Low Power Photovoltaic Converter Control and Development

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Abstract— **The paper focuses on design and simulation of the low power inverter for photovoltaic application. In the paper it is briefly discussed the DC/DC converter design for the tracking MPP of the solar array and then the design of the control algorithm for the output inverter is discussed. Both possible operation modes - work in "island mode" and operation in the supply grid are considered and a control algorithms for them were developed and simulated. Attention is also paid to the design of the output filter for the converter.**

Keywords— DC/AC converters, Current control, Filtering

I. Introduction

The renewable energy sources are nowadays discussed topic because processing the energy obtained from sun, wind or water is coming to the fore. The energy from these sources can be considered, in comparison with coal or oil, as inexhaustible. On the other hand the energy supplied by these sources fluctuates according to the surrounding conditions (intensity of sun rays, water flow, etc.). These supplies are therefore supplemented by additional converters. Low power devices are important in applications where no voltage grid is present and small amount of the electric power is required (mountains, desert expeditions, etc.).

If the solar array is not loaded, there is no load voltage UOC on its terminals. If the terminals of the array are shorted, the short circuit current ISC flows through the terminals. If the load on the terminals of the solar array will raise gradually the current increases and the output voltage starts to drop down. When the load reaches concrete level the array will output maximum power PMPP. If the load increases behind this boundary the power delivered by the solar array starts to drop down. The characteristic also depends on the temperature of the solar cell and on the sun exposure. If the converter connected to the output of the solar array will hold the constant value on its output, it can happen that the solar array will not be fully used (it will not deliver maximum power). More useful is application of control algorithm that will track the maximum power point. This will cause that the voltage on the output of the converter will not be constant.

Generally the converter consists of part that draws maximum power from the solar array (MPPT) and inverter. MPPT may be a DC converter and inverter or directly inverter. The advantage of the first variant is greater range of the input voltage, the disadvantage is that we need two converters. As MPPT can be used direct converter without transformer or indirect topologies with transformer. It is often used as a MPPT boost converter. The output voltage is higher or same as the input voltage. Another option is to use the Cuk converter. These converters can produce voltages higher or lower than the input voltage. If the input voltage for these converters is sufficiently high, they may be connected directly to the input of the inverter, and then connected to a network without using a transformer (Fig. 1a). If the input voltage is low and the converter is not able to deliver the required high voltage a transformer must be used. The transformer can be connected to the output inverter (Fig. 1b), or an indirect converter with a transformer must be used (Fig 1c).

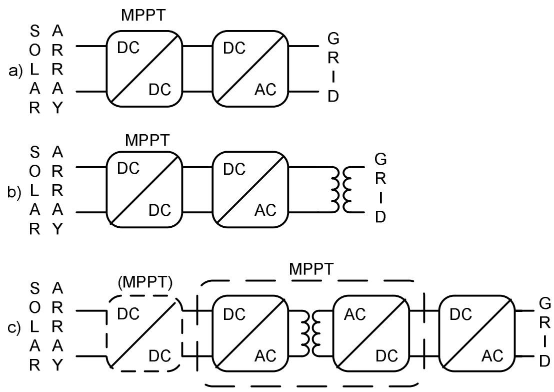

Fig. 1. Magnetization as a function of applied field.

The advantage of using indirect converter, compared to using power transformer on the inverter output, is that the transformer is designed as a high frequency, so for the same transmitted power it has a smaller size. After considering all facts the topology in Fig. 1c was selected.

II. DESIGN OF THE MPPT CONVERTER

A. DC/DC converter power part

Different converter schemas are used for MPPT for their better efficiency. The simplified block structure of the investigated topology of the converter is shown in Fig. 2. The DC-DC converter with implemented MPPT (Maximum Power Pont Tracker) is connected to the solar output. This converter is realized as simple buck converter. Its task is to stabilize the output values of the solar array and by changing its duty time the converter ensures the maximum power consumption from the array. The second DC-DC converter is boost converter with galvanic insulation. Its task is to raise the voltage to the level that is suitable for the output inverter.

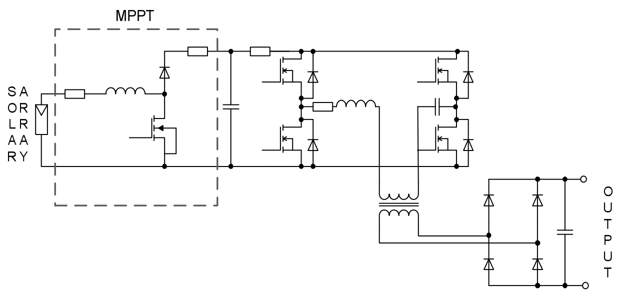

Fig. 2. DC/DC converter power part

B. MPPT controller design

The control algorithm of the DC-DC converter includes MPPT algorithm. It is necessary because the output power of the solar cell depends on the surrounding conditions and on the withdrawn current and voltage.

To find the maximum power you can use different methods. Method P & O (Perturb and Observe) changes the voltage of the photovoltaic panel and evaluates change of the delivered power. The Hill-climbing method, which changes the value of duty cycle of the converter and evaluates the change of the power, is based on the same principle. According to the sign change of output power and according to the voltage variations the method decides the change of the voltage value (duty cycle). The disadvantage of these methods is that they oscillate around the point of maximum power and quick changes in the intensity of exposure can cause errors in regulation. The advantage is easy implementation of these methods.

Method INC (Incremental Conductance) is based on the fact that the derivative of the power curve according to the voltage is zero at the point P_{MPP}. If the voltage is higher than the voltage U_{MPP}, then the derivative is negative. If the terminal voltage is lower than U_{MPP}, then the derivative is positive (Fig. 3). The disadvantage of this method is that derivatives must be calculated.

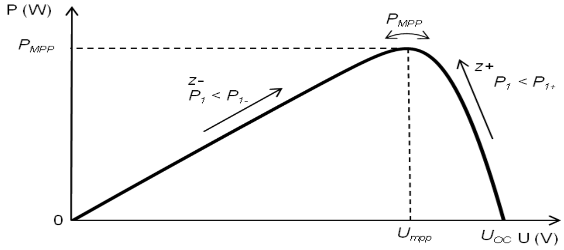

Fig. 3. MPP tracking principle

Another method is based on measuring short-circuit current (Fractional Short-Circuit Current) and the assumption that for the given intensity of the sun exposure, the current I_{MPP} is proportional to the current I_{SC}. The controller short-circuits the output of a photovoltaic panel and measures the current I_{SC} for a short period. It calculates then the current value I_{MPP}. Another possibility is to measure the open circuit voltage (Fractional Open-Circuit Voltage). A basic assumption here is that the voltage U_{OC} is proportional to the voltage U_{MPP}. The disadvantage of these methods is that it is necessary to measure voltage U_{OC} or current I_{SC} and the need to determine the transfer constants too.

III. DESIGN OF THE INVERTER

The VSI is used for converting energy from DC to AC voltage. The detailed schema of the inverter is shown in the Fig. 4. The power part of the inverter is made of four MOSFETs and the L-C-L filter is connected to the output of the inverter. This filter ensures the sinusoidal shape of the output current. The inverter can operate in two modes in the supply grid or in island mode. The current hysteresis controller is suitable for the first type of operation [5], [6]. In the second case the PWM controller is used. In order to reduce the negative side effects of the converter to the grid the filter is added to the output of the inverter.

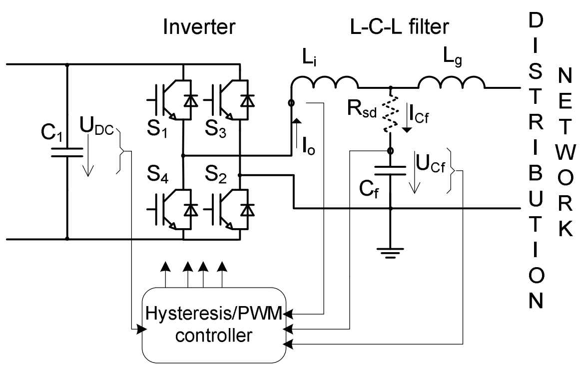

Fig. 4. Power part of the inverter

The simplest hysteresis controller can be realized as a simple bang-bang regulator. The actual value of the output current is controlled in order to remain in a defined area. This method is fast and simple, and provides good results with an L-C-L filter [10]. The generated current tracks the reference signal well, only problem is the variable switching frequency of the semiconductor switches that is a direct consequence of this control strategy. Near the moments where the reference crosses zero the reference signal and the hysteresis boundaries are drawn together and therefore the switching frequency rises. Also the descent of the generated current is not so steep and the current does not cross the hysteresis boundaries. Better results can be obtained when a control of the hysteresis width is used. According to [1], the width depends on the demanded switching frequency f_s of the converter, on the inverter side filter inductance Li, on the actual value of DC-link voltage U_{DC}, and on the filter capacitor voltage u_{Cf}.

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

Implementation of equation (1) causes that the switching frequency remains approximately constant. A further improvement of the output current shape involves adaptation of the hysteresis controller. A simple hysteresis controller alternates only between two combinations (S_1, S_2) or (S_3, S_4), which means that either $+U_{DC}$ or $-U_{DC}$ appears on the output. The bipolar switching can be easily adapted to unipolar switching. This method generates three output voltage levels $+U_{DC}$, 0, and $-U_{DC}$. The controller is shown in Fig. 5. Two hysteresis controllers of different hysteresis width are used instead of one. The first one control switches S_2, S_3 and the second one controls S_1, S_4. Outer hysteresis is used in areas where the current crosses zero and the drop in the desired current value is faster than the drop in the output current. The output current then reaches the outer hysteresis and the controller switches from S_1 to S_4 or vice versa.

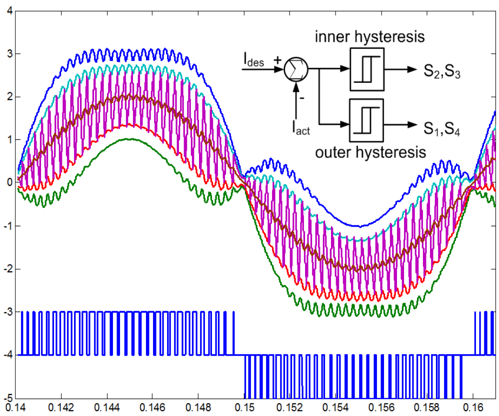

Fig. 5. Double hysteresis controller and its function

Hysteresis control cannot operate in “island mode”, because there is no supply network voltage that can guard the generated voltage. The converter is then supposed to generate the output voltage with a sinusoidal shape, as in the supply network. The PWM control algorithm was therefore used for “island mode”.

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. The main task of the synchronization circuit is to provide clear reference for synchronization of the inverter output current with the grid voltage also under distortions of the grid. The problem is that in a single phase system less information is available about grid conditions than in a three phase system. The simplest way of realization is the 2nd order filter. Filter can be realized as analogue from passive elements (resistors, inductors, capacitors) or as digital in microcontroller. This realization is simple but the filter introduces phase shift into the system. Therefore other techniques like Phase Locked Loop (PLL) were taken into account. The main problem is how to make orthogonal voltage system. The simplest way is to use transport delay which makes desired phase shift 90°. This simple solution is vulnerable to distortions. Advanced methods should be therefore used and can be found in [12], [13]. The simplified structure of PLL is in Fig. 6. The phase angle Θ is used as an input for the reference sine generator.

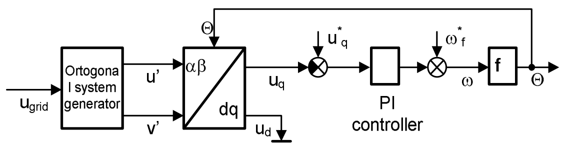

Fig. 6. PLL schematics

IV. Output Filter Design

The filter is an important part of every semiconductor converter. The filter reduces the effects caused by switching semiconductor devices on other devices. On the output of the inverter there appears frequency that is generated as an output of the inverter and then also other unwanted frequencies in the area of inverter switching frequency. The filter for this application must be therefore designed in the way it does not reduce frequencies near grid frequency and it suppresses other higher frequencies. The behavior of the filter can be observed from the transfer function of the filter.

The generation of the harmonics around the switching frequency can be filtered by large inductance connected to the output of the converter. But the large inductance decreases the dynamics of the system and also the operation range of the converter. Therefore the combinations with the capacitor like LC and L-C-L filters were simulated.

The LC-filter is second order filter and it has better damping behaviours than L-filter. This simple configuration is easy to design and it works mostly without problems. The second order filter provides 12 dB per octave of attenuation after the cut-off frequency f_0, it has no gain before f_0, but it presents a peaking at the resonant frequency f_0. Transfer function of the LC-filter is

$$F(s) = \frac{1}{1 + s \cdot L_F + s^2 \cdot L_F \cdot C_F} \tag{2}$$

The peaking around the cut off frequency of the filter must be suppressed by some damping resistor.

Next possible topology is an L-C-L filter. The attenuation of the LCL-filter is 60 dB/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. The filter must be therefore designed precisely according to the parameters of the specific converter. In the technical literature we can find many articles on the design of the L-C-L filters [2],[4]. Transfer functions of the LC and L-C-L filters are depicted in Fig. 7.

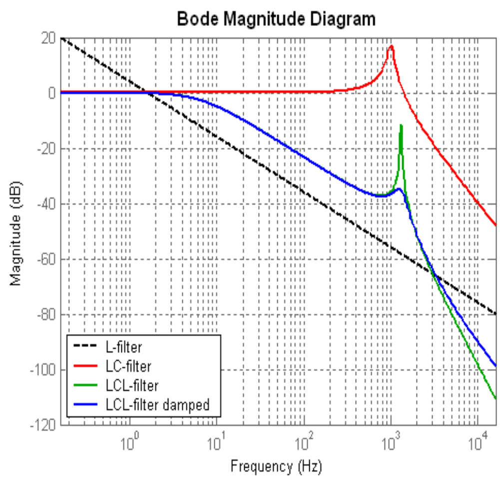

Fig. 7. Transfer functions of the filters

Now the filter design will be described. The system parameters considered for calculating the components for a filter with power approx. 1,5 kVA are shown in Table I:

TABLE I.
BASIC PARAMETRS FOR CALCULATION OF THE FILTER COMPONENTS

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

The first step in calculating the filter components is the design of the inverter side inductance L_i, which can limit the output current ripple up to 10% of the nominal amplitude. It can be calculated according to the equation derived in [3]:

$$L_i = \frac{U_{DC}}{16 f_s \Delta I_{L\_\max}} = 17{,}7mH \tag{3}$$

where ΔI_{L_max} is the 10% current ripple specified by (4)

$$\Delta I_{L\_\max} = 0{,}01\frac{P_n\sqrt{2}}{U_n} = 0{,}234A \tag{4}$$

The design of the filter capacity proceeds from the fact that the maximum power factor variation acceptable by the grid is 5%. The filter capacity can be therefore calculated as a multiplication of the system base capacitance C_b

$$C_f = 0{,}05C_b = 3{,}45\mu F \tag{5}$$

The grid side inductance L_g can be calculated as

$$L_g = rL_i = 0{,}32L_i = 5{,}7mH \tag{6}$$

The last step in the design is the control of the resonant frequency of the filter. The resonant frequency must have a 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

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{L_i + L_g}{L_i L_g C_f}} = 1{,}30kHz \tag{7}$$

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

$$R_{sd} = \frac{1}{3\omega_{res}C_f} = 11{,}2\Omega \tag{8}$$

Effects of the designed filter are in Fig. 8. The total harmonic distortion of the output is around 3,8 %.

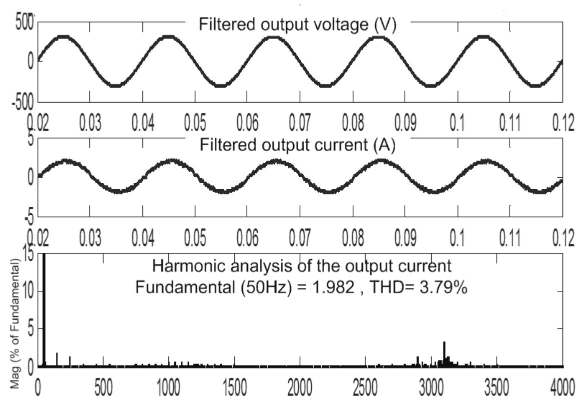

Fig. 8. Simulation of the designed filter influenc on the inverter

V. Simulation results

A model of the VSI with the control was made with the help of Matlab-Simulink SW. All simulations were made for the 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 for a filter with parameters designed in this paper L_i = 17,7 mH, C_f = 3,45 μF, L_g = 5,7 mH and damping resistor R_{sd} = 11,2 Ω.

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

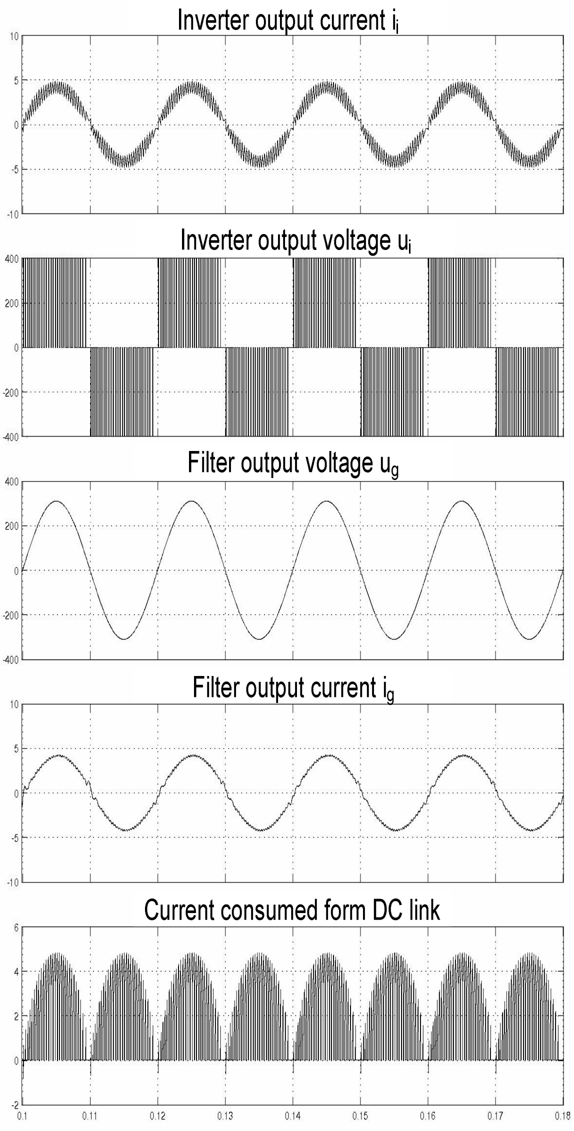

Fig. 9. Output of the converter - hysteresis control

The same simulations were done for the “island mode” operation (Fig. 10). In this case, the output voltage is regulated to u_g = 230 V and the current is determined by the load. The shape of the current is smoother, but there is a slight phase shift, caused by the output filter inductance and the load character. The harmonic content of both currents is good.

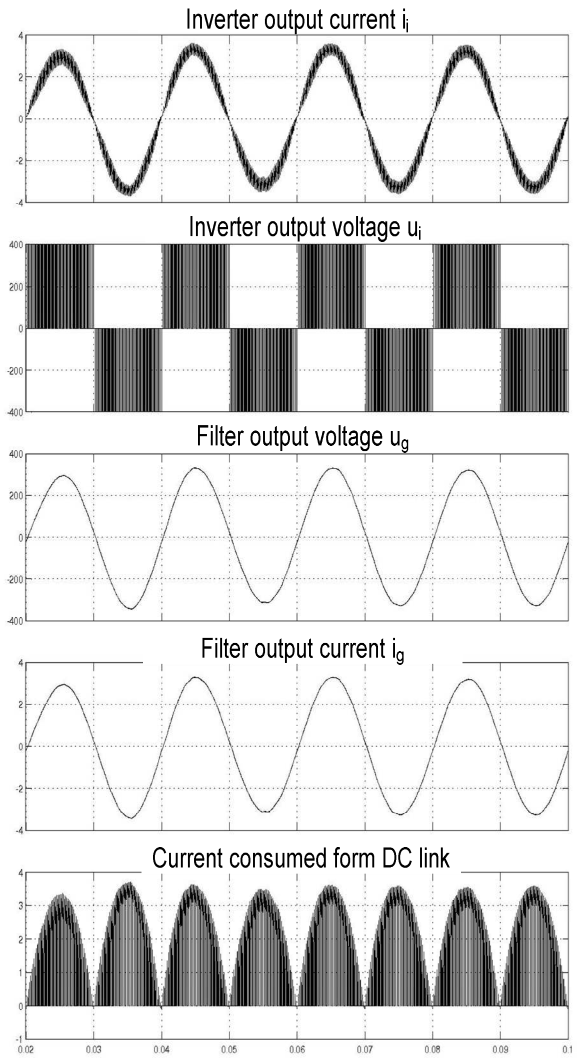

Fig. 10. Output of the converter – PWM control

VI. Summary

The control algorithm for a small converter suitable for application with solar array was presented here. A sinusoidal line current is produced due to the hysteresis controller. The switching frequency is almost constant because of the variable hysteresis width control. The output current filter has been designed and simulated. The obtained results seem to be promising. However, we will be able to evaluate whole system until after it has been realized.

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