Solar Power Station Output Inverter Control Design

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Abstract. *The photovoltaic applications spreads in these days fast, therefore they also undergo great development. Because the amount of the energy obtained from the panel depends on the surrounding conditions, as intensity of the sun exposure or the temperature of the solar array, the converter must be connected to the panel output. The Solar system equipped with inverter can supply small loads like notebooks, mobile chargers etc. in the places where the supplying network is not present. Or the system can be used as a generator and it shall deliver energy to the supply network. Each type of the application has different requirements on the converter and its control algorithm. But for all of them the one thing is common – the maximal efficiency. The paper focuses on design and simulation of the low power inverter that acts as output part of the whole converter. In the paper the design of the control algorithm of the inverter for both types of inverter application – for islanding mode and for operation on the supply grid – is discussed. Attention is also paid to the design of the output filter that should reduce negative side effects of the converter on the supply network.*

Keywords

Voltage source inverter, L-C-L filter, hysteresis controller, PWM.

1. Introduction

Increasing efforts are being made nowadays to use renewable energy sources. Processing the energy obtained from sun, wind or water is coming to the fore. The energy supplied by these sources does not have constant values, but fluctuates according to the surrounding conditions (intensity of sun rays, water flow, etc.). These supplies are therefore supplemented by additional converters. The area of high power converters for solar application is already covered by industrial manufacturers. However, the area of low power devices is not fully covered. These converters are mostly assembled from commercially produced parts that can perform demanded functions, but they are not developed for this type of application and therefore the efficiency of the whole system is not maximal. Low power devices are important in applications where there is no voltage grid present and small amount of the electric power is required (mountains, desert expeditions, etc.)

The simplified block structure of the investigated system is shown in Fig. 1. A DC/DC converter with implemented an MPPT (Maximum Power Point Tracker) is connected to the solar array. A second DC/DC converter is connected to the output of this converter. The second converter raises the voltage acquired from the solar system to the voltage level demanded by the VSI.

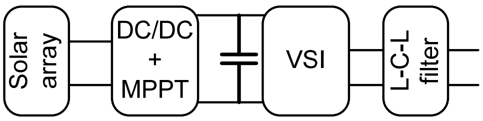

Fig. 1. Simplified block diagram of the system.

The voltage source inverter topology (VSI) is used for converting energy from DC to AC. The detailed scheme of the inverter is shown in Fig. 2. The inverter in this application can operate in two different modes. Firstly, it can operate in a so-called "island mode", which means that the converter acts as a voltage source and supplies some devices with sinusoidal voltage of the common network parameters. PWM control is used for this purpose. The second possible operation mode delivers current to the supply network. PWM control is not suitable for this operation mode and the current hysteresis control is therefore used. The L-C-L filter is connected to the output of the inverter. This filter ensures the sinusoidal shape of the output current.

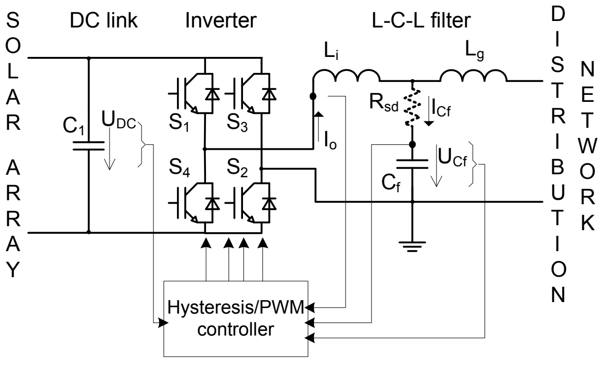

Fig. 2. Diagram of the investigated VSI.

The attenuation of the LCL-filter is 60dB/decade for frequencies above resonant frequency, therefore lower switching frequency for the converter can be used. It also provides better decoupling between the filter and the grid impedance and lower current ripple across the grid inductor. Therefore LCL – filter fits to our application. However it can bring also resonances and unstable states into the system. Therefore the filter must be designed precisely according to the parameters of the specific converter. Design of the filter is briefly described later in the article.

The different control algorithms require different information about input and output values. For the hysteresis controller information about input voltage and output current and the phase of the grid voltage is essential. The amplitude of the output current will be controlled so that the voltage on the input capacitor remains approximately constant. The output voltage amplitude will be held by the network. For the PWM controller demanded and actual value of the output voltage is important. The regulation difference is then processed in PI controller and output current is determined by the load.

2. Controller Design

2.1 PWM Controller

Hysteresis control cannot operate in “island mode”, because there is no supply network voltage that can guard the generated voltage. Then the converter is supposed to generate output voltage with a sinusoidal shape, as in the supply network. The PWM control algorithm was therefore used for “island mode”. The controller is shown in Fig. 3. The PI controller is used in the voltage control loop. The output of the controller is the duty cycle for the modulator.

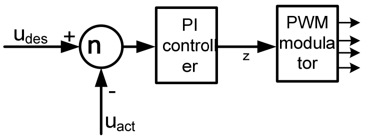

Fig. 3. PWM controller block diagram.

The modulator then operates in unipolar mode. That means three voltage levels are generated. The positive half wave of the generated voltage is produced by voltage levels +U_{DC} and 0, that means transistor S_1 is switched on and transistor S_2 is switching according to comparator output. Switching analogy with transistors S_4 and S_3 is used for negative voltage production.

2.2 Controller for Operation on the Supply Network

The converter in this operation mode is controlled to deliver current to the supply network. The task of the regulator is to assure the sinusoidal shape of the current. The PI regulator is not suitable for this mode, because it can bring oscillations to the system. Simple bang – bang controller is much more effective in this case. The controller holds current in defined area around reference sine waveform. The amplitude of the reference sine waveform and with it the amplitude of the output current is regulated to hold the power delivered to the DC- link from the solar panel and the power generated to the grid balanced. The hysteresis controller (Fig. 4) serves well for this purpose. The generated current tracks the reference signal well, but the shape of the current was notched. Problems also emerged near the moments where the reference crosses zero. The descent of the generated current was not so steep and the current does not cross the hysteresis boundaries.

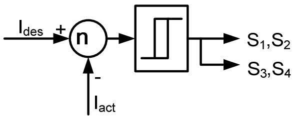

Fig. 4. Hysteresis controller.

The bipolar hysteresis controller was therefore adapted with the help of PWM modulator analogy to the unipolar – double hysteresis controller. It uses two hysteresis areas. The transistors S_1 and S_3 swap their states when the generated current reaches the outer hysteresis boundary. Transistors S_2 and S_4 are switched on/off according to the inner hysteresis area boundaries (see Fig. 5). Fig. 5 shows effects of the unipolar hysteresis control. Sine reference (brown) is enwrapped by two areas. The outer hysteresis (blue, green) waveforms, inner hysteresis (cyan, red) curves hold the output current (violet) in the desired area.

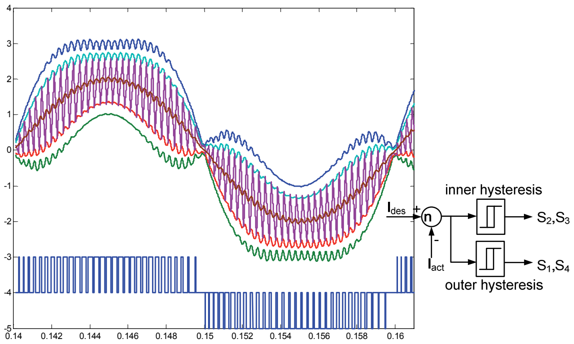

Fig. 5. Double hysteresis controller.

The other problem caused by the application of the hysteresis control is uncontrollable switching frequency. Switch on/off state is generated when output current touches the hysteresis boundary. The time between these touches depends on the selected hysteresis width and the steepness of the reference signal. Near the maximum of the sine reference rises/falls slowly than near zero. Better results can be obtained when control of the hysteresis width is used. According to [3], the width depends on the demanded switching frequency f_s of the converter, on the inverter side filter inductance L_i, on the actual value of DC-link voltage U_{DC}, and on the filter capacitor voltage u_{Cf}.

$$Hy = \left|u_{Cf}\right| \frac{U_{DC} - \left|u_{Cf}\right|}{L_i f_s U_{DC}}. \tag{1}$$

The effect of the influence of hysteresis width calculated according to (1) is in Fig. 5. The hysteresis boundaries are deformed and the switching frequency is nearly constant.

2.3 Synchronization

The inverter must also generate current that is in phase with the grid voltage that is why the fast and accurate detection of the phase angle of the grid is needed. This synchronization ensures the Phase Locked Loop (PLL). The main task of the PLL is to provide clear current reference for synchronization of the inverter output current with the grid voltage also under distortions of the grid. The problem is that in single phase system there is less information about grid conditions than in three phase system. The main problem is how to make orthogonal voltage system. The simplest way is to use transport delay which makes the desired phase shift 90°. This simple solution is vulnerable to distortions. Advanced methods should be therefore used and can be found in [5], [6]. The simplified structure of PLL is in Fig. 6. The phase angle Θ is used as an input for the reference sine generator.

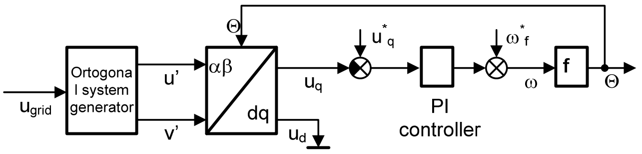

Fig. 6. Simple PLL schematics.

3. Output Filter Design

Each semiconductor converter produces distortions due to switching of semiconductor devices. These distortions must be suppressed. That is why the converter is equipped by a filter. The large inductance connected to the output of the converter can be used for suppression of the harmonic distortions caused by switching frequency. But the large inductance decreases the dynamics of the system and also the operation range of the converter. Instead of the inductance the inverter can be equipped with an L-C-L filter. The L-C-L filter has good current ripple attenuation. However it can put system in resonance, therefore the damping of the filter must be also considered. Resistor connected is series with filter capacitor is simple and effective solution, but it introduces losses to the system. In the technical literature we can find many articles concerning the design of the L-C-L filters [1], [2].

The system parameters considered for calculating the components for a filter with power approx. 1.5 kVA are summarized in Tab. 1.

Grid voltage (V)	230
Output Power of the inverter (kVA)	1,5
DC link voltage (V)	400
Grid frequency (Hz)	50
Switching frequency (Hz)	3000

Tab. 1. Parameters for the filter components calculation.

The important step in the design is the control of the resonant frequency of the filter. The resonant frequency must have a sufficient distance from the grid frequency and must be minimally one half of the switching frequency, because the filter must have enough attenuation in the switching frequency of the converter. The resonant frequency for the L-C-L filter can be calculated as (2)

$$\begin{aligned} f_{res} &= \frac{1}{2\pi}\sqrt{\frac{L_i + L_g}{L_i L_g C_f}} = \\ &= \frac{1}{2\pi}\sqrt{\frac{17.7mH + 5.7mH}{17.7mH \cdot 5.7mH \cdot 3.45\mu F}} = 1.30kHz \end{aligned} \tag{2}$$

In order to reduce oscillations and unstable states of the filter the capacitor should be added with an in-series connected resistor. This solution is sometimes called “passive damping”. It is simple and reliable, but it increases the heat losses in the system and it greatly decreases the efficiency of the filter. The value of the damping resistor can be calculated as (3)

$$R_{sd} = \frac{1}{3\omega_{res} C_f} = 11.2\Omega\,. \tag{3}$$

The transfer function of the designed filter is in Fig. 7. The filter without the damping resistor (blue) shows a significant peaking in the area of the resonant frequency.

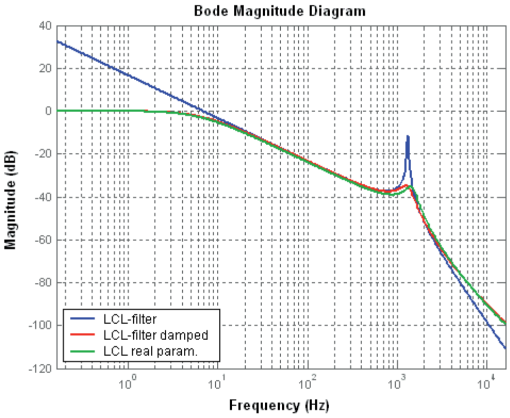

Fig. 7. Transfer function.

The two other waveforms show the transfer function of the L-C-L filter with calculated damping (red). The calculated values of the filter components were slightly modified in order to come close to the component values that can be bought (green). From the figure it is clear that this change has nearly no influence on the behavior of the filter.

Problems with the losses and decreased efficiency of the filter can be solved when we look closely at the function of the damping resistor. The inverter can be considered as a current source. The resistor reduces the voltage across the capacitor by a voltage proportional to the current that flows through it. The function of the resistor can be substituted by the control loop. The current through C_f is measured and differentiated by the term sC_fR_{sd}. A real resistor is not used, and the calculated value is subtracted from the demanded current (Fig. 8).

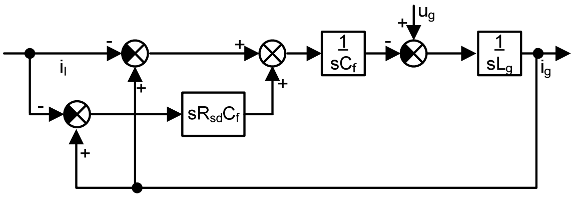

Fig. 8. Adaptation of the control loop.

In this way the filter is actively damped with a virtual resistor without losses. The disadvantage of this method is that an additional current sensor is required and the differentiator may bring noise problems because it amplifies high frequency signals.

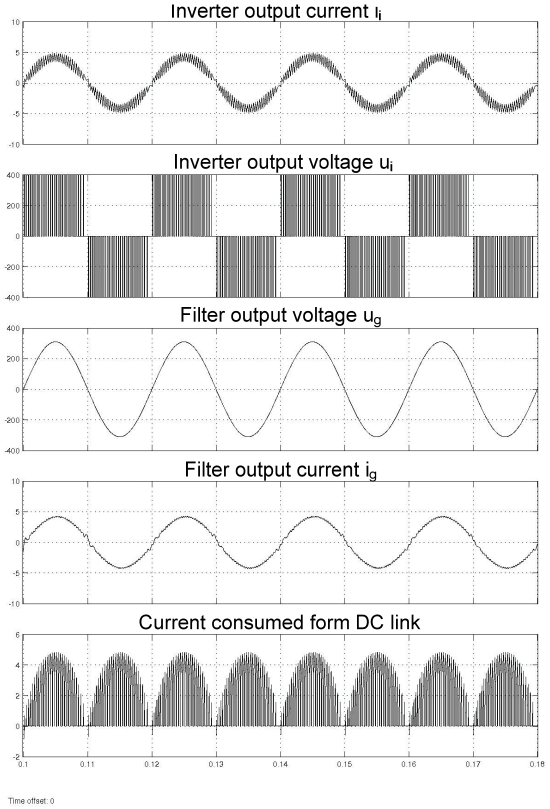

Fig. 9. Simulation results for the current hysteresis control.

4. Simulation Results

A model of the VSI with the control was made with the help of Matlab-Simulink SW. All simulations were made for output current $I_g = 3$ A, output voltage $U_g = 230$ V and output frequency $f = 50$ Hz. The switching frequency of the inverter was $f_s = 3$ kHz a filter with parameters designed in this paper $L_i = 20$ mH, $C_f = 3$ μF, $L_g = 5$ mH and virtual damping resistor.

Fig. 9 shows the simulation results of the inverter with double hysteresis control. The filtered current i_g is in the phase with the grid voltage. Except small spikes in areas where the current changes its direction, the shape of the filtered current is sinusoidal.

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Jan BAUER was born in Prague on January 14, 1983. He studied electrical engineering at CTU in Prague and was awarded his diploma degree in June 2007. He is currently working on his PhD thesis at CTU in Prague, FEE at the Dept. of Electric Drives and Traction. His main fields of interests are modern control algorithms for inverters and matrix converters.

Jiří LETTL was born in Beroun, Czech Republic, 1952. He received his Ph.D. degree from the Czech Technical University in Prague in 1980, became an assistant professor in 1993 and professor in 2009. He was employed by the Czechoslovak Academy of Sciences in Prague, by DANFOSS Vienna, and by many other industrial companies as a manager. Since 2002 he works at the Czech Technical University in Prague as the head of the Dept. of Electric Drives and Traction and on the Dept. of Electrical and Electronic Engineering and Signaling in Transport, Jan Perner Transport Faculty, University of Pardubice. His research covers optimization of electromechanical conversion of energy parameters in electric drives and power electronics systems, design and realization of advanced control algorithms of AC drives and sophisticated PWM strategies of various semiconductor power converters (such as rectifiers, frequency converters, matrix converters, etc.), electromagnetic compatibility of semiconductor power electronics systems.