Title: HOW TO CHOOSE SWITCHING FREQUENCY AND FILTER-ELEMENTS FOR A MAXIMUM EFFICIENCY PHOTOVOLTAIC INVERTER

Author: Hinz, H.
Affiliation: Technical University of Darmstadt, Institute for Power Electronics and Drives
Landgraf-Georg Straße 4 D-64283 Darmstadt
Tel.:+49-6151-162166 Fax:+49-6151-162613 Email:hhinz@srt.th-darmstadt.de

Abstract: This paper describes a system optimization of an inverter topology without transformer for grid connected photovoltaic power systems. To reduce basic losses, costs and size, the transformer, in conventional inverter concepts functionally indispensable, can be omitted. With respect to a tolerable level of the solar array dc-voltage, the single-phase three level voltage source inverter seems to be a promising approach to the input to grid below 5kW. For the operation in parallel to the mains a suited control strategy including a maximum power point tracker was developed. The presented optimization deals with the design of the ac-filter and the selection of the switching frequency of the inverter for a nominal power of 2.5 kW. In consideration of the individual characteristics of photovoltaic systems (high efficiency over a wide output power range) and the demands of grid connection (sinusoidal line current with low distortion) it is shown that the resulting inverter losses (switching and filter losses) can be reduced by choosing optimized filter eliments and proper switching frequency. Thereby the annual energy fed into the utility grid can be maximized.

Introduction

Most commercial inverters for photovoltaic applications include a transformer ([1],[2]). In principle, there is no compulsion to use a transformer. Concerning safety requirements the renunciation of the transformer is allowable, because the solar cells are isolated in the solar moduls and the metalic frames of these modelus are grounded. Basically, for grid connection without transformer a three-phase current source inverter can be used as described in [3], for power levels below 5 kW a single phase voltage source inverter (VSI) is suitable as described in [4].

Developing conventional power conversion systems the control strategy, switching frequency and filter elements are selected to ensure the desired behaviour, but inverter and filter losses are left out of consideration. These systems operate mainly at a nominal power value. Beside the operational reliability for photovoltaic systems a high efficiency is desirable over a wide output power range. To maximize the annual energy fed into the utility grid, it is profitable to optimize the filter design and switching frequency with regard to total inverter losses. This paper describesthe design procedure to obtain optimized filter elements and switching frequency for a photovoltaic VSI with a nominal power of 2.5 kW.

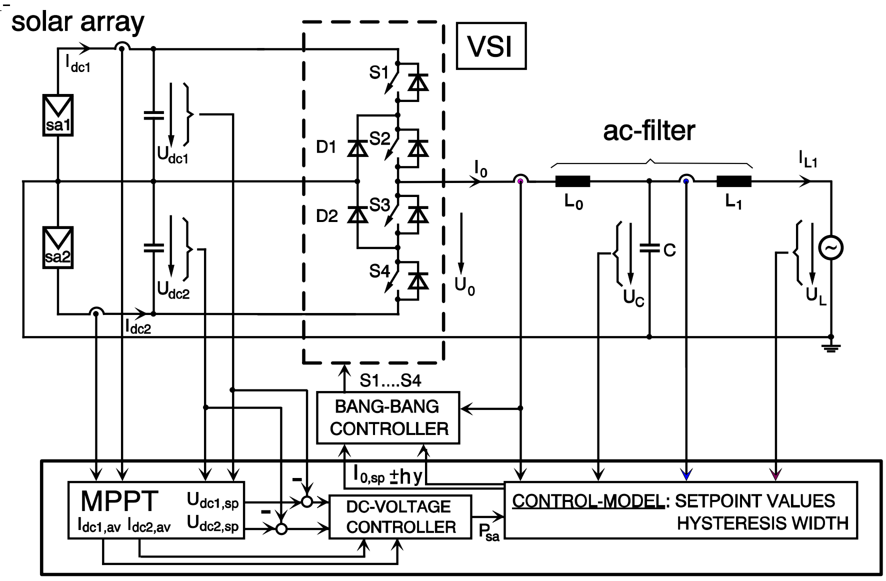

Fig. 1: Main structure of the photovoltaic system

Control of the VSI

Fig. 1 shows the investigated system. Two solar arrays and energy storage capacitors form the dc link for the single phase three level VSI with series connected switches. The connection to the utility grid is made by an ac-filter which consists of a L-C-L combination. To supply a sinwave line current I_{L1} a bang-bang control of the inverter output current is used. Good results are obtained by using a nearly constant switching frequency. This requires a variable hysteresis width H_y which depends on the filter inductance L_0, solar array voltage U_{dc}, the desired switching frequency f_s and the filter capacitor voltage u_C. The hysteresis width and the error of the inverter output current are given by the control model. The setpoint value of the inverter output current I_0 is given by a controller with state feedback to improve the dynamic behaviour. To ensure an adaption of power the control model determines the setpoint values suited to the available dc-power which is given by the dc-voltage controller. This controller is subordinated the maximum power point tracker (MPPT). The task of this tracker is to find the MPP for current environmental conditions [4].

Fig. 2 illustrates simulation results of the VSI operation at the nominal power point of 2.5kW. At output power ranges above 500W the two inner devices S2 and S3 operate under zero-current-switching at the line-frequency, if the fundamental wave of the inverter current I_0 and voltage U_0 are controlled to be in phase whereby switching losses decrease. The average switching frequency was set to $\overline{f}_s = 6kHz$, the filter elements were chosen to $L_0 = 4mH$, $L_1 = 3.1mH$ and $C = 25\mu F$. These parameters result from the optimiziation described next.

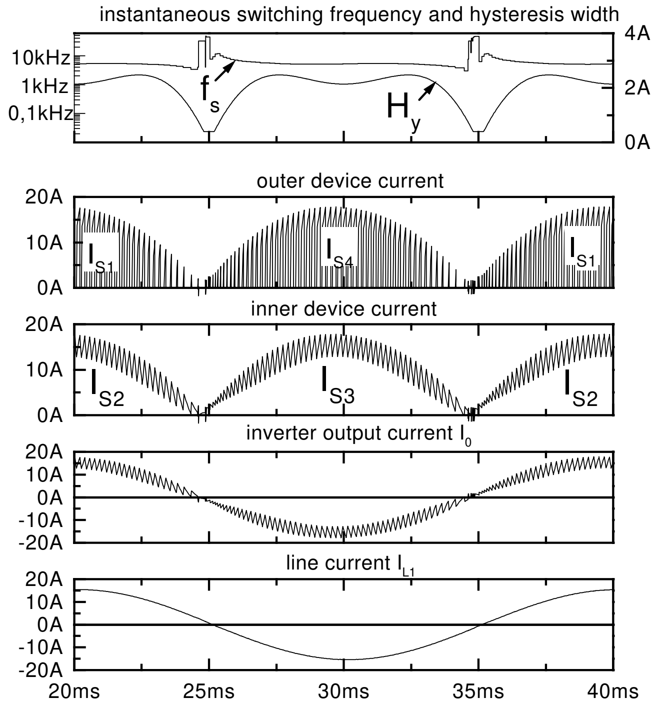

Fig. 2: Simulation results ot the three level VSI

AC-filter design

An essential aspect of the connection of the inverter to the mains is the adherence to permissible perturbation at each operating point of the photovoltaic system. Investigations show that the worst perturbation occurs at low out power levels. Fig. 3 shows the harmonic spectrum of the inverter output current I_0 produced by the bang-bang control for a minimal net input power of $P = 160W$. Designing the ac-filter international standards and VDE regulations have been followed. Fig. 3 shows the limits of system perturbation indicated in EN 60555-2 for frequencies below 2 kHz. For frequencies above 10 kHz VDE 0875 T1 has been taken into account. The conversion of the given radio interference voltages with the impedance of standard artificial mains network leads to limits for the harmonics of line current. For the remaining definition gap a linear extrapolation between 2 kHz and 10 kHz is choosen. In the case of the bang-bang control it is not possible to determine the harmonic spectrum of I_0 by mathematical methods. Therefore current waveforms need to be simulated and analysed by numerical methods. To establish the required filter elements for selected switching frequencies which limit system perturbation, the following procedure seems to be useful. The harmonic components of the inverter output current I_0 depends on the switching frequency and the inverter-side filter inductor L_0. Then I_0 is impressed into the ac-filter. The harmonic components of the line-current I_{L1} depends on the filter capacitor C and the line-side inductor L_1. For that reason in a first step the equivalent circuit as indicated in Fig. 4a) is valid, if a sinusoidal filter capacitor voltage u_C is assuemed. For a fixed switching frequency f_s and inverter-side inductor L_0 the harmonic components $I_{0,\nu}$ can be computed (Fig. 4b)). Assuming an impressed inverter current I_0 the equivalent circuit as shown in Fig. 4c) is valid. By the reduced transfer function of the filter $|F_{C,L1}(j\omega)| = 1/(1 - \omega^2 \cdot C \cdot L_1)$ the harmonic components of the line current $I_{L1,\nu}$ can be computed (Fig. 4d)). In this way filter elements C and L_1 can be varied to limit system perturbation.

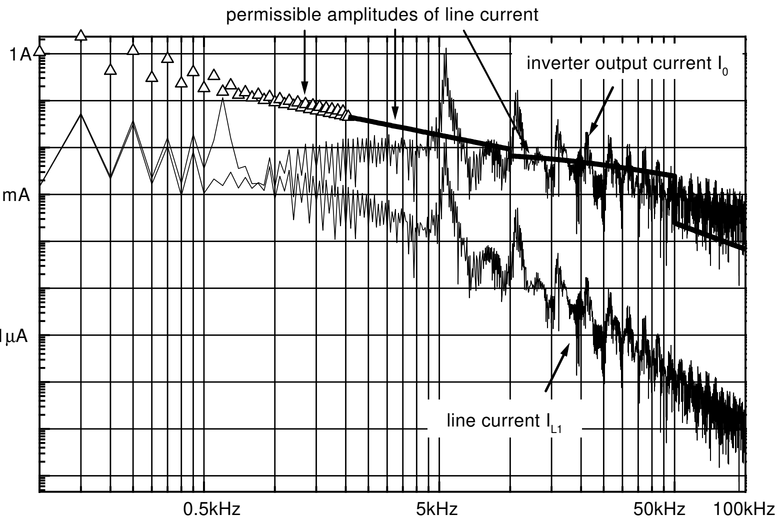

Fig. 3: Permissible emitted interference for line currents

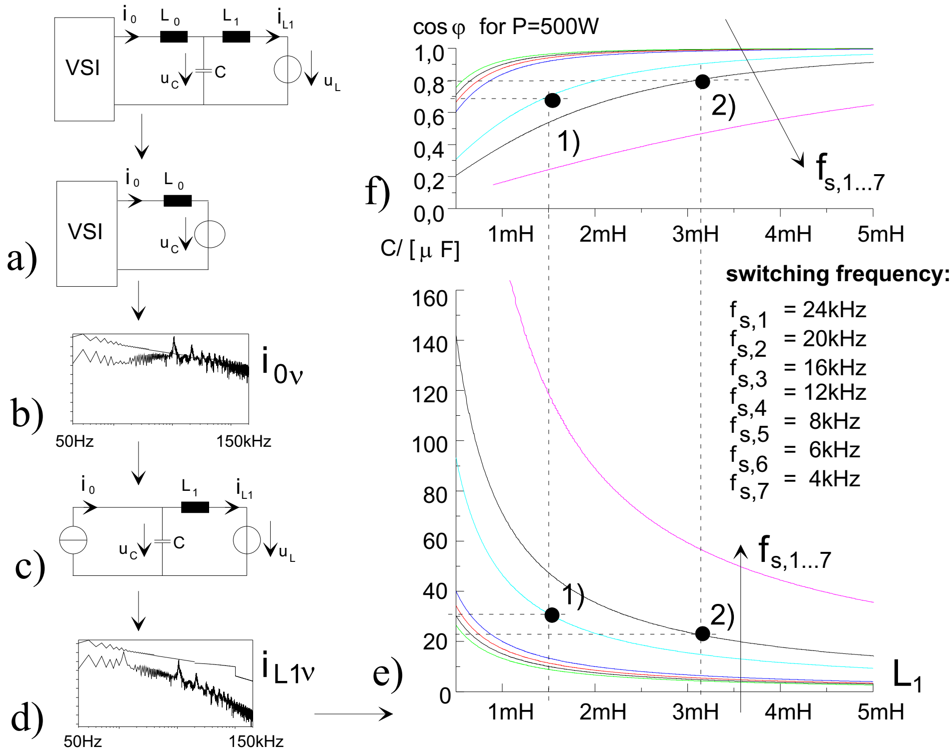

Fig. 4: AC-filter design procedure

As a result of this procedure characteristic curves as shown in Fig. 4e) are obtained. In this example for a fixed inverter-side inductor $L_0 = 4mH$ Fig. 4e) indicates how to choose the filter elements C and L_1 for different switching frequencies f_s. Designing the ac-filter it must be considered that $cos\varphi = 0.8$ is the minimum allowed power factor for feeding power into the public grid. Fig. 4f) shows the dependence of $cos\varphi$ of the filter inductor L_1 for constant power input to net of $P = 500W$. Using Fig. 4e) and f), for instance, following parameters can be found ($L_0 = 4mH = const.$): 1) $f_s = 8kHz$,$C = 31\mu F$ and $L_1 = 1.5mH$, $cos\varphi = 0.7$. To determine the filter elements definitly it is commited that C and L_1 have to choose so that the power factor will be $cos\varphi = 0.8$ at a power of $P = 500W$. In that case, for instance, following parameters can be found: 2) $f_s = 6kHz$, $C = 23\mu F$ and $L_1 = 3.1mH$, $cos\varphi = 0.8$. With this parameters the line current I_{L1} with a harmonic spectrum as shown in Fig. 3 can supplied into the utility grid. The described procedure has been executed for various values of L_0 so that in an inverter-side inductor range from $1mH$ up to $5mH$ and switching frequency range from $4kHz$ up to $24kHz$ all filter elements are calculated. In the next step device and filter losses has to be calculated to determine the efficiency of the photovoltaic inverter. To find the optimized switching frequency and filter elements, total losses must be calculated in consideration of the annual distribution of insulation and temperature. The full paper contains equations to estimate device and filter losses and describes the procedure to optimize the efficiency of the photovoltaic inverter in detail.

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