GRID INTEGRATION OF PHOTOVOLTAIC PLANTS – A GENERIC DESCRIPTION OF PV PLANTS FOR GRID STUDIES

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ABSTRACT

This article presents an approach to modelling of three-phase photovoltaic (PV) inverters for RMS-based grid integration studies under balanced and unbalanced conditions. The inverter model was rigorously derived from accurate instantaneous value models that were simultaneously used for the development of inverter control and operations software. This approach leads to a precise generic phasor model in the dq reference frame that can be used both for certification purposes and for dynamic interconnection studies of PV power plants and allows implementation on several simulation platforms.

The new model describes the basic functionality of inverter front-ended generators, and can be modularly extended with common features like voltage control or frequency control. Thereby grid operators are enabled to account for the grid supporting features of PV power plants in grid simulations.

INTRODUCTION

It is well known that by means of an increasing portion of installed PV power, simultaneously its influence on the existing electrical grid structure grows. In new revisions of national as well as international grid codes and terms of technical installations, requirements are currently being defined which illustrate a paradigm shift regarding the grid behaviour of photovoltaic plants and other decentralised generators of electrical energy.

Adjacent to the resulting requirements to inverter manufacturers for the implementation of functions like feed-in management or dynamic grid support, the demand for simulation of photovoltaic plant properties for the purpose of planning and design of distribution and transmission systems increases.

Grid operator knowledge of decentralised energy generator behaviour is frequently not established sufficiently. In contrast the inverter manufacturer is challenged to provide models for the simulation of the plant.

More precisely, the certification of devices and plants according to the current grid codes, e.g. [1], has to be mentioned. In addition to the verification of the electrical characteristics [2], requirements for the modelling are defined [3].

Simulation of wind farms as elements of power systems started with vendor-specific generator models provided by the manufacturers of wind generators, as was pointed out in [4]. These dynamic models were successfully used for transient stability studies but were also lacking easy handling capabilities in simulation environments due to the fact that they contained proprietary information. For that reason the development of generic publicly available models was started where all respective parameters can be modified according to any practical implementation.

It soon evolved that the various types of wind generator technologies could not be represented by only one generic model and so the now well-known four types of wind generator models were suggested. In accordance to this development a similar strategy is currently being explored for PV generators that make use of the "type 4" wind generator model – the full converter interface ([5], [6], [7]).

DISTRIBUTED GENERATION

While wind generator models are mainly used for transmission network studies, PV generator models also play a significant role in the context of distribution network simulation. The high penetration of distributed generation (DG), primarily PV systems, leads to changes in grid operation, power flow direction and voltage profiles in distribution networks. Moreover the natural variation of solar irradiation causes fluctuations of the voltage V. Accordingly, PV systems should be able to participate in grid support and, when possible, in grid control. Active DG operation can be realised by implementation of primary control algorithms: e.g. $Q(V)$ control, $PF(P)$ control, $P(V)$ control, dynamic grid support[1] (DGS) to actively influence the grid voltage and increase the hosting capacity of the network, or $P(f)$ control in order to impact the grid frequency f and support the grid if possible (here, Q is the reactive power, P is the active power, and PF represents the power factor).

Additionally, a secondary or coordinated control can be realised.

Especially for studies of the potential of grid support through PV DG, accurate inverter models are required that represent all grid supporting functions of the equipment.

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1 also known as fault ride-through (FRT)

MODELLING PV SYSTEMS

The electrical properties of PV plants are determined mainly by the inverters which often exhibit a similar architecture. A generic approach to modelling will be presented showing the dynamic grid behaviour of photovoltaic inverters in this paper. Figure 1 shows a typical setup of a PV inverter with feed-in management, reactive power control and dynamic grid support capability (grid management). The input signals for the operating system are obtained from: a synchronisation unit (Sync) which provides the grid quantities (voltage, frequency), an interface unit (Settings) for receiving settings by e.g. supervisory control and an MPP tracker for determination of the generator operating point in which the power output of the PV panel is maximised.
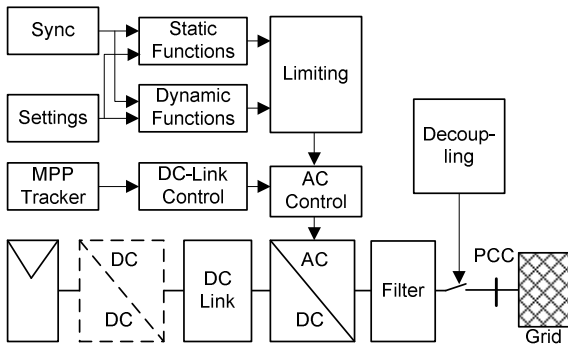

Figure 1: General block diagram of a PV system.

All grid management functions are realised as static or dynamic functions which are distinguished according to their response times. A more detailed explanation is provided below. The set points generated by grid management functions need to be limited to the inverter's characteristics resulting in the AC control unit which controls the inverter bridge. Furthermore, there is a decoupling unit which trips the generator in case of erroneous voltage or frequency values. The system might additionally have a DC converter if the PV panel output needs to be adapted for feed-in conditions.

In contrast to wind turbines, the dynamics of photovoltaic generators are negligible because of their small energy storages components.
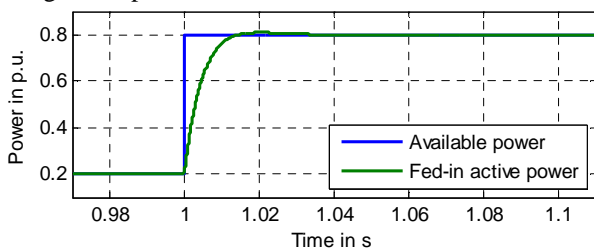

Figure 2: Active power feed-in response to step function stimulus of irradiation.

To illustrate, Figure 2 shows the response of a PV inverter to a step-function irradiation stimulus. The generator settles well within 20 ms, i.e. one period of grid oscillation. Furthermore, an irradiation step function does only

exist under laboratory conditions and will not be observed in real systems. Sub-cycle phenomena like this are generally not considered in quasi-static RMS simulation modelling. Hence, the description of the primary energy conversion, the photovoltaic generator, as well as an optional DC-DC converter can be neglected.

SMA GENERIC INVERTER MODEL

The description of the system is accomplished by the concept of symmetrical components V_0, V_+, V_-.

$$\begin{bmatrix} V_0 \\ V_+ \\ V_- \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad a = e^{j(2\pi/3)}$$

Where V_a, V_b, V_c are the unbalanced phasors of the three-phase system.

A quasi-static phasor model was derived from accurate average value models and allows the simulation of PV inverters for the purpose of grid analysis using established simulation software like DIgSILENT PowerFactory®, Siemens PSS®E etc.

Through simple adaptations like device-specific parametrisation and dimensioning of the control loop dynamics, particular inverter types can be represented with sufficient precision as required for certification purposes according to [1].

Regarding the dynamics mentioned before the modelling of PV systems for system integration studies and stability studies, RMS models, with the structure shown in Figure 1 can be simplified to the block diagram given in Figure 3. With respect to the high dynamics of the inverter, all levels of power-conversion and filtering are neglected resulting in a no-order system. The feed-in unit is the tool-dependent ideal interface for connecting user-defined control structures to the physical grid model. E.g. using PowerFactory® the Static Generator can be used as feed-in unit.

As there are some dynamics caused by system behaviour and control interaction, simplified low order low-pass filters can be added for fitting model dynamics.
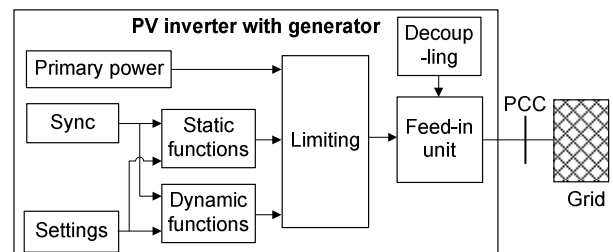

Figure 3: SMA generic RMS model block diagram of a PV system.

The block Primary power is the p.u. based available DC power according to the inverter's rated power. According to the characteristic shown in Figure 4 there is no need for any PV panel modelling and the primary power can directly be interpreted as irradiation.

Figure 4 shows more precisely the realisation of the grid management functions, required by various national as well as international grid codes. E.g. the four options for providing reactive power, shown in Figure 4 fulfil the current requirements of German grid codes.

Static functions for active power limiting work in parallel as they define a maximum active power value.

Any other reactive and active power characteristic can be realised by adding the structure or supervisory control using the inverter as an actuator.
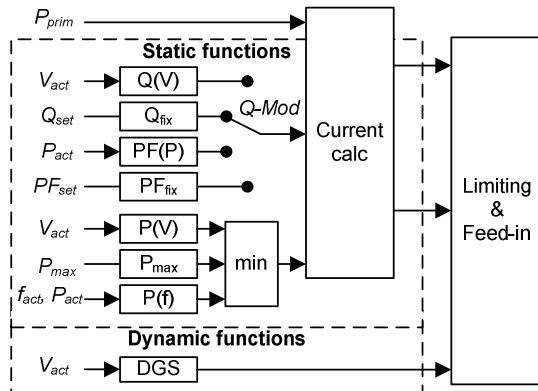

Figure 4: Grid management and feed-in structure of a PV inverter.

The static functions as well as the available power signal (P_{prim}) output power quantities. As the inverter is limited by its ampacity, the resulting currents need to be calculated (Current calc).

Dynamic functions, here dynamic grid support, as defined in [8] and described in [9] specify a reactive current characteristic for grid support in case of voltage dips. The resulting reactive current is defined as an offset to prior static working conditions and has to be provided in milliseconds.

The resulting current set points can exceed the inverter's ampacity and have to be limited before being passed to the feed-in unit. Using different priorities for limiting active current, reactive current as well as for positive and negative sequence currents and regarding inverter specific over-current capabilities the limiting method can be adjusted by parameter settings to fit different inverter types.

MODEL VALIDATION

The most challenging part of RMS inverter models is the simulation of DGS capabilities, concerning the high dynamics and the tolerances defined in [3]. Therefore, model validation is demonstrated on measured DGS characteristics for the SMA Sunny Central 630CP, a 630 kVA central inverter and the Sunny Tripower 15000TL, a 15 kVA string inverter. Although the dynamics of the inverters differ, the characteristics for both of them can be simulated with the SMA generic inverter model as shown in Figure 5 and 6.

For model validation the compared values are the voltage

(V), reactive current (I_Q) and active power (P). Additional signal declarations are index "1+" for positive sequence basic component, index "1-" for negative sequence basic component, index "Meas" for measured and index "Sim" for simulated curves with the following definition according to the *pq* theory described in [10]:

$$\overline{p} = 3V_{1+}I_{1+}\cos(\phi_{v1+} - \phi_{i1+}) + 3V_{1-}I_{1-}\cos(\phi_{v1-} - \phi_{i1-})$$

as the mean value of the instantaneous real power, defining

$$P_{1+} = V_{1+}I_{1+}\cos(\phi_{v1+} - \phi_{i1+})$$
$$P_{1-} = V_{1-}I_{1-}\cos(\phi_{v1-} - \phi_{i1-})$$

and

$$\overline{q} = 3V_{1+}I_{1+}\sin(\phi_{v1+} - \phi_{i1+}) - 3V_{1-}I_{1-}\sin(\phi_{v1-} - \phi_{i1-})$$

as the mean value of the instantaneous imaginary power, defining

$$Q_{1+} = V_{1+}I_{1+}\sin(\phi_{v1+} - \phi_{i1+})$$
$$Q_{1-} = V_{1-}I_{1-}\sin(\phi_{v1-} - \phi_{i1-})$$

and

$$I_{Q1\pm} = -\frac{Q_{1\pm}}{V_{1\pm}}.$$

Figure 5 shows measured and simulated characteristics of the Sunny Central 630CP under a balanced voltage dip. The measured characteristics are calculated from high-frequency sampled instantaneous current and voltage values. Obviously, measured and simulated positive sequence data fit very well and fulfil the requirements specified in [3].
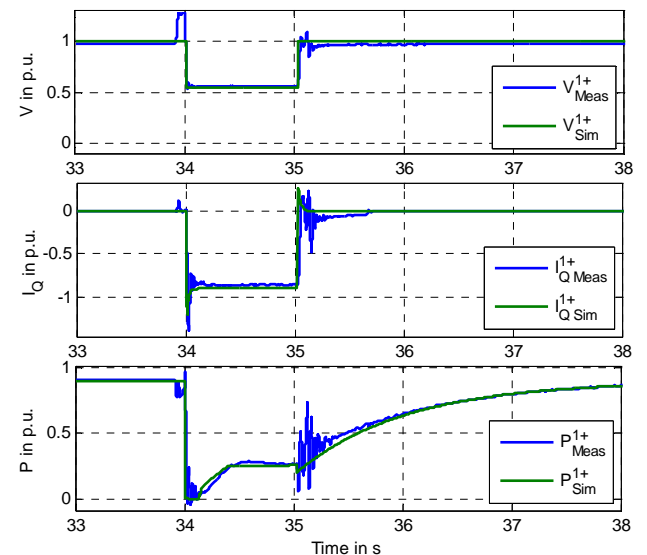

Figure 5: Measured and simulated p.u. characteristics of an Sunny Central 630CP under a balanced voltage dip

The characteristics of the Sunny Tripower 15000TL shown in Figure 6 are very different but can also be simulated with the SMA generic inverter model by adjusting a few parameter settings.

In addition to the positive sequence values Figure 6 shows the negative sequence characteristics, as they are

unequal to zero during unbalanced voltage conditions. The negative sequence simulated values comply with the measured values in the same manner as the positive sequence values do.
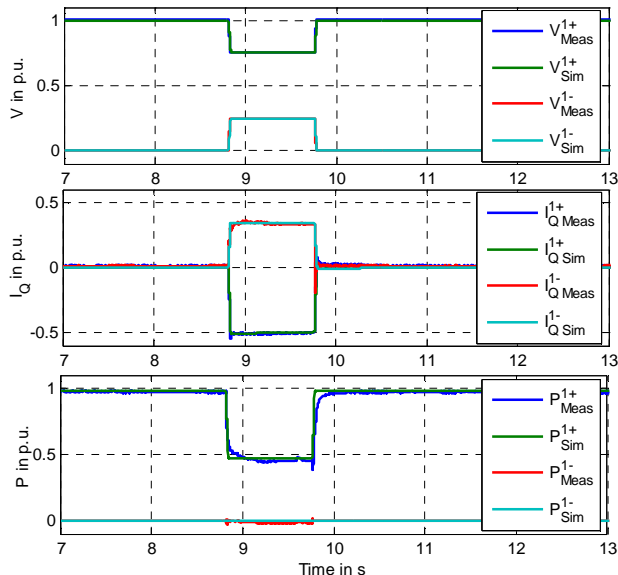
Figure 6: Measured and simulated p.u. characteristics of an Sunny Tripower 15000TL under an unbalanced voltage dip type D according to [11]

Another advantage of this structure is the possibility of a tool-independent implementation as shown in Figure 7 where the quantities V and I_Q under a balanced voltage dip are given for model implementation on Matlab/Simulink®, DIgSILENT PowerFactory® and Siemens PSS®E.
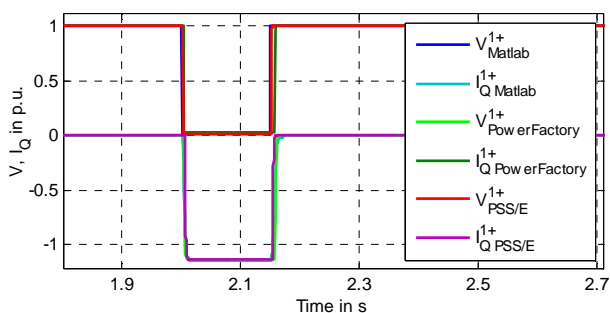
Figure 7: Simulated p.u. characteristics of an Sunny Tripower 15000TL under a balanced voltage dip with different simulation tools

CONCLUSION

In this paper a new model structure for inverter frontended generators is shown that allows the simulation of photovoltaic inverters for the purpose of grid analysis under balanced and unbalanced conditions. The model is designed on symmetric components with a p.u. basis whereby the structure is compatible for model implementation in different established simulation software. This model can be regarded a generic model since multiple particular inverter types can be represented with the accu-

racy required for certification purposes according to [1] by simple adaptations. Thus, on the basis of this model the certification of the SMA inverter series Sunny Tripower TL and Sunny Central CP has already been achieved according to [3].

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