I/V) and incremental conductance ($\Delta I/\Delta V$), MPP is met when both of conductances are equal [4], [5]. The speed of MPPT is adjusted by the increment step size. By large increment step size, on the one hand fast MPP tracking can be obtained but on the other hand the system would oscillate around MPP. In order to minimize oscillation different procedures have been proposed [6]. Fractional open-circuit voltage and fractional short-circuit current are two similar approaches that are taking the advantage of close linear relationship between V_{MPP} and V_{OC}, $V_{MPP}=k_1V_{OC}$, as well as I_{MPP} and I_{SC}, $I_{MPP}=k_2I_{SC}$, for varying environmental conditions [6], [7]. Where k_1 and k_2 depend on PV array characteristic and must be calculated for different atmospheric conditions in advance. Once the k_i (i=1,2) values determined, V_{MPP} and I_{MPP} can be determined by measuring V_{OC} via shutting down the power converter which leads to temporarily loss of power. Moreover this approach is based on the linear approximation and increment step size, by doing so exact MPP might not be achieved. In fractional short-circuit current method measuring I_{SC} during operation of the system needs extra switch to periodically short the PV modules to get I_{SC} which brings about power reduction. Moreover as fractional open-circuit voltage, exact MPP is not finely matched. There are other types of MPPT algorithms available in literature. In [6], it is mentioned that there are at least nineteen distinct algorithms in literature. However, P&O and IncCond are widely employed in industry.

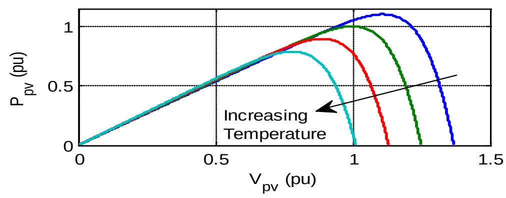


Fig. 4. Temperature impact on power-voltage characteristic of a PV cell

MPPT plays a key role in performance of the PV system to the extent that speed of the system is dominated by the MPPT, this issue has been addressed in [8] and according to it a dynamic model for the PV system based on the analyzing of experimental results was developed.

V. MODELS FOR VOLTAGE STABILITY STUDIES

A large fraction of the PV systems that are being installed are connected in the LV distribution system at the end costumer's premises. The implication of that is that the operating conditions of the LV voltage grid are changed significantly. In particular often there will be bi-directional power with rapid changes which has an impact on the voltage level and the voltage fluctuations of the grid. It is thus necessary to have tools enabling analysis of the voltage issues and investigation of possible solutions. These tools should be able to assess the impact of the PV connected along a feeder i.e. they should be able to simulate the LV grid with consumption and realistically represent the PV input. Since many of the issues with integration of PV are associated with the fluctuations it is necessary to be able to do proper time series simulations to be able to assess the statistical properties of the voltage such as distribution of voltage level and amount and size of voltage fluctuations.

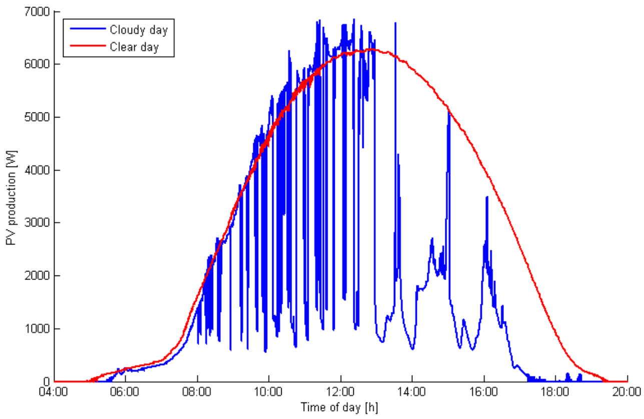


Fig. 5. Active power production from a PV plant showing two days with different cloud coverage

The electrical models to analyze the grid impact will be standard load flow models of the grid [9] implemented in simulations tools for power systems [10], [11]. The main problem is proper modeling of the input to represent the fluctuations of the PV production on the relevant timescales, seconds-hours but also representing the correct distribution between different types of days such as days without cloud cover, days with different types of partial cloud cover (large /small, fast/slow moving) and days with unbroken cloud cover. A related issue of importance is correlation between different PV installations connected to a feeder and correlation with consumption. Another important issue is the ability of the tools to represent the control of the active components of the system e.g. inverters, storage units and controllable loads.

To illustrate some of the issues the power fluctuations for the PV installation that is part of SYSLAB @ Risø DTU [12] have been analyzed. The power production from the PV plant is shown in Fig. 5 for the days analyzed. The data has been processed to show the fluctuations at different timescales. Fig. 6 shows the fluctuations on a day with clear sky while Fig. 7 illustrates the situation on a day with passing clouds. It is very clear from the figures that it is necessary to have a good description of the input i.e. the solar irradiation on both short on short timescales (intra-day) and longer timescales, day to day and over the year.

The solar power production will induce voltage variations in the grid due to the impedances of the grid. For traditional LV grids the voltage is highest at the bus bar and decreases along the feeder to have the maximum capacity without violating the voltage range. When solar power is introduced the picture gets slightly more complicated since the solar power is contributing to raising the voltage. The result is that situations could occur where the voltage is above the upper limit allowed due to the solar power production and the consumption. The situation for a feeder in SYSLAB is shown in Fig. 8. The maximum and minimum voltage curves are for situations with maximum solar power/minimum consumption resp. minimum solar power/maximum consumption while the two curves in between illustrates how the inverter on the PV installation can be controlled to narrow the range of voltage level variation by consuming resp. producing reactive power.

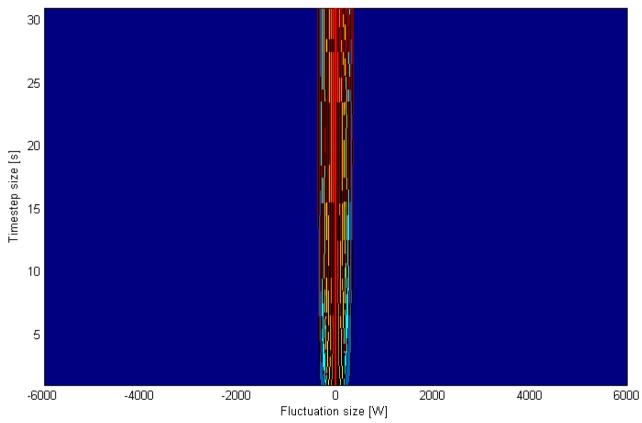


Fig. 6. Fluctuations of the power output of a PV plant on a cloudless day. The color map shows the number of fluctuations at different power levels against the length of time from the observation to the change in power output

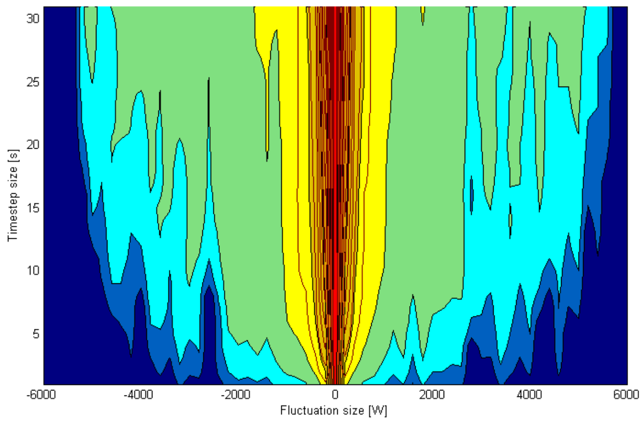


Fig. 7. Fluctuations of the power output of a PV plant on a cloudy day. The color map shows the number of fluctuations at different power levels against the length of time from the observation to the change in power output

The above figure illustrates one of the options that exist to mitigate the issue of voltage level variations. Other options exist such as on load tap changers or energy storage. This emphasizes the importance of being able to model the various options with realistic input and control of the active components.

VI. MODELS FOR HARMONIC INTERACTION STUDIES

Harmonic interaction studies can be done in the time domain, frequency domain, or as hybrid calculations [13], [14].

Time domain calculations use differential equations, and therefore require detailed models of power electronic devices, including the control algorithm of the PV inverter. With a detailed model of a device, they are known to be very accurate when predicting behavior in different conditions. Examples of studies done in the time domain are given in [15]-[18]. A restriction of time domain calculations is that they are difficult to do for systems with a large number of different units. Including the control algorithm of several different devices can be a problem or even impossible, since their control algorithms are not always available.

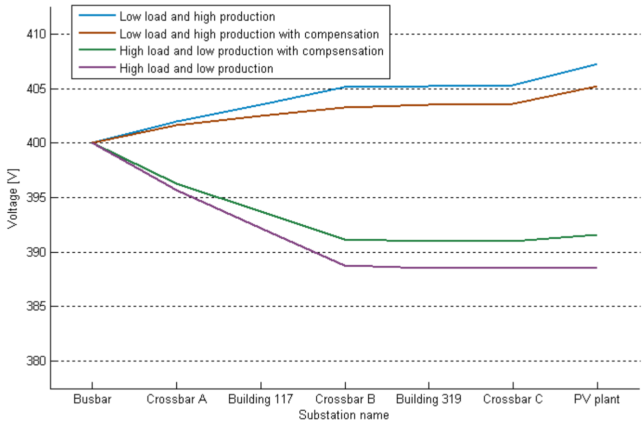


Fig. 8. Voltage levels along a feeder connected to a busbar at one end and a PV plant at the other. The figure shows four different states of production and consumption; a low load and high production state; a high load and low production state and then those two states with compensation from the PV plant

Calculations in the frequency domain are widely used for harmonic studies. Sources of harmonic currents are represented as ideal or non-ideal current sources, or the current is determined from a look-up table based on the voltage of the busbar. As [14] suggests, a harmonic source can also be represented as voltage source with a series impedance, or as a current source dependent on the system impedance (current re-injection), which emphasizes the effect of the system impedance on the current of the source.

Several types of calculations are proposed in the frequency domain [13], [14]: current source method, power flow method, and iterative harmonic analysis. Examples of studies in the frequency domain are given in [19]-[23].

Current source method solves the network equation:

$$[Z][I] = [U] \tag{5}$$

for each harmonic frequency. Harmonic currents are assumed to be independent of voltages which makes the calculation relatively simple, but also reduces the accuracy. Network elements that do not generate harmonics are modeled as linear impedances. Background harmonic voltages that originate from higher voltage levels can be modeled as voltage sources.

Harmonic power flow method uses a Newton-type algorithm to solve current and voltage equations at the same time for a single frequency. This allows the harmonic current sources and other elements to be voltage dependent, and gives more accuracy. On the other hand, the calculation becomes more complicated than the current source method. A number of software tools use this method for harmonic analysis of the system.

Iterative harmonic analysis is an advanced version of direct and power-flow calculations. The original methods are supplemented with voltage dependent current sources, and sometimes even the frequency coupling. The direct matrix or power-flow simulation is initially executed with assumed voltages on busbars of non-linear elements, resulting in initial harmonic current values. These voltages are then compared with calculated voltages for those busbars, and if needed, the calculation is repeated with new values for current sources. This iterative procedure is repeated until the voltage changes on busbars are within the desired error margins. The accuracy of these methods is dependent on the complexity of models used. When detailed models of all elements are used very accurate results can be achieved, but on the other hand the models require a lot of parameters, which sometimes makes them difficult to implement for complex systems.

Hybrid calculations are a mixture of time and frequency domain methods. Currents of non-linear elements are calculated in the time domain, based on the voltages which are solved in the frequency domain, usually with iterations. This type of calculation was still not used for harmonic studies with photovoltaic systems.

Frequency dependent impedance of the system is important for harmonic interaction studies. Harmonic voltages are often increased due to a resonant or near-resonant condition, and therefore attention should be given to the effect of impedance of PV inverters. Other nearby equipment, such as power factor correction capacitors, should be taken into account.

In the case of multiple inverters connected to the system, an aggregated model can be used to substitute the effect of all units. Summated current can have a maximal value equal to the arithmetical sum of individual currents, but due to the phase angle diversity of individual currents the sum is usually lower than that. Technical reference [24] suggests using a generalized summation law for determining the total harmonic current of random loads:

$$I_{SUM} = \sqrt[\beta]{\sum_i I_i^\beta} \tag{6}$$

where β is the summation coefficient with a value of 1 or greater, depending on the harmonic order. General considerations about the summation of random currents are given in [24]-[27]. Examples of aggregated models of PV inverters are given in [28], [29]. Reference [28] presents measurement result in which β had a value of approximately 1 (arithmetic summation) for harmonic orders up to 17, and a value of approximately 2 for higher orders.

VII. Models for Electro-Magnetic Transient Studies

Behavior of PV inverters during electro-magnetic transients can be accurately modeled in the time domain. As mentioned in previous sections, this requires significant modeling effort. Converters control plays a key role during transients and has to be modeled accurately. This makes it difficult to model large systems with a great number of inverters. Examples of time domain studies are given in [30], [31].

Aggregation of PV inverters in electro-magnetic transient studies still needs to be explored. More work in this field is needed to obtain simplified models of a large number of inverters, because new regulations oblige even small inverters to comply with certain low voltage ride-through requirements.

VIII. Conclusions

Considerations on Photovoltaic system modeling for grid interaction studies are presented in the paper. An overview of different PV models for different types of studies is given, with their applications and limitations.

For load flow calculations, they can be modeled as constant active and reactive power nods, or voltage dependent, as described in section II.

PV systems and other converter-interfaced generators were often neglected in short-circuit studies, but new fault ride-through requirements are increasing their contribution in short-circuit currents. The approach for modeling them is described in chapter III.

PV modules are modeled with single diode or double diode circuits. Different MPP tracking algorithms are described in section IV.

For LV network voltage level studies it is important to take into account the effect of weather conditions, such as solar irradiance, temperature, and cloud formations. These effects are emphasized in section V.

Harmonic interaction studies are usually done in the frequency domain, using ideal or non-ideal current sources as models of PV systems. Simulations can also be done as iterative or in the time domain. It is important to estimate the effect of PV inverters on the frequency dependent impedance of the rest of the system. These effects are described in section VI.

Electro-magnetic transient studies are done in the time domain, using detailed models of power electronics and controls of inverters. At present, no simplified models are proposed for this type of studies.

Concerning the aggregation of multiple PV systems, for load flow studies they can be summated arithmetically, and for harmonic studies using summation coefficients. For stability and electro-magnetic transient studies more work is needed to obtain simplified summated models.

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