Recommissioning and optimization of a modular photovoltaic multilevel-inverter

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Abstract— **With the increasing electrical demand, the traditional fossil fuels should be limited or even replaced, because of their bad influences on climate. The solar energy is obviously one of the most important renewable energies. To improve the grid connection of photovoltaics is very important. The Institute of Electrical Energy Systems of FAU has developed a multilevel inverter for module integrated photovoltaic plants. The device has been disassembled and deactivated for the past few years. Within a laboratory practicum, the inverter is rebuilt and its components are retested and redesigned according to actual requirements. The paper summarizes the work within the practicum.**

Keywords-multilevel inverter; MPP tracking; flyback converter; photovoltaics

I. INTRODUCTION

The paper deals with a modular photovoltaic multilevel converter based on the cascaded H-bridge multilevel converter (CHBC). The circuit is published and explained in detail in [1] and [2].

Fig. 1 shows the different concepts for the grid connection of photovoltaic plants.

Central inverters are most common used for the grid connection of large plants, because of their cheap layout. They have only one inverter for adapting all DC-values to the AC-grid. This leads to high energy losses due to different orientations of the solar modules and partial shading [3, 4].

Another possibility for the grid connection of solar plants is the string concept, which features one inverter per string. Compared with the central inverter, the string concept offers a more flexible plant layout and the safeguarding against failure can be improved. As there is one operating point for each string, the efficiency of the solar plant is higher compared to concepts with central inverters. However, there is still a lack of efficiency due to partial shading and mismatching [3, 4].

A possibility to solve these problems are modular plants. For every single solar module, they have one small inverter. Therefore, it can be achieved, that each solar module can be separately connected to the grid, and work at its Maximum Power Point (MPP). As result, the feed-in for every solar module is optimized leading to a higher income compared to the other concepts. However, it is necessary to improve the investment costs for modular plants, as more components are necessary. Furthermore, the technical concept is more complex [2].

The paper is structured as follows: In chapter II, the circuit layout of the modular photovoltaic multilevel inverter is introduced. In chapter III, the experimental results of the laboratory work are presented. At the end a conclusion is given.

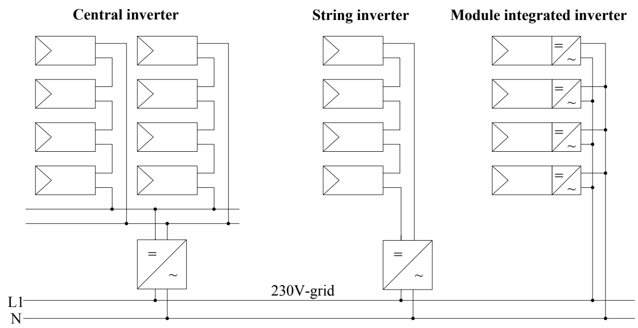

Figure 1: Concepts for the grid connection of solar plants [2]

II. CIRCUIT LAYOUT

A. Concept of the modular photovoltaic multilevel-inverter

An improvement of the modular concept is the use of a multilevel inverter instead of separately grid-connected inverters. Here, a cascaded H-bridge multilevel inverter is used to replace the AC inverters. The basic concept of multilevel inverters is to synthesize a staircase voltage waveform by using several lower voltage DC power supplies (such as solar modules here).

The advantages of multilevel inverters are [5, 6]:

- High voltage quality due to a staircase voltage waveform (low THD)
- Low electromagnetic compatibility problems due to reduced switching frequencies
- High efficiency due to reduced switching losses
- Smaller or less series connected electronic devices due to a reduced blocking voltage

For reasons of simplicity, the developed prototype is a 5-level converter for the grid connection of two solar modules. However, as the circuit layout is flexible the number of levels can be increased easily. In Fig. 2 the principle circuit layout is given. Two solar modules are connected to the grid via a cascaded multilevel inverter. DC/DC converters are used for the MPP tracking and a galvanic isolation.

The specific design of the prototype is given in Fig.3. The output form solar modules are connected to the DC/DC converters (flyback converters), which generate three DC output voltages to achieve a three-phase operation. These voltages are the input voltages of the multilevel inverter. A MPP-tracker is used to control the DC/DC converters in that way that the solar modules operate at their MPP. The multilevel inverter, under the control of a dSpace system, can generate a five level output AC staircase voltage waveform. Different modulation strategies can be implemented at dSpace, which allow operation of the multilevel inverter with fundamental switching frequency (e.g. SHE, SVFF) or with high switching frequency (e.g. PWM, SVPWM).

Fig.4 shows a normalized measured output voltage waveform of the prototype at a passive load. Space Vector Fundamental Frequency Switching (SVFF) is used for this case [7]. Because of a three-level zero voltage between the star point of the load and the star point of the converter, there are eleven levels in the load voltage. At this, the output voltage at the converter has only five levels. The voltage levels are balanced by swapping, meaning that each output DC voltage is used for a different level after one half-period.

Fig. 5 shows the prototype of the multilevel inverter. For practical reasons a solar generator based on the one-diode model is used instead of two solar modules. Each part of the circuit is explained in the following section. At this, the results of the laboratory work are presented.

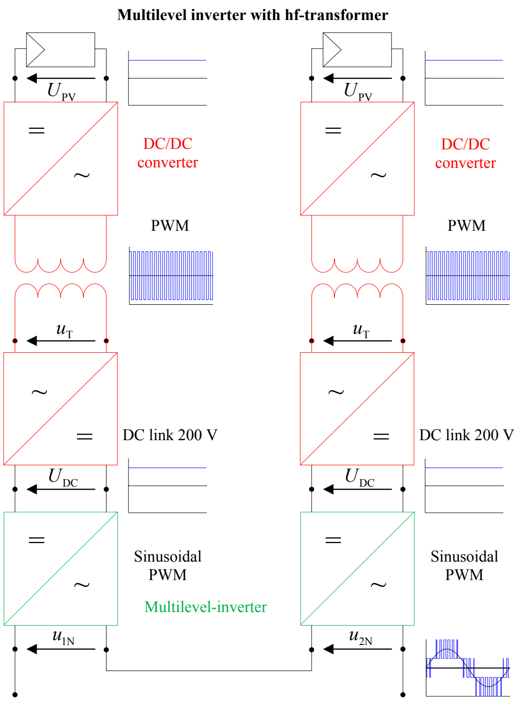

Figure 2: Principle Topology of the photovoltaic multilevel-inverter [2]

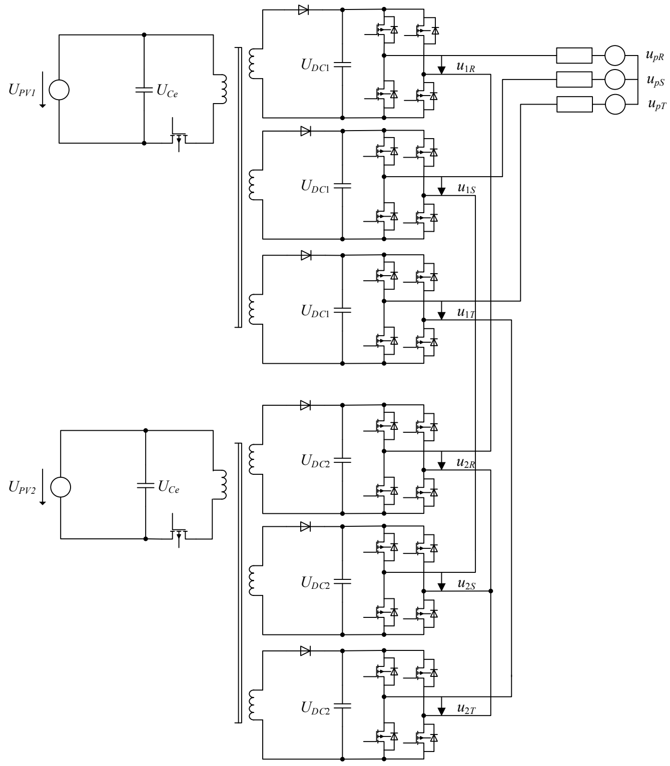

Figure 3: Layout of the implemented photovoltaic multilevel-inverter

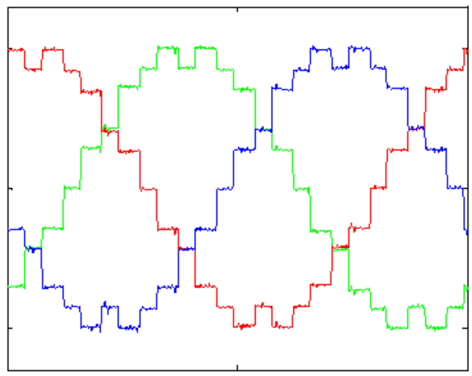

Figure 4: Measured eleven-level output voltage waveform [1]

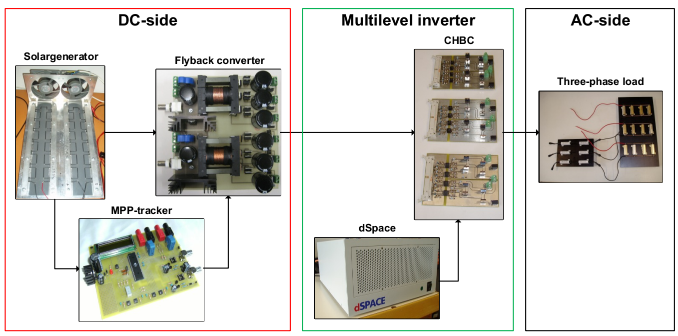

Figure 5: Prototype of the module integrated photovoltaic multilevel inverter

III. Experimiental Results

A. Solar Generator

For experimental purposes, a solar generator is used according to the one diode model. The solar generator reproduces the behavior of two 210 W modules of the type Advent 210 of the company Advent Solar, Inc. The characteristics of the solar modules are approximated by a series connection of 14 diodes (DSEP 15-12CR of company IXYS). An active cooler is also installed, which has a positive influence on the solar characteristic. Fig. 6 shows the one diode model and Fig. 7 the according measured solar characteristic.

By testing the solar generator, its output values were compared with former measurements of [1]. The solar model still works without any problems.

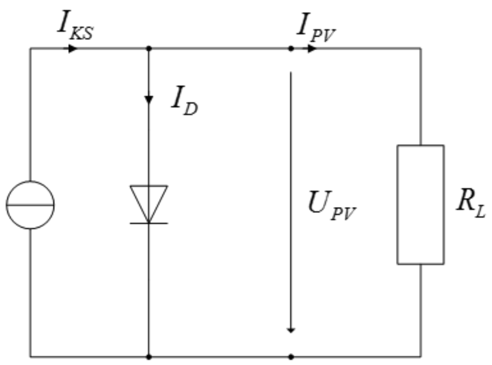

Figure 6: One diode representation of solar module [1]

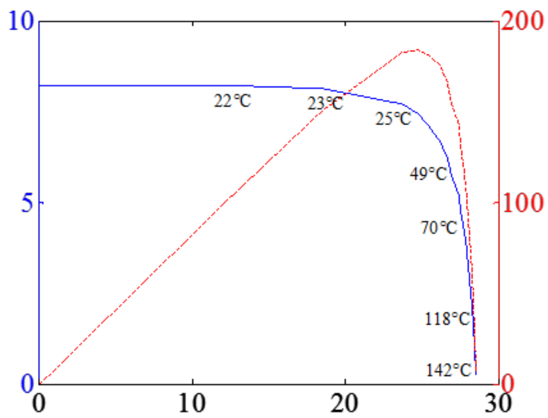

Figure 7: Measured solar and power characteristic [1]

B. DC/DC converter

In order to connect the two solar modules with the CHBC, two DC/DC converters are used, which base on three-phase flyback converters. One flyback converter is illustrated in Fig. 8. The input voltage of the flyback converter is the output voltage of the solar module. The output voltages of the flyback converter are the input voltages of the multilevel converter. For security reasons, the galvanic isolation that is provided by the DC/DC converters is advantageous. As otherwise, high capacitive currents can appear if a grounded person touches a solar module [3, 10].

One of the main tasks for the DC/DC converters is to supply the DC input voltages for the multilevel converter. Another task is, under the control of MPP-tracker, to ensure, that the solar modules work at the maximum power point.

Changing the duty cycle of the MOSFET T, the DC/DC converters can control the power flow from solar modules. The equation between the duty cycle of the MOSFET and the in-feed power from solar modules is given in (1) [8].

$$\delta = \frac{1}{U_C}\sqrt{\frac{2L_p \cdot P_{PV}}{T}} = \frac{1}{U_{MPP}}\sqrt{\frac{2L_p \cdot P_{MPP}}{T}} \qquad (1)$$

Where δ is the duty cycle of the MOSFET, U_{MPP} and P_{MPP} are the voltage and power of the solar module at the MPP.

Due to fluctuations in environmental conditions, the momentary voltage characteristics of the solar module will change permanently and the duty cycle must be adjusted dynamically. The method used to detect the best operating point which means that the correct duty cycle is calculated, is called MPP tracking [9].

The MOSFETs of the DC/DC converters operates at high frequencies (50 kHz). Therefore, the input capacitance C_e decouples the DC current of the solar module and the pulsating current of the flyback converter. A smoothed solar current is important for minimizing the oscillation around the MPP.

By testing the circuits, the problem was found that the MOSFETs could not be fully switched on and there is still a voltage drop among the MOSFETs in the on-state. This leads to additional switching losses and to a strong heating of the MOSFETs. After several tests, a defect on the DC/DC converter could be excluded. The reason why the MOSFETs were not fully switched on was a low PWM voltage from the MPP tracker (see section C.).

According to its data sheet the MOSFET can be fully switched on, when the voltage between gate pin and source pin is about 12 V. The provided PWM signal from MPP tracker is below 5 V and therefore is in the range of the threshold voltage.

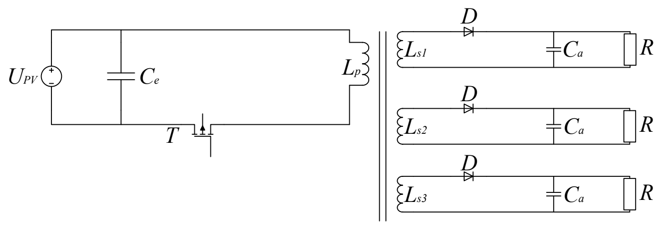

Figure 8: Flyback converter

C. MPP Tracker

The MPP tracker identifies the optimum operating point of each solar module. Different types of MPP tracking methods are implemented on a microcontroller (e.g. hill climbing, incremental conductance, etc.):

At first, the MPP tracker measures the voltage and currents of both solar modules. Afterwards it finds the maximum power points of the solar modules by varying the duty cycle of the flyback converters and calculating the related power. At this, both solar modules can operate in different maximum power points as for each flyback converter the duty cycle is calculated independently. The calculation of the duty cycles is running on the microcontroller, which receives the measurement of voltage and current of each solar module and gives two digital PWM signals to two amplifiers. The digital signal for high (on) is around 5 V. After amplifying, the signals they are transmitted to the MOSFETs of the flyback converters.

By measuring the output signal of the MPP tracker it is found, that the PWM signals after the amplifier have only about 4.6 V amplitude instead of the aspired 12 V. After testing the circuit, the problem is found in the amplifier circuit.

The implemented layout of the amplifier is given in Fig. 9. For a high signal at base, the upper NPN transistor should switch on and provide 12 V at the emitter and for a low signal the lower PNP transistor should switch on and provide ground potential at the emitter. But the given amplifier is a current amplifier, which means that the emitter potential can only follow the base potential, with an additional voltage drop between base and emitter (about 0.4V by measurement). The mode of operation is explained as follows: For a high signal of about 5 V, the potential at the emitter (*E* in Figure 9) is a bit lower due to the internal diode from base to emitter of the NPN transistor. The measured voltage is about 4.6V. This means that for a high signal at base the voltage from collector to emitter of the NPN transistor is about 7,4 V and the transistor is not fully switched on. The 4.6 V at the emitter are not sufficient to fully switch on the MOSFET of the DC/DC converter. For a low signal at base, the potential at the emitter is a bit higher due to the internal diode from base to emitter of the PNP transistor. The measured value is about 0.4V.

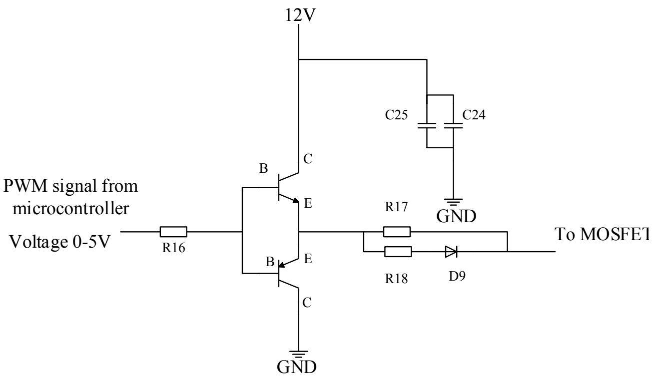

Figure 9: Originally implemented amplifier circuit

A correct possible implementation of the amplifier is given in Fig. 10. Compared with Fig. 9, a small MOSFET and some resistors are added to the circuit. The resistor R19 can hold the emitter at a stable potential. Q5 is a small MOSFET, which can be controlled by 5V from the Microcontroller. By switching on Q5, the potential at base is pulled down to ground. If Q5 is switched off, the voltage at the base is pulled up to 12 V and the emitter voltage is about 11.6 V. Therefore, the emitter voltage varies between 0.4 V and 11.6 V, which is sufficient for switching on the MOSFET of the DC/DC converter.

In order to solve the problem easier, the transistors are replaced by two standard MOSFET PWM drivers, which can amplify the 5 V voltage from the microcontroller to 12V. The new implemented amplifier circuit is given in Fig. 11. With the new installed MOSFET PWM drivers, it could be verified that the MOSFETs of the DC/DC converters can be switched on fully.

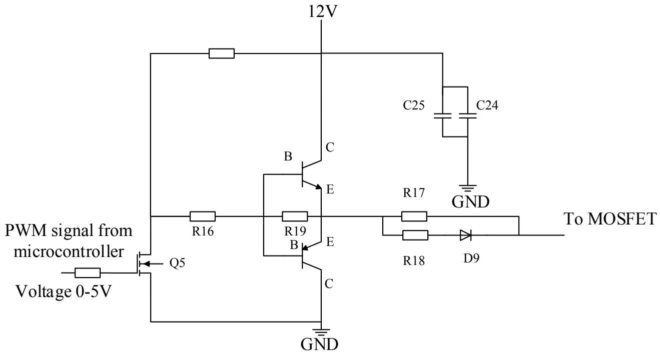

Figure 10: Correct possible amplifier circuit

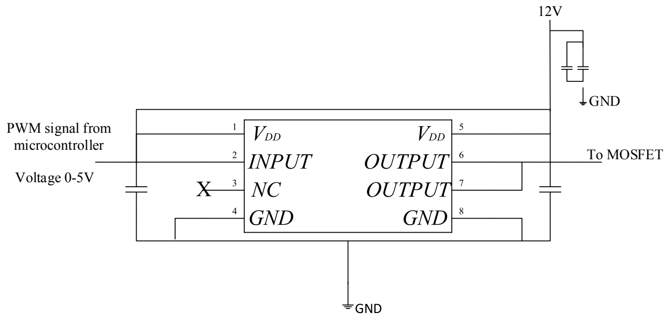

Figure 11: New amplifier circuit with MOSFET driver

D. Inverter

The multilevel inverter is under the control of dSpace. Different control strategies are implemented on the dSpace system. The CHBC consists of three separate 5-level inverter arms (one per phase, see Fig. 3). The three inverter arms were tested separately.

Two of the inverter arms can generate perfect output signals and the waveforms can meet the requirements. In another words two inverter arms can generate a 5-level staircase voltage waveform. However, one of the inverter arms can only produce a three level output voltage. Figure 12 shows the 5-Level output voltage of one operational inverter arm, tested with two ideal DC voltage sources.

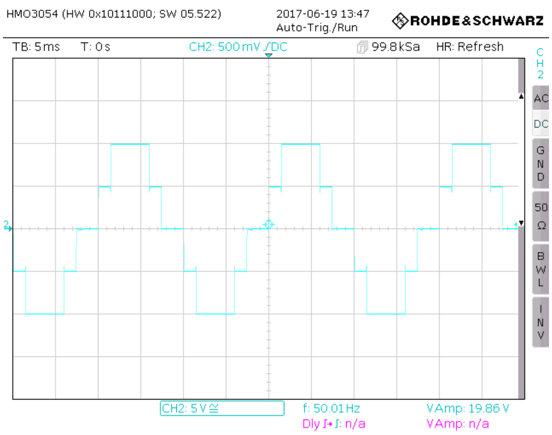

Figure 12: Measured 5-level output voltage

By testing the inverter arm, a defect can be identified in two of the MOSFET half-bridge drivers that are installed to amplify the output signals from the dSpace system.

As the Fig. 3 shows, the inverter consists of two full bridge circuits. When the MOSFET driver of one full bridge circuit is defect, the multilevel inverter works only as a three level inverter. That means, there are only +V, 0, -V at the output.

To solve this problem, the MOSFET drivers have been replaced.

IV. Conclusion

In this papers a module-integrated cascaded multilevel inverter is introduced, which has been disassembled and out of operation for several years. But now the circuit is rebuild and its components are tested and according to the new requirement redesigned. The most remarkable advantage of this type of plant is the higher efficiency compared with the central inverters and the string inverters, because each module can work in its own maximum power point. In addition the modular concept can provide a simple and flexible plant layout, and it is easy to enlarge the solar plant later on.

During the laboratory work two defects have been found and solved. The first problem was that the PWM output voltage from the MPP tracker is not high enough according to the data sheet of the MOSFETs that are installed in the DC/DC converters. The original output signal of the MPP tracker can not fully switch on the MOSFETs which leads to additional losses. The original amplifiers have been replaced to solve the problem. Furthermore, two MOSFET driver at one of the inverter arms were defect and replaced by new MOSFET drivers.

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