Design of Power Converter for Model of Photovoltaic Power Plant

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***Abstract*—This paper deals with hardware design of power stage of three phase power converter for model of photovoltaic power plant. The device is designed for the three-phase 22 kV power line model. It contains also description individual parts of proposed power converters (i.e. DC-DC and DC-AC) output filter and auxiliary circuits for measuring electrical parameters that are necessary for control of power converter. It also includes a simulation model of the power converter in Multisim. The model of Photovoltaic power plant can be used for emulating the Smart grids along with other models of renewable energy sources.**

***Keywords*—power conveter; photovoltaic inverter; renewable energy source; photovoltaic power plant;**

I. Introduction

The effects of global warming, the necessary reduction in contaminant emissions and the huge dependence on fossil fuels (becoming increasingly expensive) have led, over recent decades, to the development of new energy sources based on renewable systems. In fact, the European Union presented a plan for the period 2011–2020 to establish the lines for the development of renewable energy sources, emissions reduction and energy efficiency. The targets addressed by this plan to be achieved by 2020, usually called 20/20/20, are as follows:

- 20 % reduction in greenhouse gases to below the values of 1990,
- 20 % of energy consumption must be generated by renewable energy sources,
- 20 % reduction in consumption of primary energy.

It must be noticed that in 2010, these objectives were far from being achieved and, thus, remain a significant challenge for the European governments [1].

Due to global environmental concerns, photovoltaic (PV) systems are becoming more common as a renewable energy source. The main drawbacks of PV energy are the high cost of manufacturing silicon solar panels and the low conversion efficiency. However, with the latest techniques in manufacturing, PV systems are becoming more efficient, as well as cost effective [1].

PV devices directly convert sunlight into electricity. The generated DC is then converted to AC and fed to the grid, or used in isolated load. In an autonomous system, there is usually a battery backup energy source. The generated DC voltage is boosted by a DC–DC converter before inversion to AC by a PWM sinusoidal inverter. The DC–DC converter controls the maximum power output of the string by MPPT control. The channels are parallel connected at the AC side and boosted in voltage by a transformer before connecting to the AC grid. The PV devices have the advantages that they are static, safe, reliable, and environmentally clean (green) [1], [2], [3], [4].

In this paper, attention is paid to creation of the hardware design of power converter. This power converter is part of photovoltaics power plant model.

II. Model of Photovoltaic Power Plant

This part describes the model of photovoltaic power plant and connection to model of 22 kV power line. The base structure of this model is shown in Fig. 1.

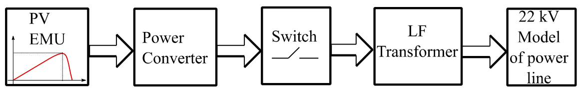

Fig. 1. Base structure of Photovoltaic Power Plant model.

The model of photovoltaic power plant consists of these three following parts:

- Photovoltaic panel emulator.
- Three-phase power converter.
- Three-phase low frequency transformer.

A. Photovoltaic Panel Pmulator

The main task is replacing a real PV panel or string of PV panels by PV emulator. Input parameters of this emulator are solar irradiance and temperature. Based on these input parameters PV emulator will generate output voltage and current accordance with the physical model of the PV panel.

B. Power Converter

The PV emulator is followed by a power converter. The power converter has on input side passive filter, generally a capacitor, which is used to decouple the input voltage and current from the subsequent power stages by reducing current and voltage ripple at the PV side.

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The input filter can be followed by a DC–DC stage, which is generally used to perform the Maximum Power Point Tracking (MPPT) of the PV system, elevate its output voltage and in some occasions also provide galvanic isolation (when using DC–DC converters with high-frequency (HF) transformers). In order to capture the maximum energy from the PV module, solar inverters must guarantee that the PV module is operated at the MPP (Maximum power point) as shown in Fig. 2. This is accomplished by the maximum power point control loop known as the MPPT.

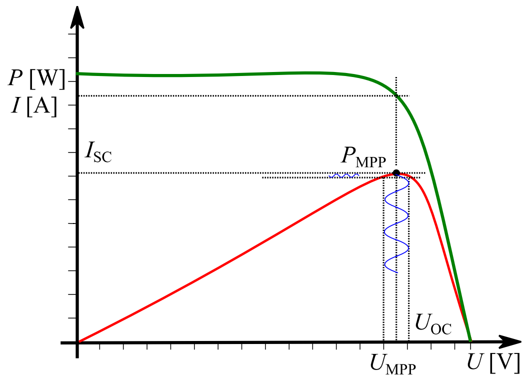

Fig. 2. Electrical characteristic of PV module.

The DC–DC power stage (or the input filter, if DC–DC stage is not used) is connected through the DC link to the grid-tied DC–AC converter, commonly referred to as the PV inverter. In PV systems, where DC–DC stage is not used, the input filter is equivalent to the DC-link capacitor as shown in Fig. 3. The PV inverter is connected to the grid via an output filter, usually made of a combination of inductors (L) and capacitors (C), typically in L, LC, or LCL configurations. The AC filter enables harmonic mitigation and assists the converter–grid interface control [1], [2].

C. Three-phase Transformer

Depending on the PV system requirements and the grid connection available is used a low-frequency (LF) transformer to elevate the voltage and provide isolation.

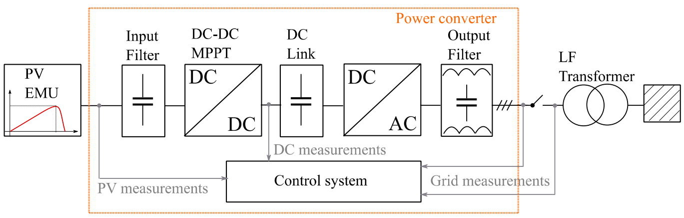

Fig. 3. Block diagram of photovoltaic power converter.

III. Design of Power Converter

The photovoltaic power converter is a double stage, grid-connected converter. This means that the DC power from the solar panel is not converted directly to the AC power. Input voltage from PV emulator is initially elevated by DC-DC converter and then converted to AC voltage by DC-AC converter. This converter has been designed to connect to PV emulator having a power rating of approximately 230 watts, with an input voltage range of 25 V to 45 V DC.

Features of the design include:

- peak efficiency 94.8 %,
- maximum Power Point Tracking 99.5 %,
- maximum Output Power 230 W,
- grid Voltage 220 V AC,
- input Voltage Range: 25 V to 45 V DC.

A. Input Filter

As mentioned at the input side of power converter is passive filter, generally several capacitors (decoupling capacitors). These capacitors balance the variable instantaneous power in the system. As the input power from the PV panel is to remain constant to maximize the energy harvested from the panel, there will be an instantaneous power mismatch between the input power and output power. The decoupling capacitors are also required to reduce the ripple voltage from the PV panel in order to achieve a utilization factor greater than 99% (maximum power utilization) [2], [3]. The ripple voltage U_{ripple} can be determined by:

$$U_{ripple} = \sqrt{\frac{(k_{pv} - 1) \cdot 2 \cdot P_{MPP}}{3 \cdot \alpha \cdot U_{MPP} + \beta}} \quad (1)$$

where α and β are coefficients of a second-order Taylor polynomial and k_{pv} is the utilization factor.

With a known ripple voltage, the required capacitance can be determined to meet the ripple specifications, according to [2]:

$$C = \frac{P_{MPP}}{2 \cdot \pi \cdot f_{ripple} \cdot U_{MPP} \cdot U_{ripple}} \quad (2)$$

The f_{ripple} is ripple frequency. The ripple frequency, power and voltage in maximal power point (P_{MPP}, U_{MPP}) have been taken as worst case. For this design were selected five 2200 µF capacitors. These capacitors have a rated voltage of 63 V.

B. Design of DC-DC Stage

As mentioned above the DC-DC converter is designed to increase voltage from input side to the required value for the input of DC-AC converter. DC-DC converter must also provide the function of MPPT (Maximum Power Point Tracker). The value of the input voltage was set at $U_{DC\text{-}DC}$ = 25V. Converter must be able to supply an output current $I_{DC\text{-}DC}$ = 4.8 A. Converters will consist of classical non-insulated boost converter topology with a single switch and inductor shown in Fig. 4. Converters installed in the USA must be insulated between DC and AC side. In the Europe insulation is not necessary.

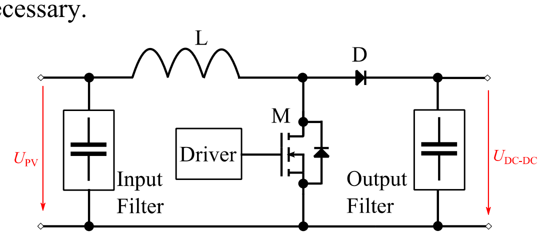

Fig. 4. DC-DC Converter.

To achieve of 48 volts on output the DC-DC converter, the duty cycle must be D = 0.48. The output voltage of DC-DC converter can be determined by (3):

$$U_{\mathrm{DC-DC}} = U_{\mathrm{PV}} \cdot \frac{1}{1-D} \quad (3)$$

where $U_{\mathrm{DC\text{-}DC}}$ is output voltage and U_{PV} is input voltage of DC-DC converter [5], [6], [7].

The voltage stresses of semiconductors growth with increase of the duty cycle. At higher values of duty cycle (i.e. at higher values of output voltage $U_{\mathrm{DC\text{-}DC}}$), is transistor the more current stressed than the diode. Transistor is dimensioned for a peak value of current and the diode for average value of current. The transistor must be dimensioned so that the maximum of peak current does not exceed the value from datasheet. For this converter was as a switching transistor selected type SPP20N60S5. The average value of current flowed by transistor can be determined by:

$$I_{\mathrm{Tavg}} = I_{\mathrm{PV}} \cdot D \quad (4)$$

where I_{PV} is input current of DC-DC converter and D is duty cycle. The RMS value of current can be calculated by:

$$I_{\mathrm{TRMS}} = I_{\mathrm{PV}} \cdot \sqrt{D} \quad (5)$$

As a MOSFET driver circuit was used IR2125PBF circuit. Its use is necessary due to the fact that the microcontroller is not able to directly deliver the required voltage level for the switching transistor. The wiring of the MOSFET driver was taken from the manufacturer's datasheet. The input of driver is connected to PWM output of microcontroller. Diode of boost converter must be rated for the average value of current and can be determined by:

$$I_{\mathrm{Davg}} = I_{\mathrm{DC-DC}} \cdot (1-D) \quad (6)$$

where $I_{\mathrm{DC\text{-}DC}}$ is output current of converter. The RMS value of current flowed by diode can be evaluated as follow.

$$I_{\mathrm{DRMS}} = I_{\mathrm{DC-DC}} \cdot \sqrt{1-D} \quad (7)$$

For this converter was chosen type of diode BYV79E-200. The converter will operate in continuous mode currents, and the switching frequency was set at f_s = 62.5 kHz. The switching frequency has affects the size of inductor, current ripple and with larger frequency is necessary less value of inductance for reduce ripple of current. For determine resultant value of inductance for inductor is necessary to define value of ripple current.

$$I_{\mathrm{ripple}} = \frac{U_{\mathrm{PV}} \cdot D}{L \cdot f_s} \Rightarrow L = \frac{U_{\mathrm{PV}} \cdot D}{I_{\mathrm{ripple}} \cdot f_s} \quad (8)$$

For converter was selected inductor with the next higher value of inductance L = 680 µH and current rated 13 A. Output current of converter from simulation is shown in Fig. 7. At the maximum load was output current of converter 9.29 A. Simulation model of power converter is shown in Fig. 10.

The size of the decoupling capacitor (DC-link) can be computed as:

$$C_{\mathrm{DC}} = \frac{P_{\mathrm{DC}}}{2 \cdot \omega \cdot U_{\mathrm{DC-DC}} \cdot U_{ripple}} \quad (9)$$

where P_{DC} is the average DC-link power, ω is the grid frequency, $U_{\mathrm{DC\text{-}DC}}$ is the average DC-link voltage and U_{ripple} is the amplitude of the ripple voltage. The value of the DC-link capacitor is computed by (9) to 100 µF at 230 W into the DC-link. A 100 V capacitor is selected in order to allow for some over voltages, without damaging the capacitor [3].

The grid current cannot be controlled if the DC-link voltage is lower than the peak grid-voltage plus the voltage drop across the semiconductors and filter. The minimum usefulness DC-link voltage at 10 % over-voltage in the model of grid is 19.75 V.

For control of the power converter is necessary measuring of voltages and currents on input and output side of DC-DC converter and also on output of DC-AC converter. The output voltage of PV panel (U_{PV}) and output voltage of DC-DC converter is measured by voltage divisor circuit as is shown in Fig. 5. The resistor divisor scales down the PV panel voltage to the ADC input voltage level (0-5 V) and the capacitors are used for additional signal filtering.

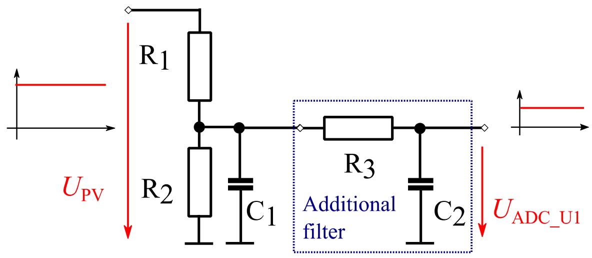

Fig. 5. PV voltage measurement.

The output voltage from voltage divisor can be determined by (10).

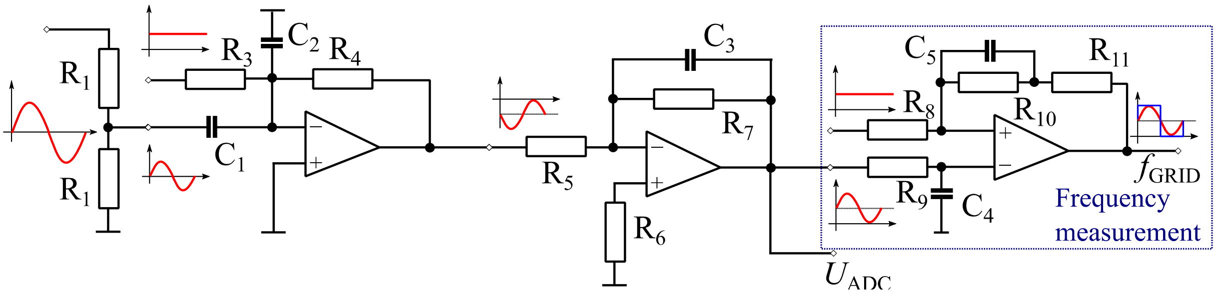

Fig. 6. Measurement of grid voltage and frequency.

$$U_{\mathrm{ADC\_U1}} = U_{\mathrm{PV}} \cdot \frac{R_2}{R_1 + R_2} \tag{10}$$

The sensed PV panel voltage is used for Maximum Power Point tracking and for protection. The measurement of grid voltage and frequency is realized by the circuit shown in Fig. 6. This circuit is consisting of four parts the voltage divisor, inverting summing operational amplifier, inverting op. amplifier and comparator. The voltage divisor scales down the grid voltage to the ADC input voltage level (0-5 V) and is connected by decoupling capacitor to summing operational amplifier. The main task of summing operational amplifier is providing an offset of input voltage signal. The output signal from summing amplifier has an offset of 2.5 V and is inverted. The output signal is connected to the inverting operational amplifier with a first-order low pass filter (i.e. Anti-aliasing filter). The filter is configured so that the attenuation of harmonic higher than fortieth-order. The resonant frequency of filter can be evaluated by:

$$f_{\mathrm{rez}} = \frac{1}{2 \cdot \pi \cdot R_7 \cdot C_3} \tag{11}$$

The output signal from inverting operational amplifier is connected to input of A/D converter and also to comparator which is used to measuring of frequency and zero-crossing detection for determine the grid voltage angle.

For measuring of PV current, output current of DC-DC converter and currents flowing into the grid was selected sensor ACS712. A Hall effect-based linear current sensor is connected to input and output of DC-DC converter and between the inverter output and the grid. This current sense IC measures the inverter output current flowing into the grid. The selected Hall effect current sensor can measure current with 80 kHz bandwidth. The output signal from this Hall sensor has an offset of 2.5 V and sensitivity 180 mV/A. The output voltage signal from sensor can be computed to current by:

$$I_{\mathrm{PV}} = \frac{(U_{\mathrm{ADC\_I}} - 2.5)}{0.1} \tag{12}$$

where $U_{\mathrm{ADC\_I}}$ is output voltage signal form Hall sensor.

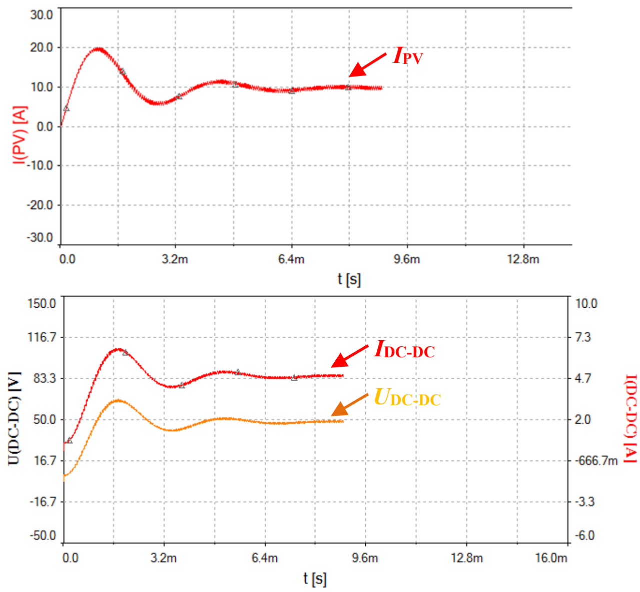

Fig. 7. Input and output voltage and current of DC-DC converter.

C. DC-AC stage

The photovoltaic power converter generates a sinusoidal current. The power stage of DC-AC converter is composed of six MOSFET transistors STP11NK50Z type. Each of transistors has the diode connected in parallel with each other. Gates of transistors are connected to MOSFET drivers IRS21844PBF.

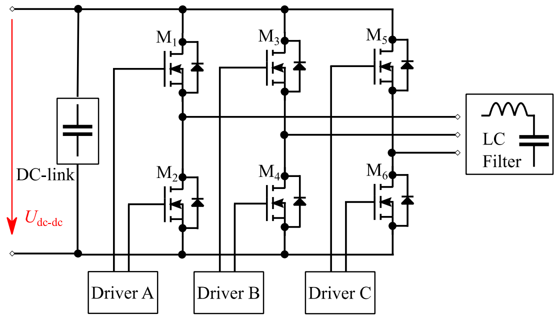

Fig. 8. DC-AC Converter

These types of drivers were selected because they have integrated a dead-time generator. The dead-time can be adjusted by value of resistor according to the datasheet. Dead-time was set using a 100 kΩ to approximately 3μs. Another reason was that the control of inverter would suffice three PWM outputs of microcontroller. The MOSFET driver creates by negation another three outputs for control of lower transistors M_2, M_4, M_6. For control of converter will be used microcontroller dspic30F6011.

To achieve the sinusoidal output waveform was needed to design output filter. The harmonic filter is implemented as LC filter of a second-order. The parameters of LC filter were determined by simulation in Multisim.

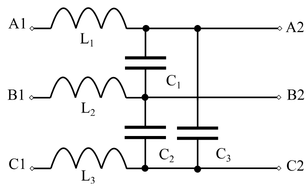

Fig. 9. Output LC filter of DC-AC converter

The filter will consist of three inductors and three capacitors. The inductions of these inductors have value 33 mH. Each of capacitor has value of capacitance 4.7 μF.

The output of LC filter is connected to three phase low frequency transformer which is used to elevate output voltage form DC-AC converter, because the model of 22 kV power line operated with phase-to-phase voltage 220 V. The basic requirement was that the output phase-to-phase voltage of the secondary side of transformer was 220 V. Therefore the output phase to neutral voltage of DC-AC converter must be 12.7 V. The transformer ratio must be p = 0.1 and can be determined by:

$$p = \frac{U_{1\mathrm{f}}}{U_{2\mathrm{f}}} = \frac{12.7}{127} = 0.1 \tag{13}$$

where $U_{1\mathrm{f}}$ is primary voltage and $U_{2\mathrm{f}}$ is secondary voltage of transformer with windings connected as wye/wye.

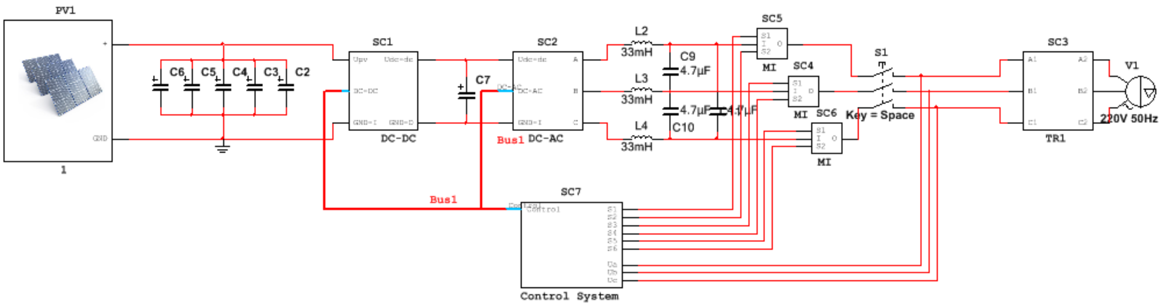

Fig. 10. Simulation model of power converter

But this connection is not generally used for the 22 kV power line .The wye connection is usually used only for low voltage side of transformer and high voltage side is connected to delta. Therefore transformer ratio for the transformer in wye-delta connection can be determined by:

$$p = \frac{U_{1f}}{U_2} = \frac{12.7}{220} = 0.0577 \quad (14)$$

where the U_{1f} is phase to neutral voltage on primary side of transformer and U_2 is phase-to-phase voltage on secondary side.

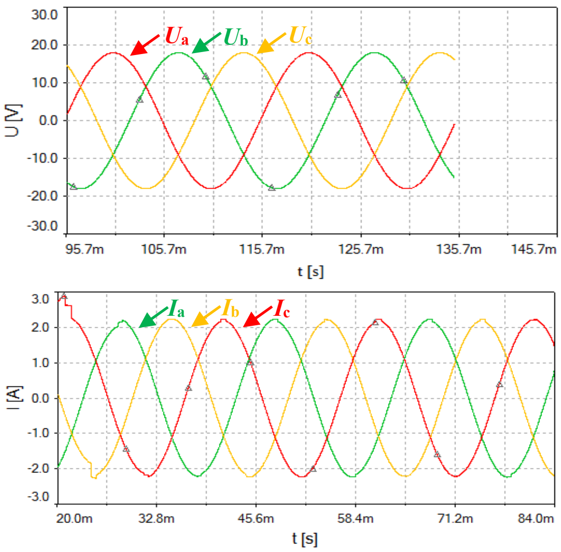

Fig. 11. Output phase to neutral voltages and line currents of DC-AC converter from simulation

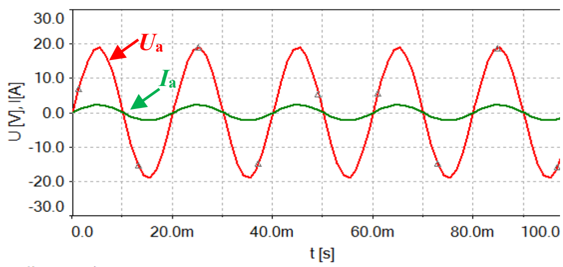

Fig. 12. Voltage and current in phase A

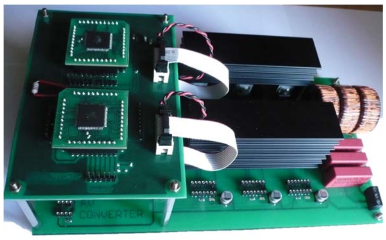

Fig. 13. Designed Photovoltaic Power Converter

IV. CONCLUSION

The created Photovoltaic Power converter is primary designed for a model of 22 kV and is part of Photovoltaic power plant model. The Power Converter will be used mainly for testing different methods of maximal power point tracking. The power converter can be also used for educational purposes. These methods are usually implemented in control of DC-DC converter for maximum use of solar energy. Or can be used for testing the different modulation techniques to achieve sinusoidal output voltage and current, and their impact on the power quality. For example the variable modulation techniques have a different harmonic distortion of current. The model of photovoltaics power plant can be used for a demonstration of Smart grid operation together with other models of renewable energy sources.

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