Title: Inverters without transformer in photovoltaic applications
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Abstract:

It is proposed to omit the transformer in inverters for grid connected photovoltaic systems in order to reduce losses, costs and size. With respect to a tolerable level of the dc-voltage and the leakage current, the 1-phase three level VSI and the 3-phase CSI seem to be promising approaches and are discussed in more detail. For the 3-phase CSI the leakage current is reduced greatly by a novel control method.

Inverters without transformer in photovoltaic applications

1. Introduction

Most of the commercially available inverters for photovoltaic applications include a transformer, which enables the selection of a suitable dc-voltage U_{dc} according to the components and avoids ground-loops between pv-generator and grid. Inverters including a transformer either use a 50 (or 60) Hz line transformer or a medium frequency (20...50kHz) transformer. In the latter case, inverters are primary pulsed and primary modulated and include three sections of power-electronic conversion [1]. These inverters are pretty complex and the question arises whether simplification and improvements in losses, costs, weight and size are possible by omitting the transformer.

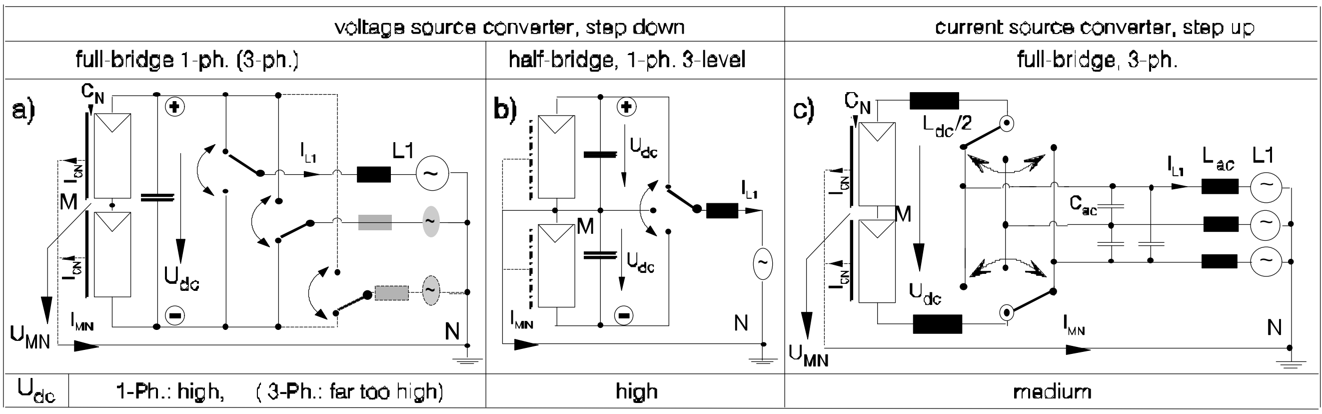

Fig. 1: Converters without transformer (strongly simplified)

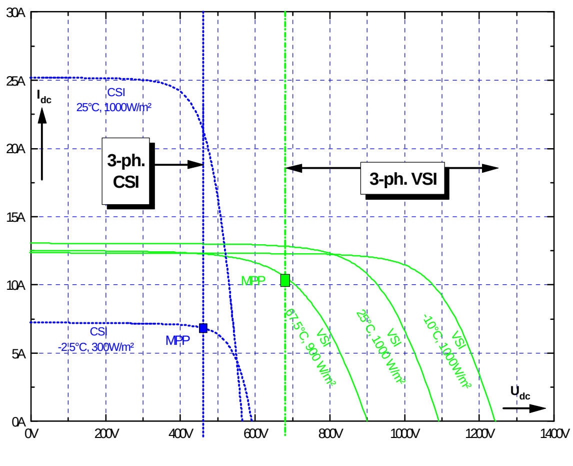

Fig. 2: Current-voltage characteristics of PV-generators

Basically, there is no unavoidable demand to include a transformer, but before avoiding the transformer, some questions have to be answered. Two of them are addressed in this paper concerning

a) the magnitude of U_{dc} and

b) the leakage current I_{CN} .

Figure 1 shows the strongly simplified schematics of the (step-down) Voltage Source Inverter (VSI), which needs a high dc-voltage and the (step-up) Current Source Inverter (CSI), which works with a lower dc-voltage. As an example for a 10kW PV-plant, figure 2 outlines the strongly temperature dependent current-voltage characteristics for the 3-phase full bridge VSI and CSI . Considering e.g. the 3-phase full bridge VSI , the ratio of maximum to minimum dc-voltage is nearly as large as 2, and the maximum dc-voltage exceeds clearly 1kV, which is not allowed for today's available PV-modules. Without transformer, there is a galvanic connection of grid and PV-generator and a leakage current I_{CN} may flow through the capacitance between PV-generator and ground. (see fig. 1) The magnitude of this capacitance depends on environmental influences, it will be large e.g. when the PV-generator is covered with salty fog forming a conductive path to the grounded metallic frame of the PV-modules. Simulations show, that in this situation the voltage between PV-generator and ground as well as the current I_{CN} may heavily oscillate and far exceed acceptable levels, thus the full-bridge VSI (Fig. 1a) is not considered to be a practicable approach.

As the midpoint of the PV-generator is grounded in the 1-phase, half-bridge VSI (Fig. 1b), the above mentioned oscillations do not appear with this type of inverter. In a 1-phase inverter voltages are reduced by a factor of $1/\sqrt{3}$, U_{dc} does not exceed ±700V, which is allowed for today's PV-modules. Due to this relatively high U_{dc} , a three level 1-phase inverter is interesting, especially in the range below 5kW. Chapter 2 deals with this type of inverter.

In Germany, single-phase power infeed in the public 400V ac-grid from PV-plants is limited to 5kW. For higher power levels more phases must be used.

As with the 1-phase CSI the smoothing reactor will be relatively large (100Hz power pulsation), the CSI is interesting mainly as 3-phase inverter for power levels above 5kW (see Fig. 1c) and has the advantage of a clearly lower U_{dc} (see Fig. 2). Chapter 3 deals with this type of inverter, which has been proposed further in [2] and [3].

2. Single-phase, three level VSI

Due to the low forward voltage drop, an approach using MCTs is shown in figure 3. During normal operation, the control enforces the fundamental waves of U_O and I_O to be in phase. In this case, the MCTs T_2 and T_3 are not pulsed, they merely perform zero current switching at line frequency, so their switching losses should be neglectable. For the MCTs T_1 and T_4 a low loss snubbers are used. In the paper, the simulated behaviour of this converter will be discussed.

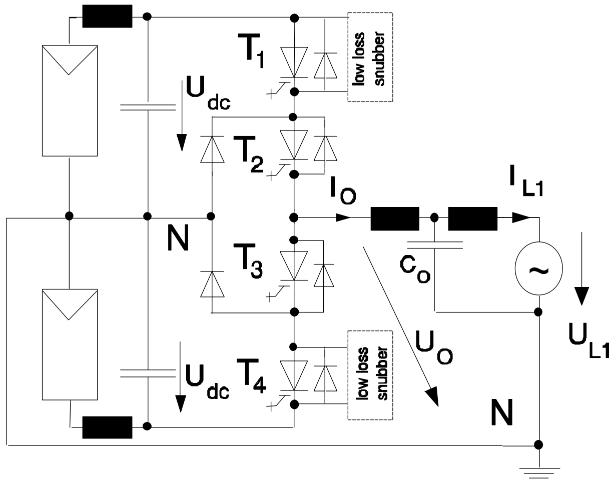

Fig. 3: Single-phase three-level VSI

3. Three-phase CSI

Figure 4 outlines the investigated system. The power circuit consists of the solar array, the dc-filter, the inverter followed by the ac-filters and finally the utility grid. Because of reverse blocking requirements one switch of the CSI is made up by an IGBT and a series-connected diode.

3.1 Control

Figure 5 shows a simplified structure of the controlled system. According to figure 4, models of the solar array, the dc-filter, the inverter and the ac-filter are shown. All non-linear parts of the system (i.e. the inverter and solar array) are linearized to design the controller. The non-linear behaviour of the solar array is approximated by using a voltage source with internal resistance (R_{sol}). The non-linear transfer function of the inverter (i.e. $I_{0d} = I_{dc}\, k_d$) must be reduced to (i.e. $\Delta I_{0d} = \Delta I_{dc}\, k_{d0} + I_{dc0}\, \Delta k_d$).

Figure 6 shows influence of the varying operation conditions (weather) on the parameters of the controlled system assuming the system operating at the Maximum Power Point of the PV-generator . It is obvious that especially the rising of the internal resistance of the solar array (R_{sol}) reduces the damping of the dc-filter.

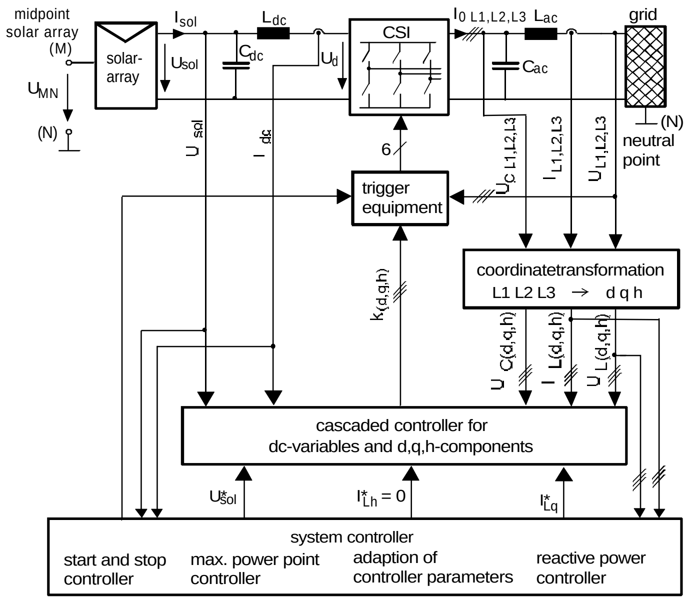

Fig. 4: Main structure of the PV-system (incl. CSI)

<u>Cascaded control structure</u>:The ac-signals are transformed into a rotating d-q-coordinate system, where the d-axis is oriented at the line voltage (Eq= 0; I_{ld} and I_{lq} causing active and reactive power respectively).

The control system includes six cascaded controllers one for each state variable.(U_{Cd}, U_{Cq}, I_{Ld}, I_{Lq}, I_{dc} and U_{sol}). The solar array voltage is controlled by the outermost control loop. The setpoint value of this loop is given by the Maximum Power Point Controller. Next I_{Ld} is controlled, which represents the active current into the grid. The reactive power is controlled by the I_{lq}-controller. The manipulated variable of the innermost control loop k_d and k_q are connected to the trigger equipment.

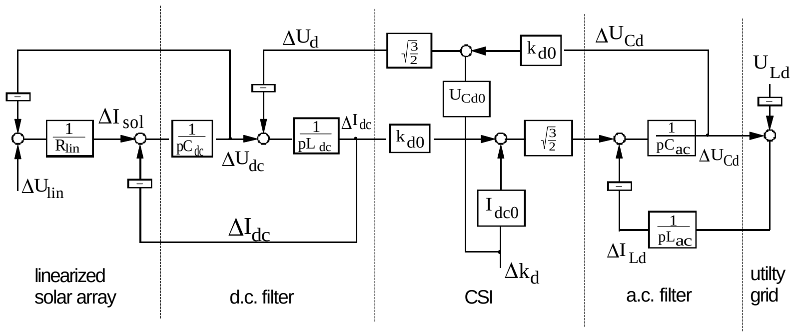

Fig. 5: Simplified controlled system

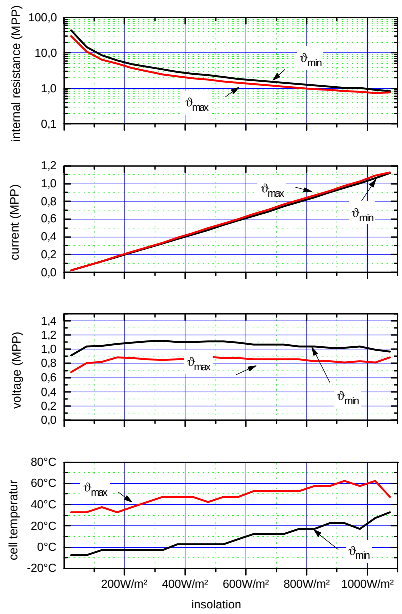

Fig. 6: Parameters of a solar array depending on insolation and temperature (rated at 1kw/m^2 and 25°C)

3.2 Control method to reduce I_{CN}

The PWM-unit contains a conventional pulse with modulator described in [4]. The step-up operation of the CSI is performed by bypassing the direct current i_{DC} through a freewheeling arm. One out of the three possible freewheeling arms has to be selected. Assuming the capacitance C_N between PV-generator and ground to be zero, two methods for this selection are compared in Figure 7 (using a reduced modulating frequency):

a) A conventional selection resulting in minimal switching frequency (MSF, dotted line) gives a high voltage U_{MN} between the midpoint of the solar array and ground

b) Selection of the phase with the instantaneous voltage closest to zero (SCZ, solid line) gives a much lower voltage U_{MN} .

Figure 8 shows simulated results for both methods, where C_N is assumed from a plate-type capacitor model. It is obvious, that minimal switching frequency (MSF) produces unacceptable high values of U_{MN} and I_{CN} , whereas selection of the phase with the instantaneous voltage closest to zero (SCZ) reduces U_{MN} and I_{CN} to a well-tolerable level.

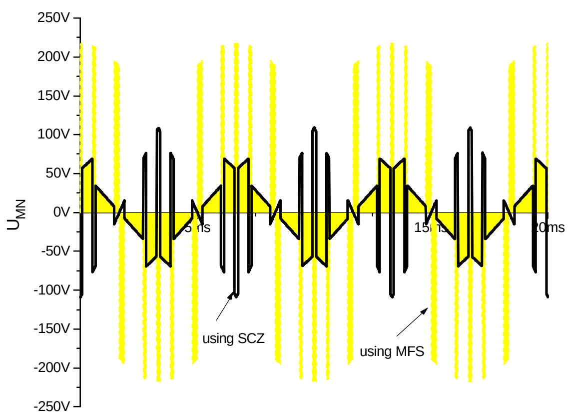

Fig. 7: Influence of freewheeling arm selection on the voltage U_{MN}

4. References

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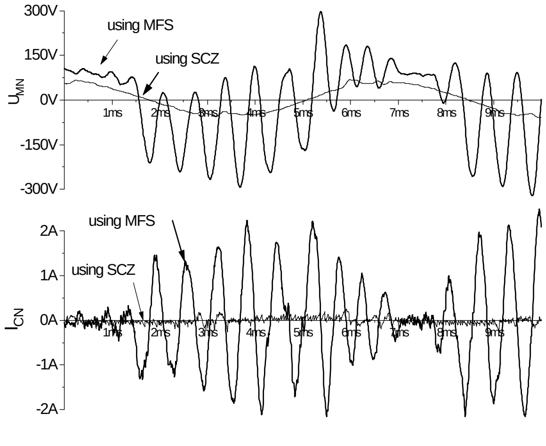

Fig. 8: Current and voltage at the capacitance C_N between PV-generator and ground