Control and Design of an Inverter for Grid Connected Photovoltaic (PV) Generation System and Research Opportunities (A Report of Theorical Review)

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***Abstract*— one type of renewable energy source is the photovoltaic (PV) cell, which converts sunlight to electrical current, without any form for mechanical or thermal interlink. PV cells are usually connected together to make PV modules, consisting of 72 PV cells, which generates a DC voltage between 23 Volt to 45 Volt and a typical maximum power of 160 Watt, depending on temperature and solar irradiation. The electrical infrastructure around the world is based on AC voltage, with a few exceptions, with a voltage of 120 Volt or 230 Volt in the distribution grid. PV modules can therefore not be connected directly to the grid, but must be connected through an inverter. The two main tasks for the inverter are to load the PV module optimal, in order to harvest the most energy, and to inject a sinusoidal current into the grid. The aim of this paper is therefore to develop new and cheap concepts for converting electrical energy, from the PV module to the grid. Research has therefore been done in the field of inverter technologies, which is used to interface a single PV module to the grid. The inverter is developed with focus on low cost, high reliability and mass-production.**

***Keywords*— PV Cell, Inverter, DC/DC Converter**

I. INTRODUCTION

The ‘direct current’ to ‘alternating current’ (DC-AC) inverter concepts for photovoltaic (PV) applications. The PV module is capable of generating electric DC power, when exposed to sunlight. The interest in this topic is especially on inverters where the load is the low-voltage AC public utility network and the source is a single PV module.

The photovoltaic effect is the basic physical process through which a PV cell converts sunlight directly into electricity. PV technology works any time the sun is shining, but more electricity is produced when the light is more intense and when it is striking the PV modules directly when the rays of sunlight are perpendicular to the PV modules.
Sunlight is composed of photons, or bundles of radiant energy. When photons strike a PV cell, they may be reflected, absorbed, or transmitted through the cell.

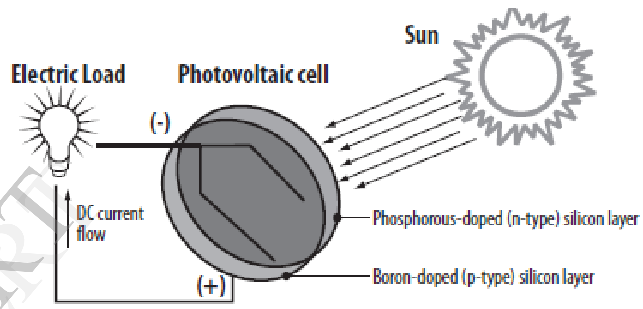

***Fig -1**: Sunlight of Electricity*

A. Size and Shape of PV Cell

PV cells are many shapes and sizes. The most common shapes are circles, rectangles, and squares. The size and the shape of a PV cell, and the number of PV cells required for one PV module, depend on the material of which the PV cell is made.

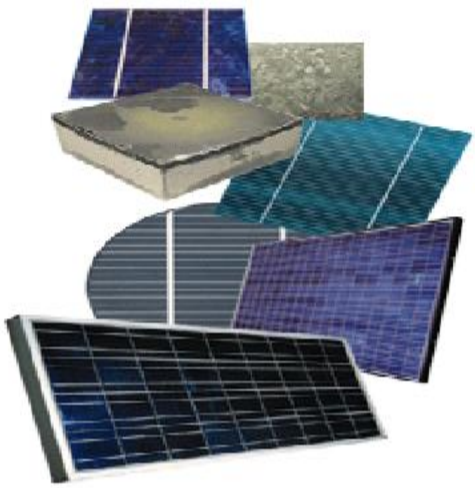

Fig -2: Size and Shape of PV Cell

B. Photovoltaic Arrays are Made up of Individual Cell

For more power, PV cells are connected together to form larger units called modules. Photovoltaic cells are connected in series and or parallel circuits to produce higher voltages, currents, and power levels. A PV module is the smallest PV component sold commercially, and can range in power output from about 10 watts to 300 watts. A typical PV module consists of PV cells sandwiched between a clear front sheet, usually glass, and a baking sheet, usually glass or a type of tough plastic. This protects them from breakage and from the weather. An aluminum frame can be fitted around the PV module to enable easy affixing to a support structure. Photovoltaic arrays include one or more PV modules assembled as a pre-wired, field- installable unit. A PV array is the complete power-generating unit, consisting of any number of modules and panels.

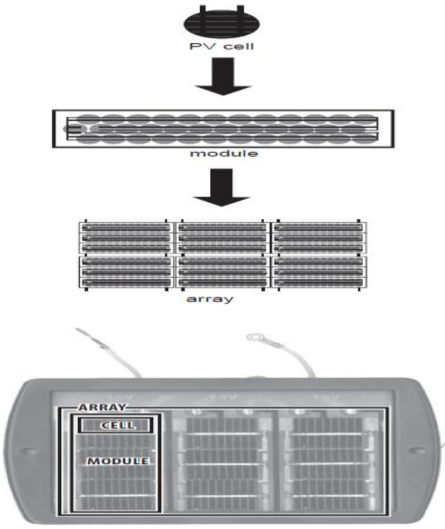

Fig -3: Photovoltaic Arrays are made up of Individual Cell

C. Grid Connected PV System

Grid-connected systems are designed to operate in parallel with, and interconnected with, the national electric utility grid. What is the grid? It is the network of cables through which electricity is transported from power stations to homes, schools, and other places. A grid-connected system is linked to this network of power lines. The primary component of a grid-connected system is the inverter, or power conditioning unit (PCU). The inverter converts the DC power produced by the PV system into AC power, consistent with the voltage and power quality requirements of the utility grid. This means that it can deliver the electricity it produces into the electricity network and draw it down when needed; therefore, no battery or other storage is needed.

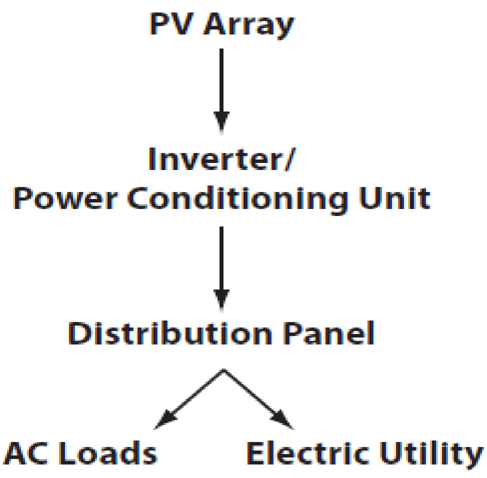

Fig -4: Grid Connected PV System

II. WORKING OF PV CELL

A. Photovoltaic cell

Solar cells are the building blocks of PV array. These are made up of semiconductor materials like silicon etc. A thin semiconductor wafer is specially treated to form an electric field, positive on a side and negative on the other. Electrons are knocked loose from the atoms of the semiconductor material when light strikes upon them. In an electrical circuit is made attaching a conductor to the both sides of the semiconductor, electrons flow will start causing an electric current. It can be circular or square in construction. It is made up of various semiconductor materials. But mono-crystalline silicon and polycrystalline silicon are mainly used for commercial use.

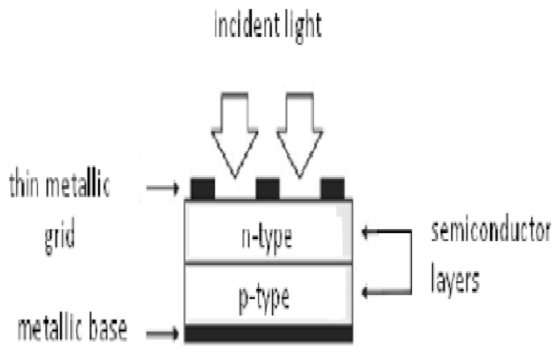

Fig – 5: Basic PV cell structure

Working of PV cell is based on the basic principle of photoelectric effect. Photoelectric effect can be defined as a phenomenon in which an electron gets ejected from the conduction band as a consequence of absorption of the sunlight of certain wavelength by the matter. So, in a photovoltaic cell when sunlight strikes its surface, some portion of the solar energy is absorbed in the semiconductor material. If absorbed energy is greater than the band gap energy of the semiconductor, the electrons from the valence band jumps to the conduction band. By this, pair of hole electrons are created in the illuminated region of the semiconductor. The electrons thus created in the conduction band are now free to move. These free electrons are forced to move in a particular direction by the action of electric field present in the PV cell. These flowing electrons constitutes current and can be drawn for external use by connecting a metal plate on top and bottom of PV cell. This current and voltage created because of its built in electric fields produces required power.

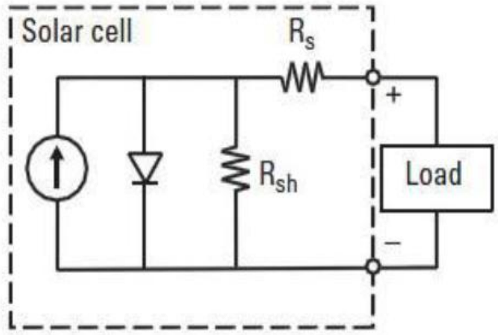

Fig – 6: DC Equivalent circuit

The photovoltaic cell output voltage is basically functioning of the photocurrent which is mainly determined by load current depending on the solar irradiation level during the operation.

$$V_V = (A * K * T_C / e)\ln\left[\left(I_{ph} + I_0 - I_C / I_0\right) - R_S * I_C\right] \quad (1)$$

The symbols used are

V_C = cell output voltage

T_C = reference cell operating temperature

R_S = series resistance of cell

I_{ph} = photocurrent, function of irradiation level and junction temperature

I_o = reverse saturation current of the diode

I_C = cell output current

K = Boltzmann constant (1.38*10-23j/k)

e = electron charge (1.602*10-19c)

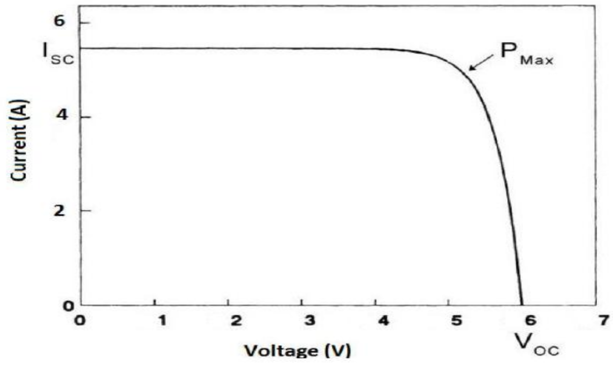

Fig – 7: Typical I-V Characteristics of Solar Panel

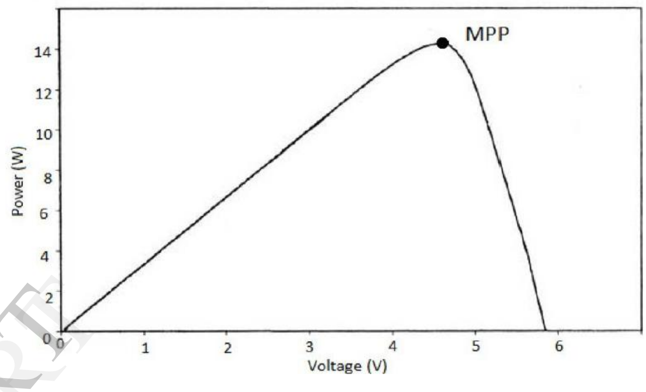

Fig – 8: Typical P-V Characteristics of a Solar Panel

B. Photovoltaic Modules or Solar Panels

Due to low voltage of the individual solar cell (mainly 0.5v) several cells are wired in series for manufacture of a laminate. Then the laminate is assembled into a protective weather proof enclosure thus making a photovoltaic module or solar panel. Modules are then strung together into a photovoltaic array.

A photovoltaic array is a linked assembly of PV modules. Most PV array use an inverter to convert the dc power produced by the modules into alternating current. The modules in a PV array are connected in series to obtain the desired the voltage, the individual string are then connected in parallel to allow the system to produce more current.

A solar or PV inverter converts variable direct current (DC) output of the photovoltaic solar panel into a utility frequency alternating current that can be fed into a commercial electrical grid or it is used by the local or off grid electrical network. It is a critical component in the photovoltaic system allowing the use of ordinary commercial appliances. Solar inverters have special functions adapted for use with the photovoltaic arrays including maximum power point tracking and anti islanding protection.

C. Grid connected PV generation system

Grid connected PV generation system is mainly composed of the PV array, the inverter device with the function of maximum power tracking and the control system. Photovoltaic system use solar panels to convert sunlight into electricity. A system is made up of one or more solar PV panels, an ac or dc power converter that holds the solar panels, and the interconnections and mounting for the other components.

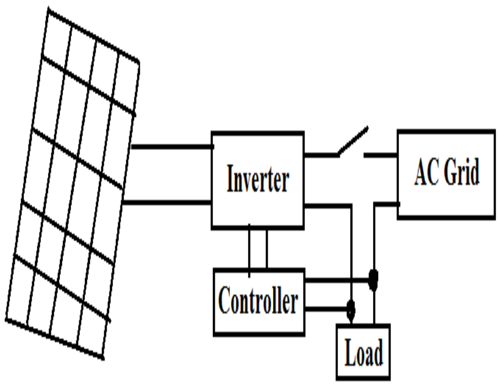

Fig –9: Grid connected PV generation system Structure

III. AIMS OF PV PAPE

A. *Objectives*

The main objective for this paper is to develop an inverter for AC module applications. The target is to develop new and cost-effective solutions for injection of electrical power, generated by PV modules, into the grid. The project must result in an inverter for use with a single PV module, approximately from 120 W to 160 W. The inverter should be made with low-cost, high reliability, and mass-production in mind.

B. *Outline of the Paper*

The photovoltaic device is followed up by an explanation of it principles of operation. This leads into the electrical and thermal models for the PV cell and module. Finally, the behavior of the PV cell and PV module, during different operating point, are explored.
The specifications for the PV module to inverter, and inverter to grid interfaces are given. Some specifications regarding safety and compliances are also mention.
The photovoltaic inverter topology overview gives an introduction to different system layouts, and different topologies within the single- and dual-stage DC-AC inverter families. They include an estimation of power losses and cost for each topology. The estimations are used to select the final topology.
The design of the power-electronic circuits is presented. This includes both the DC-DC converter and the DC-AC inverter.
The design of the controllers included in the PV inverter is documented. They are the Maximum Power Point Tracker, control of PV current control of intermediate voltage, and control of grid current.
The PV inverter is tested, and verified. The tests include the efficiency of the MPPT algorithm (ability to track the MPP), energy efficiency (from PV terminals to grid terminals), and grid performance.
Finally, a conclusion on the obtained results is presented. This also includes the novelties within the work, and suggestions for future work.

IV METHOLOGY

Review of different PV technologies, e.g. mono-crystalline silicon modules and thin film modules is done. The mechanism behind the photon-to-electron conversion inside the PV module was also mention. This ended up with a model of the PV module, taking into account the inherent PN junction and the current generated by the incoming sunlight. Other parts inside the PV module are also briefly described, e.g. resistances and capacitances. The model was used to investigate the role of partial-shadow and voltage/current ripple at the PV module terminals, in respect to power degradation. Based on the analysis of the PV module, the present and expected future standards for the grid-interface, the specifications for the inverter to be designed. The main specifications are: PV module voltage is defined in the range from 23 V to 50 V. Maximum PV power is equal to 160 W. The RMS value of the grid voltage is guaranteed in the span 197 V - 253 V, by the utility companies, and the power factor shall be better than 0.95 at 50% generation (80 W).
Two different systems layouts, the PV module and inverter integrated into one device, placed on the roof, or the inverter situated inside the residence. The selected inverter was designed with the specifications in mind and focus on cost and efficiency. For example, the size of the grid-connected filter was cost-optimized by searching the solution within 15 combinations of different inductor and capacitor sizes, when the resonant frequency of the filter was kept constant. The size of the transformer included in the DC-DC converter was chosen as a trade off between power losses and cost, whereas the size of the DC-link inductor was optimized in respect to its cost.
A dedicated current mode controller (integrated circuit - IC) is used to control the DC-DC converter, where the reference is the current drawn from the PV module. It becomes in this way possible to regulate the operating point of the PV module.
The controllers included in the microcontroller are designed, which includes: a Maximum Power Point Tracker (MPPT) for optimizing the captured energy from the PV module, a Phase Locked Loop (PLL) to synchronize the inverter with the grid, detection of islanding operation, control of the DC-link voltage, and control of the grid current.
A survey of different MPPT algorithms showed that the traditional algorithms all have some problems with finding the Maximum Power Point (MPP). A novel MPPT algorithm has been proposed and tested with both a PV emulator and with real PV modules.
A single phase PLL is also designed for the inverter. Two different implementations of the trigonometric functions were discussed in order to minimize the ripple into the included PI controller when the actual frequency does not agree with the nominal frequency. The frequency output from the PLL is also used to determine the state of islanding operation, together with the determination of the value of the grid voltage. Four different schemes for computing the value of the grid voltage

have been evaluated, and the RMS approach has been identified as the most accurate solution.

The reference for the DC-link voltage is made equal to a function of peak grid voltage and average power injected into the grid, in order to keep the DC-link voltage as low as possible, and hereby lowering the switching losses in the MOSFETs and protecting the electrolytic capacitor in the DC-link. The controller is based on a classical PI controller, where the output from the PI controller is the peak current reference. The values of the parameters included in the PI controller are designed so as not to cause too much third harmonic current injection into the grid, caused by the twice-the-line-frequency voltage ripple in the DC-link. Finally, the grid current controller is also based on the PI controller, with a feed forward of the grid voltage. The stability of the system is evaluated for parameter variations in the grid-connected, reduced order, LR-filter. The stability is also evaluated for the full-order model of the LCL filter, and a proper size of the damping resistor, included in the LCL filter, is determined to obtain a minimum phase system. Three possible voltage feed-forward schemes were shortly discussed, and a 20 ms delayed signal is applied in the control. Compensation of the blanking time effect was also discussed in brief, to reduce the harmonic currents. No compensation should be used, but the blanking time is kept small, without causing shoot-through in the MOSFETs. The evaluation includes measurements on the interfaces between the grid and the inverter, and between the PV module and the inverter.

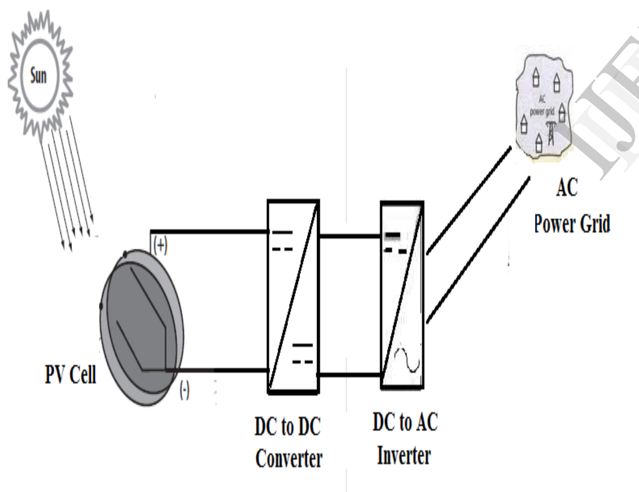

Fig – 10: Block Diagram of Inverter PV System

IV. COMPONENTS.

- Controllers: Control of PV current and control of grid current.
- MPPT: optimizing of the captured energy from the PV module.
- Filter: L filter, LC filter and LCL filter are used.
- Capacitor: Electrolytic capacitors are used.
- IC: IC is used to control the DC - DC converters
- PLL (Phase Looked Loop): to synchronized the inverter with the grid.
- MOSFET: for PWM
- Inductor, diode, oscilloscope and power analyzer, SMPS, measuring circuit, and protection circuit are used.

V. EXPECTED OUTCOME OF RESEARCH WORK

- The main objective for the research presented in this paper has been to develop an inverter for the AC module, which is the combination of a single PV module and a DC-AC inverter connected to the grid. Focus has been on obtaining a low-cost solution with high reliability, i.e. long lifetime, and high efficiency. This has been accomplished by theoretical analysis of cost, efficiency and ratings for many different inverter topologies, on which basis a topology was selected for further design. The design of the selected topology was also based on theoretical analysis, supported by numerical simulations and measurements on the realized prototype. The main conclusions for this research are listed here -

- A theory for the reduction in available power from the PV module, as function of low frequency ripple in the modules voltage and current, is presented. The theory predicts a power loss of 1%, i.e. a utilization ratio of 99%, for a mono-crystalline PV module when the amplitude of the ripple voltage is equal to 6% of the MPP voltage, and a loss of 2% when the ripple equals 8.5%. The desired lifetime for the inverter is equal to 25 years, based on the specified PV module lifetime. It is concluded that the capacitor must be placed in the DC-link, between the two power stages, if the inverter is to be integrated with the PV module. On the other hand, the capacitor can either be placed in parallel with the PV module or in the DC-link if the inverter is to be placed indoor. The conclusion is based on measured daily maximum temperature over a span of ten years, and computed monthly maximum solar irradiation.
- Two novel inverter topologies, the modified Shimizu inverter, and the isolated fly back in parallel-series connection, were presented. Both inverters offer good power decoupling with small capacitors, the fly back inverter even with film capacitors, but they suffer from large internal currents that results in low efficiencies.
- A method for analytic comparison of different inverter topologies, with focus on component stress and ratings, cost, and efficiency, is proposed. The methodology ensures that the components in the different topologies are exposed to the same amount of electrical and thermal stress, so as to make a fair comparison.
- A novel Maximum Power Point Tracker (MPPT) algorithm, which solves some problems within the standard algorithms with tracking the MPP during partial shadow of the PV module and rapid changes in the weather conditions, is proposed. The algorithm initially locates the global MPP by sweeping (scanning) the voltage current characteristic of the PV module. The co-ordinates for the MPP is recorded, and the recorded MPP current is used as a new reference for the next period of normal operation (non-scanning period), until the voltage across the PV module changes more than from the recorded MPP voltage.
- Finally, the realized prototype is tested against the specifications. The measurements show that the inverter is

close to keep all the demands, which include operating range (voltage and current) for the PV module, and the grid, interfaces. The grid voltage monitoring is capable of detecting islanding operation, within the specified range, but the frequency monitoring is omitted in the prototype and therefore not tested.

VI. Conclusions

The photovoltaic (PV) module is an all-electrical device that converts sunlight into electrical DC power. Solid-state power electronic inverters have been used to connect PV modules to the AC utility grid since the early seventies. The inverter has two major tasks: to inject a sinusoidal current into the grid, and to optimize the operating point of the PV modules, to capture the maximum amount of energy.

Large, megawatt, PV systems were connected to the grid in the eighties, but the trend is now to connect smaller systems to the grid, in order to overcome certain problems, like non-flexible designs, mismatch losses between the PV modules, etc.

These systems are either based on the string-concept, with multiple modules connected in series, or on a single PV module.

The main objective for this research was to develop an inverter for the AC module, with special focus on cost, reliability, and efficiency. A topology, among several different, has been pinpointed as the best candidate based on detailed analysis. The inverter has been optimized in respect to cost, reliability, efficiency, and a prototype has been build and tested.

VI. Future work

There are many interesting aspects and many problems to be investigated in the future.

Some of them are listed here -

- Diagnosis of the PV modules and determination of the series resistance, in the modules and connections, can inform the operator to inspect the systems for bad connectors, and suggest her/him to remove the source of the partial shadow (e.g. a local impurity of the modules).
- A deeper investigation of the inverters lifetime, based on hourly temperature variation and the applied power semiconductors, is probably needed to reach the desired lifetime of 25 years. The analysis applied in these paper only accounts for the daily maximum-temperature inside the applied electrolytic capacitor.
- Burst-mode operation should be analyzed in depth and tested on the realized prototype in respect to increased efficiency and degradation of grid performance. It is believed that burst-mode can increase the efficiency, but it may also cause flicker on the grid, if large amounts of PV power is installed.
- An active clamp circuit should be included in the DC-DC converter to lower the requirements for the diodes included in the rectifier, and to increase the efficiency.
- Cost and loss comparison of the voltage-source DC-DC converter, which is applied in this research, and the current-source DC-DC converter. The current-source converter also solves the problems with the requirements for the diodes included in the rectifier, but other problems may appear.
- Further investigations of different controllers for the grid current, e.g. the resonant controller, and repetitive control for cancellation of harmonic currents are interesting. The effect of compensating the blanking time should be investigated, to get a better grid performance in terms of lower harmonics, etc.
- The inverter should be tested for immunity to abnormal grid operation, e.g. voltage swells and sags, and phase jumps. Besides, the immunity to notches and spikes should be investigated.
- Analyze the impact on the grid performance (power quality) when multiple inverters are connected to a local grid. Especially, the effect from different waveform generators, for the current reference, and different current control strategies should be investigated. Both when the grid voltage is a pure sinusoidal and when it contains harmonics.
- Make a SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis of the AC module concept, to see whether it is better than other concepts, e.g. the string and the multi-string concepts.
- Finally, the next step for product development is to optimize the inverter in respect to the microcontroller, the switch mode power supply, measuring- and protection circuits, etc.

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