# Voltage Source Inverters for Grid Connected Photovoltaic Systems

Hinz, H.; Mutschler, P.
Darmstadt University of Technology,
Institute for Power Electronics and Drives
Landgraf-Georg Straße 4 D-64283 Darmstadt
Tel.: +49-6151-162166 Fax: +49-6151-162613
email: hhinz@srt.tu-darmstadt.de pmu@srt.tu-darmstadt.de

ABSTRACT: This paper describes a novel concept of an inverter for grid connected photovoltaic arrays. It is shown that the use of a three level voltage source inverter without transformer is a reasonable solution for the input to grid in the lower power range (< 5kW). The structure of the photovoltaic power system is presented. Each component of the system will be discussed in detail. The demands of photovoltaic inverters and special design procedures are presented. Simulation results demonstrate the suitability of the suggested solution for a grid connected photovoltaic system which is currently under development.
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## 1. INTRODUCTION

In photovoltaic applications the grid interface between source (solar array) and load (utility grid) consists of the inverter. To maximize the system efficiency the inverter must be optimized in design and control. For a 2.5kW photovoltaic power system a single phase voltage source inverter is developed which requires only a minimum number of components.

Most commercial inverters for photovoltaic applications include a transformer and several sections of power conversion ([1],[2]). To reduce the degree of complexity it is proposed to omit the transformer and to use only one section of power conversion. Thereby system losses, size and costs decrease.

## 2. PHOTOVOLTAIC INVERTER

Fig. 1 shows the main structure of the photovoltaic system, which consists of the solar array, transformerless inverter, ac-filter and utility grid (line). The renunciation of the transformer brings up fundamental characteristics:

1. There exists a galvanic connection between solar array and grid. This admits a leakage current through the parasitic capacitance between solar array and ground ([3]), if the mid-point of the solar array is not connected to ground. Thereby the voltage between array and ground may heavily oscillate and exceed acceptable levels (over 1000V, [4]).

2. By the mode of operation of a voltage source inverter (step down), the solar array voltage is not free eligible. To guarantee the operation for various environmental conditions the right number of series connected solar modules has to be selected. In the worst case (high temperature) the array voltage must always exceed the amplitude of the line voltage. If a string of the solar array is designed by this requirement the array voltage reaches high levels at low temperatures.

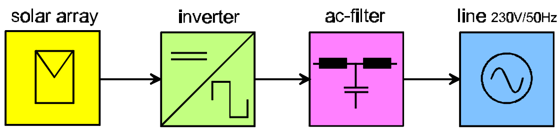


**Fig. 1:** Main structure of the PV-system

For this high dc-voltage the three level half bridge seems to be a promising approach for the transformerless inverter, since in the three level inverter each IGBT has to block only half of the voltage compared with a conventional two level inverter. Fig. 2 shows the structure of the investigated system. The solar array is splitted into two strings. The mid-point is connected to the ground, so that the described influence of the capacitance between solar array and ground will be eliminated. The relatively high levels of the array voltage are no problem for the power section using IGBTs with a blocking capability of *1200V*. Also the permissible array voltage of the applied modules (max *1000V*) will not be exceeded. For the investigated system one solar array consists of *25* series connected *55W* modules. For a low temperature of e.g. $\vartheta = -25°C$ the open-loop voltage of one module is approximately *28V*. So in the worst case (low temperatures) the maximum array voltage ($\approx 700V$) will always below the permissible value.

## 3. CONTROL

Fig. 2 shows the basic elements of the control-loop block which have been implemented in a digital signal processor (software).

3.1 AC-current control

For the inverter output current $I_0$ a hysteresis control with a variable hysteresis width is used. To supply a line current $I_{L1}$ with low distortion the connection to grid is

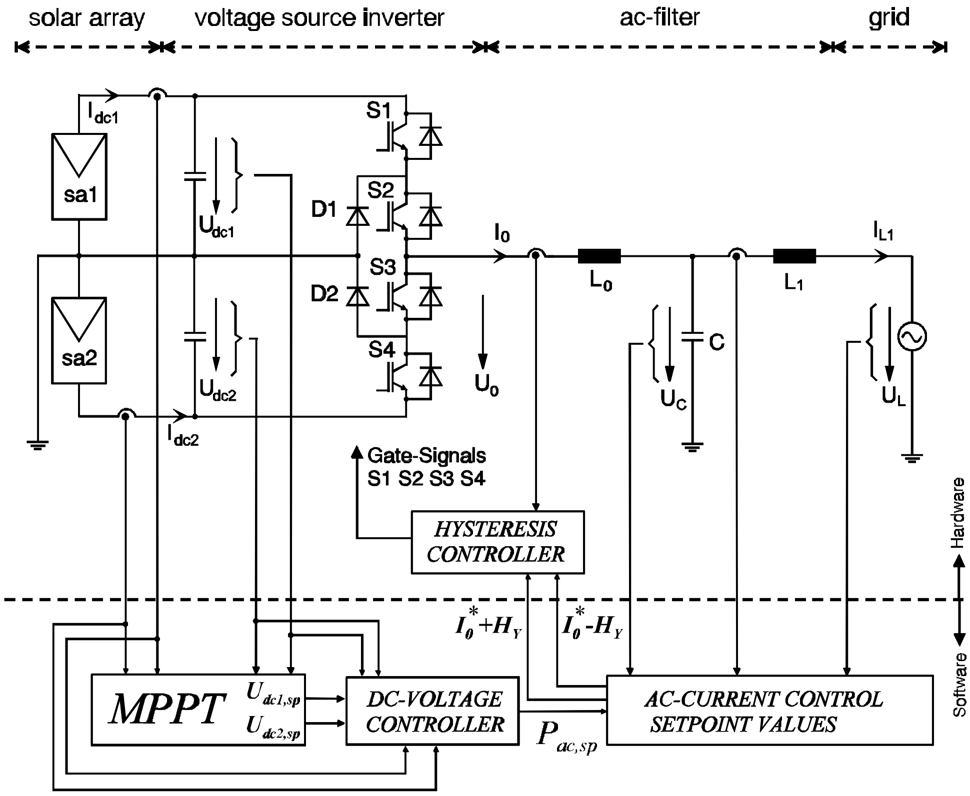


**Fig. 2:** Three level half bridge without transformer for grid connected pv-systems

made via an ac-filter, which consists of an L-C-L-combination. By a superimposed control of all state variables, described in [3], the ac-filter is actively damped. Fig. 3 shows the block diagram of the current control. The error of the instantaneous values of the state variables (filter capacitor voltage $u_C$ and the line current $i_{L1}$) and the calculated setpoints ($u_{C,sp}$, $i_{L1,sp}$) are fed back. The coefficients of the state feed back $r_C$, $r_L$ are determined by the selection of poles [3]. The switching thresholds $I_0^* \pm H_Y$ are generated by the DSP (see Fig. 2)

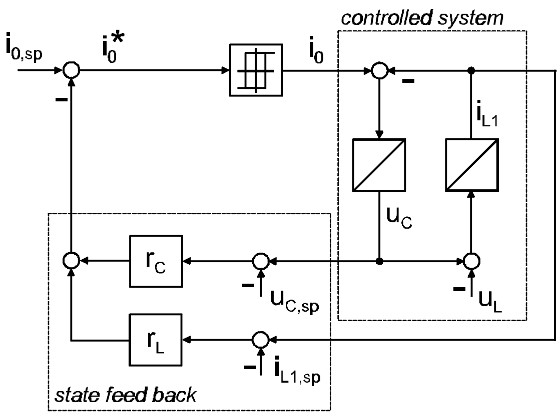


**Fig. 3:** Block diagram of the ac-current control

3.2 DC-voltage control

To achieve a steady-state operation the available dc-power $P_{dc}$ supplied by the solar arrays and the ac-power $P_{ac}$ fed into the grid must be balanced. The available dc-power depends on the environmental conditions (temperature and insolation) and the array voltage. Fig. 4a) shows the power voltage characteristic of one solar array. The inverter should always operate in the MPP to maximize the efficiency. To find the Maximum Power Point for all conditions a tracking method is used, which is based on the fact that in a single phase system the instant power oscillates with twice the line frequency ($f_l=50Hz$). This oscillation in ac-power also leads to a *100Hz* ripple in the dc-voltage and dc-power.

It can be observed that operating in area *I* (left side of the MPP) the power voltage slope is positive ($dP_{dc}/dU_{dc}>0$), operating in area *III* the slope is negative ($dP_{dc}/dU_{dc}<0$). This leads to a fixed phase relationship between the array voltage and output power as shown in Fig. 4b). Operating in area *III* the voltage maximum and power minimum occurs at the same time (phase opposition), operating in area *I* the maximum of voltage and power occurs at the same time (in phase). If the system operates in the area around the MPP, the ripple of the dc-power is minimized. This features can be used to detect in which part of the power-voltage characteristics the system operates. The MPPT adjusts the array voltage by a secondary dc-voltage controller to track the load (grid connected inverter) towards the MPP.

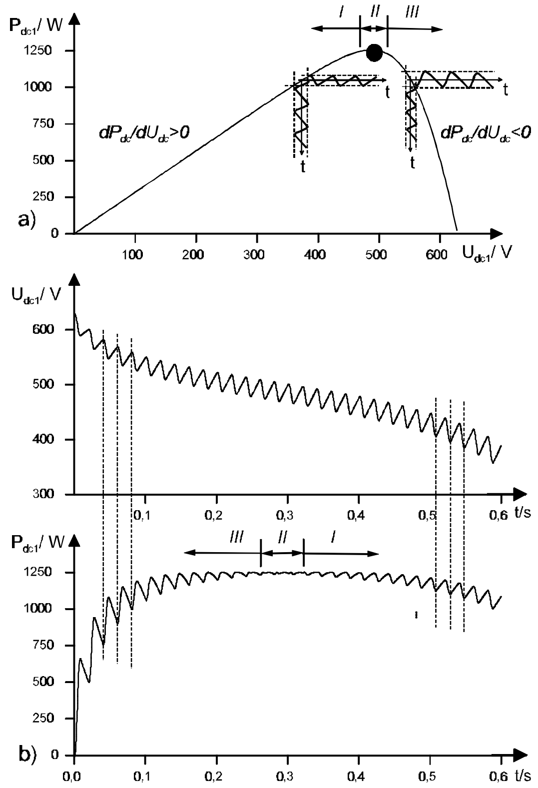


**Fig. 4:** Principle of the MPPT

# 4. SYSTEM OPTIMIZATION

As mentioned above a sinusoidal line current with low distortion should be supplied. In the grid connected application it must be considered that the system perturbation must be limited according international standards (EN 60555-2, DIN VDE 0875 T1). The harmonic components of the line current depends on the choice of switching frequency and ac-filter elements. To maximize the efficiency of the system an optimization procedure as described in [5] has been used.
The goal is to find the ac-filter elements and switching frequency at which the harmonic components can be limited and the overall inverter losses can be minimized. To estimate the inverter losses which consists of the IGBT- (switching and conducting losses) and filter-losses, approximation formula have been employed. Calculating pv-inverter losses it must be considered that the supplied solar array power is not constant. It depends on the temperature and insolation and is extremely variable for diverse operating points in one year. Thereby appearing losses are variable too. To find the right parameters a typically, yearly energy production of the location of the inverter (Germany) has been considered.
Fig. 5 shows the calculated efficiency of the inverter for various switching frequencies (*$f_S$=4...24kHz*) and filter inductors (*$L_0$=1...5mH*). A maximum efficiency can be achieved by using a switching frequency of *$f_S$»6kHz* and filter elements *$L_0$=4mH*, *$L_1$=3.1mH* and *C=23mF*. With

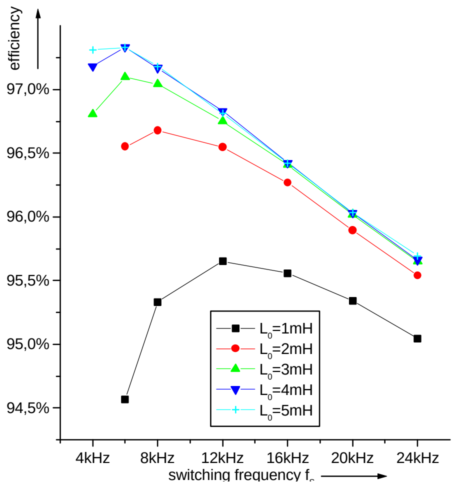


**Fig. 5:** System optimization

this parameters in theory over *97.3%* of the solar arrays annual energy can be fed into the utility grid.

# 5. RESULTS

5.1 Maximum Power Point Tracking
To demonstrate the dynamic behaviour of the photovoltaic system using the described MPPT an unrealistic abrupt change of temperature was simulated. Fig. 6 shows the simulation results of the system operating at a constant insolation of *E=1000W/*m$^2$ and a change of temperature from *$J_1$=25°C* to *$J_2$=15°C* at *t=0.6s*. It is assumed that both solar arrays have the same environmental conditions. Fig. 6b) shows the two p-u-characteristics of one solar array *sa1* valid for the chosen temperatures before (*$J_1$*) and after (*$J_2$*) the change. In Fig. 6a) (zoom of Fig. 6b) ) the crosses display the change of the mean power $P_{dc1,m}$ supplied by *sa1* at each operating point. The simulation starts in area *III*. The MPPT reduces the setpoint of the array voltage *$U_{dc1,sp}$* by a value of *DU =1V*. In this situation the setpoint *$U_{dc1,sp}$* is lower than the mean value *$U_{dc1,m}$*. The dc-voltage controller increases the setpoint of the ac-power *$P_{dc,sp}$*. This leads to a continuously discharge of the dc-link capacitor until the system reaches area *II* (*t@0.4s*). In *II* the setpoint is given by *$U_{dc1,sp}$=$U_{dc1,m}$*. Under steady state conditions the voltage in the MPP is not found precisely, because in reality measurement errors occur.
At *t=0.6s* the abrupt rise of temperature occurs. Now the system operates in area *I* (Fig. 6a) curve *$J_2$*). The MPPT increases the setpoint of the array voltage *$U_{dc1,sp}$* by *DU*. For the new temperature *$J_2$* the supplied power of array *sa1* is higher than for *$J_1$* (Fig. 6a). The setpoint of the ac-power *$P_{ac,sp}$* changes only slightly. Until *t@0.85s* the supplied dc-power of the solar arrays is higher than the ac-power fed into the grid. The resulting excess energy charges the dc-link capacitor until the new MPP is found at *t@1s*. This simulation shows that the dc-voltage controller is capable to track the load by an abrupt change of temperature, which results in a visible variation of the MPP-voltage. In reality only the insolation can change

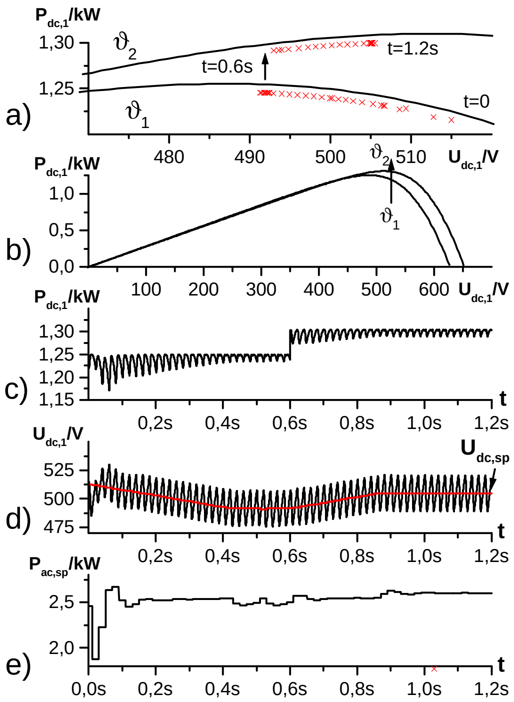


**Fig. 6:** Maximum Power Point Tracking

suddenly (caused by passing clouds). In this case the MPP-voltage varies only slightly. The suggested method stands out for its good control response and an accurate tracking without a periodically (forced) variation of the array voltage compared to the conventional perturb and observe method. Thereby a superfluous power swing can be avoided. The tracking algorithm and dc-voltage controller can be easily implemented in a μ-controller which is required for the ac-current control anyway.

5.2 Current control

Fig. 7 shows the simulation results of the inverter using the described ac-current control. In the simulation an ideal sinusoidal line voltage $u_L$ was assumed. The power was set to $P=2{,}5kW=P_N$ at $\cos j=1$, for the filter elements and switching frequency the optimized parameters were chosen. By the hysteresis control of the inverter output current $I_0$ a sinusoidal line current $I_{L1}$ can be fed into the grid. The filter capacitor voltage $u_C$ is almost sinusoidal. The inverter has been realised with the

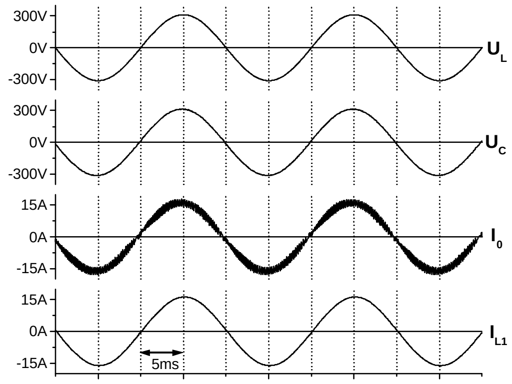


**Fig.7:** Simulation results

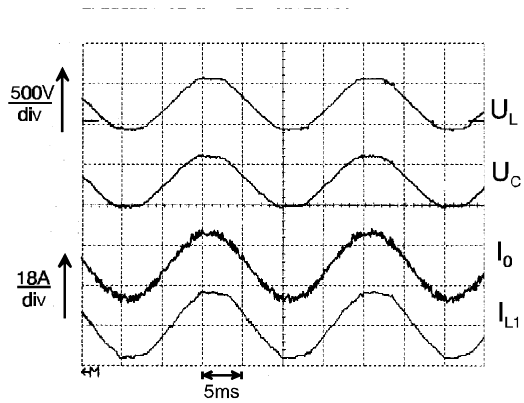


**Fig.8:** Experimental results

optimized filter elements. In a first step of experimental analyses the dc-link is supplied by two line-commutated rectifiers. The inverter is connected to a *230V,50Hz* grid. Fig 8 shows the experimental results for a net input of $P=2.5kW$ at $\cos j=1$. The dc-link voltage (mean value, *index m*) was set to $U_{dc1,m}=U_{dc2,m}=435V$. This value corresponds to the MPP-voltage of one solar array operating at the nominal power point.

## 6. CONCLUSION

A concept of an inverter without transformer for grid connected photovoltaic systems has been presented. Using a three level half bridge parasitic capacitance between solar array and ground can be eliminated and tolerable levels of blocking voltage of IGBTs can be achieved. A suited control has been developed. An optimization procedure results in an optimal combination of switching frequency and filter elements to minimize inverter losses.

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