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POWER CONVERSION SYSTEMS DC-DC; AC-DC; AC-AC; UPS

Control of a single phase three level voltage source inverter for grid connected photovoltaic systems

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Abstract:

An improved approach for grid connected photovoltaic systems is the application of inverter without transformers. The single phase three level half bridge is a reasonable solution for systems in the lower power range. To achieve a steady state operation the control of the dc-side (solar array) and the ac-side (utility grid) is required. This paper describes the control strategy of the transformerless photovoltaic inverter.
The maximum available power of the solar modules depends on insolation and temperature. To operate the system at the maximum power point, a suited tracking method is applied. This method depends on the fact, that in a single phase system the instant power oscillates with twice the line frequency. This oscillation in ac-power also leads to a 100 Hz ripple in the dc-voltage and dc-power. The maximum power tracking is based on the analyses of the phase relationship between the oscillation in the dc-voltage and dc-power.
To supply a sinusoidal line current with low distortion the connection of the inverter to the utility grid is made via an ac-filter which consists of an L-C-L combination. For the inverter output current a hysteresis controller with a variable hysteresis width is used. Additionally the state variables of the filter are fed back by a superimposed state variable controller to achieve an actively damped filter.
The final paper explains the control method and discusses simulation and experimental results.

Introduction

As state of the art, most commercial inverters for grid connected photovoltaic systems include a transformer and several sections of power conversion [1]. To improve existing systems it is proposed to omit the transformer and to use only one section of power conversion.

Using transformerless inverters for the grid connection, parasitic capacitance between solar array and ground can lead to oscillations of the array voltage and leakage current. This impairs the system performance; leakage currents distort the line current and array voltages exceed permissible levels. The influence of the capacitance can be eliminated, if the mid-point of the dc-link can be connected to the ground. For that reason the three level half bridge is a reasonable solution for the transformerless grid connection, since in the three level inverter each IGBT has to block only half of the voltage compared to the conventional two level half bridge.

Photovoltaic power system

Fig. 1 shows the main structure of the investigated photovoltaic system with a nominal power of *2.5kW*. The solar arrays are split into two strings, the mid-point is connected to the ground. The three level half bridge is realized by series arranged IGBTs. The connection to the utility grid is made by an L-C-L-filter to reduce system perturbation.

Fig. 1 shows also the basic elements of the control-loop block. The Maximum Power Point Tracker (MPPT) has the duty to find the MPP for all environmental conditions. The array voltage is adjusted by a secondary dc-voltage controller.

For the inverter output current a hysteresis control is used. To damp the ac-filter actively a superimposed state feed back controller is applied. The setpoint values of the ac-variables are determined suited to the available dc-power of both arrays ($P_{dc1} + P_{dc2} = P_{ac}$).

MPPT and dc-voltage control

The output power P_{dc} of the solar arrays varies with the temperature ϑ and insolation E as shown in Fig. 2 (power voltage characteristics of one solar array with a nominal power of 1.25kW for various temperatures and insolations); The MPP tracking method is based on the fact, that in a single phase system the instant power oscillates with twice the line frequency. This oscillation in ac-power also leads to a 100Hz ripple in the dc-voltage and dc-power. The maximum power point tracking uses an analyses

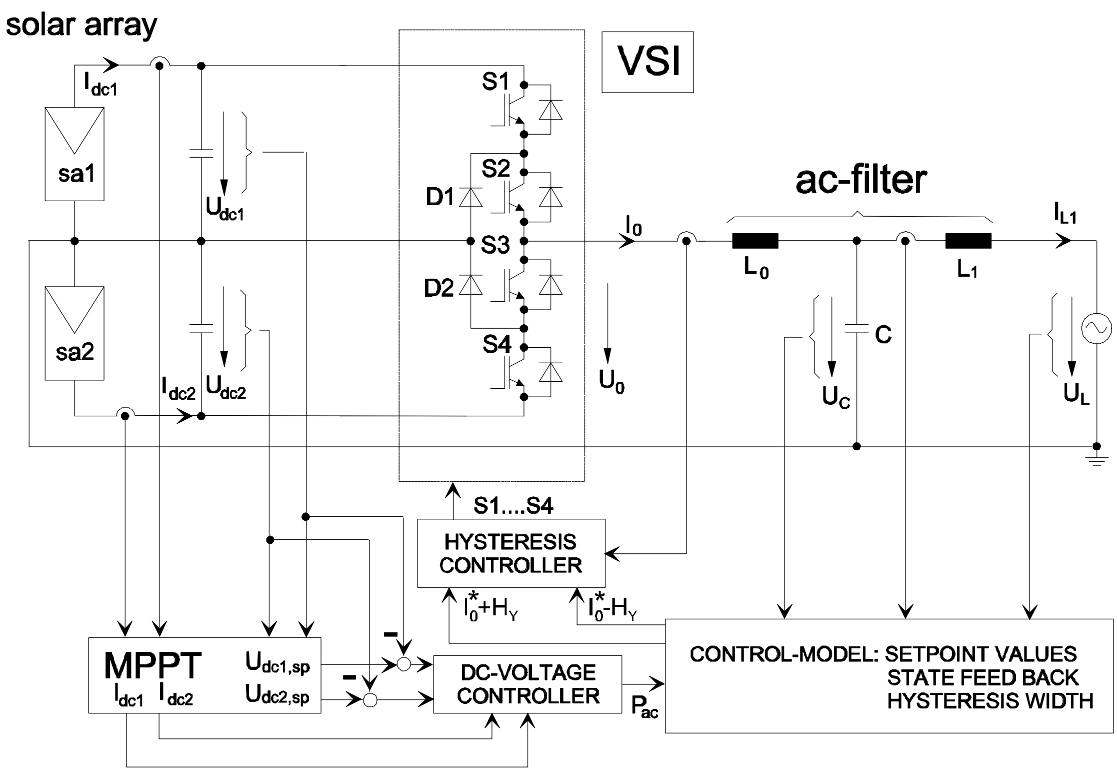

Fig. 1: Main structure of the photovoltaic system

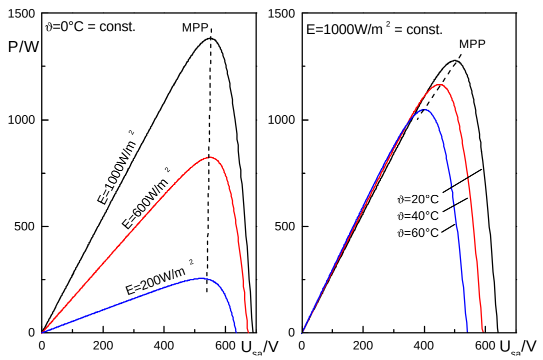

Fig. 2: Power-voltage characterisitcs

of the phase relationship between the oscillation in the dc-voltage and dc-power to track the MPP, as proposed in [2]. To find the MPP for all environmental conditions, the algorithm of the applied MPPT uses the power-voltage gradient dP_{dc}/dU_{dc} of the characteristics in Fig. 3a). Operating on the left side of the MPP (area *I*) the gradient is positive. This leads to an „in phase" condition of the array voltage U_{dc1} and power P_{dc1}: the maximum of U_{dc1} and P_{dc1} occurs at the same time. Operating on the right side of MPP (area *III*) the gradient is negative; this leads to a phase opposition; the maximum of U_{dc1} and minimum of P_{dc1} occurs at the same time. Operating around the MPP (area *II*) the ripple of the array power is minimised (Fig. 3 shows the waveforms of one array, the same characteristics can be observed for the other array just shifted by $T_{line}/2= 10ms$). This

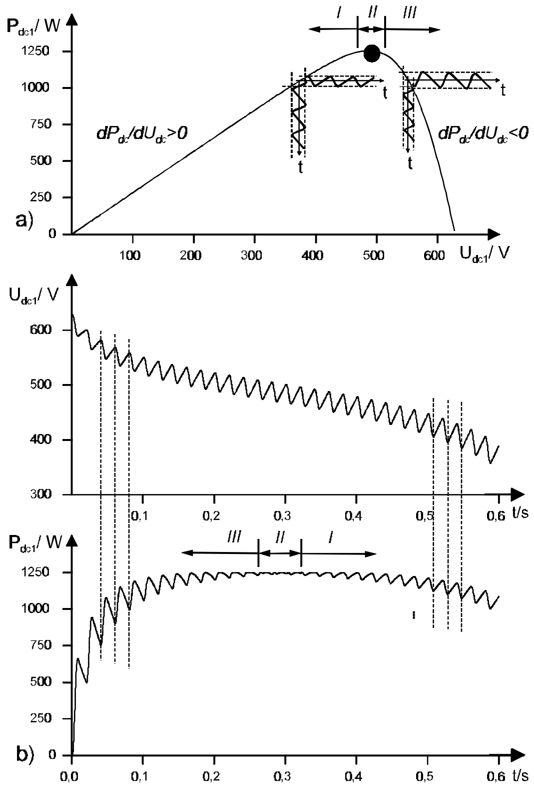

Fig. 3: Principle of the MPPT

features can be used to detect in which part of the power voltage characteristics the system operates and which actions must be taken by the MPPT. In the case of the voltage source inverter operating points can be set by controlling the dc-voltage U_{dc}. The MPPT gives the set point of the array voltage $U_{dc,sp}$ to the secondary dc-voltage controller (see Fig. 2) which consists of a proportional controller and a feedforward control of the array current I_{dc}. In the case of the three level half bridge the dc-voltage of both solar arrays must be controlled. To achieve steady state operation the supplied dc-power of the solar arrays and the ac-power fed into the utility grid must be balanced. The dc-voltage controller gives the setpoint of the ac-power to the control model where the setpoints of the filter-variables are determined.

The final paper will present more details of the dc-voltage controller and MPPT as well as simulation results.

Current control and state feed back

To supply a sinusoidal line current the connection to the utility grid is made via an L-C-L-filter.

For the inverter output current a hysteresis control is used. Good results are obtained by using an almost constant switching frequency. This can be easily achieved by an open loop control of the hysteresis width, which dependes on the dc-link voltage U_{dc} and filter-capacitor voltage u_C , the inverter-side filter inductor L_0 and the required value of the switching frequency f_S :

$$H_y = |u_C| \frac{U_{dc} - |u_C|}{f_S \, L_0 \, U_{dc}}$$

Additionally the ac-filter is actively damped by a superimposed control of the state variables. In the case of the hysteresis control of i_0 the inverter output current is impressed into the filter. For that reason the state variables fed back are the line current i_{L1} and the filter-capacitor voltage u_C :

$$\dot{\underline{x}} = \underline{A}\,\underline{x} - \underline{B}\,\underline{R}\,\underline{x}$$

with $\quad \underline{x} = \begin{pmatrix} i_{L1} \\ u_C \end{pmatrix} \qquad \underline{A} = \begin{pmatrix} 0 & \frac{1}{L_1} \\ -\frac{1}{C} & 0 \end{pmatrix}$

$$\underline{B} = \begin{pmatrix} 0 \\ \frac{1}{C} \end{pmatrix} \qquad \underline{R} = (\, r_L \;\; r_C \,)$$

The controller matrix $\underline{R}$ can be determined by the selection of the poles; using a real double pole the solution of the characteristic polynominal will give equations for the coefficients of the state feedback:

$$det[\, s\underline{I} - (\, \underline{A} - \underline{B}\,\underline{R} \,)\,] = (\, s - l_{12} \,)^2$$

$$\Rightarrow \;\; r_C = -\, l_{12}\, 2\, C \qquad r_L = l_{12}^2 L_1\, C - 1$$

Fig. 4 shows the block diagram of the state feed back with the secondary hysteresis control of the inverter output current i_0 . Under steady state conditions the state controller expects constant

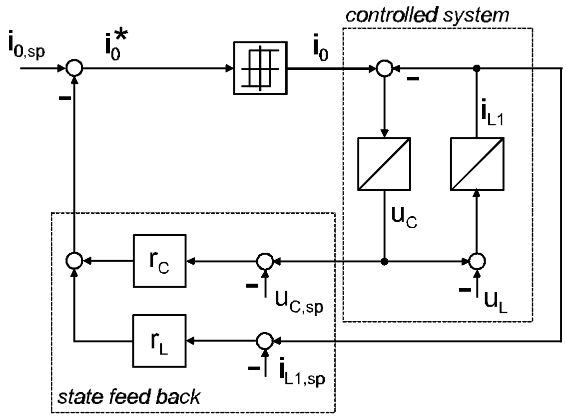

Fig. 4: Block diagram of the state fed back

values of the state variables; in the case of the filter they are sinusoidal. For that reason the setpoint values of the filter-capacitor voltage $u_{C,sp}$ and the line current $i_{L1,sp}$ are subtracted. Fig. 5 shows simulation results of the inverter operating at the nominal power point of $2.5kW$. The switching frequency was set to $f_S = 6kHz$ the filter elements to $L_0 = 4mH$, $L_1 = 3.1mH$ and $C = 23mF$, these parameters are the results of an optimising procedure described in [3] at which the efficiency of the inverter can be maximised. Fig. 5 shows the instantaneous switching frequency f_S and hysteresis width H_Y , the out and inner IGBT currents (I_{S1}, I_{S4} *and* I_{S2}, I_{S3}) the hysteresis controlled inverter output current I_0 and the sinusoidal line current I_{L1} . In the shown situation the fundamental waves of the inverter output I_0 current and voltage U_0 are controlled to be in phase, so that the two inner IGBTs are only switched at the fundamental

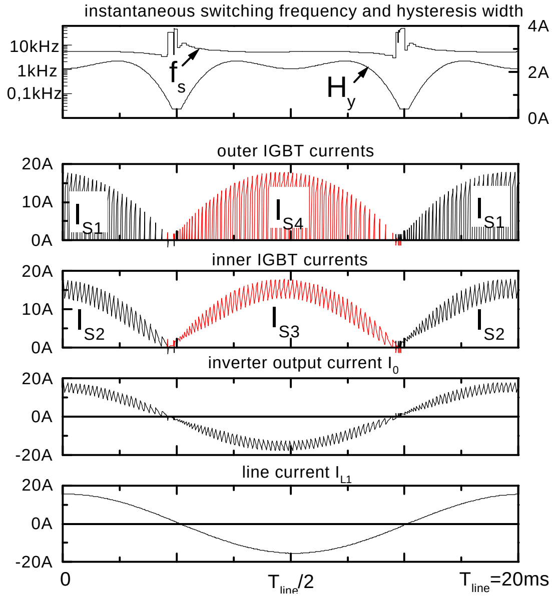

Fig. 5: Simulation results

frequency. By this strategy inverter losses can be reduced.

In the final paper the current control will be presented in detail as well as the practical realisation and experimental results.

Conclusion

For grid connected photovoltaic systems the control of a single phase three level inverter without transformer has been presented. A maximum power point tracker in combination with a dc-voltage controller has been developed to operate the system at the MPP for all environmental conditions. A sinusoidal line current can be supplied by using a hysteresis controller which operates with an almost constant switching frequency. The ac-filter is actively damped by a superimposed state controller.

Literature

[1] Steigerwald, R. et. al.: Investigations of a family of power conditioners into utility grid, SAND, 81-7031, 1981

[2] Avril, J.: Untersuchungen zur Betriebs-optimierung eines einphasigen Pulswechselrichters für Photovoltaikanlagen im Netzparallelbetrieb, Thesis Hagen 1994

[3] Hinz, H.: How to choose switching frequency and filter elements for a maximum efficiency photovoltaic inverter, PCIM 1997 pp 429-438