Modeling Grid Connection for Solar and Wind Energy

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***Abstract*—Modeling of grid connected converters for solar and wind energy requires not only power electronics technology, but also detailed modeling of the grid synchronization and modulation techniques. Control of active and reactive power in both single and three phase grid connections can be achieved by quadrature controllers, analogous to field oriented control in electrical drives. Modulation strategies, loss determination and thermal cycling, as well as life time estimation are important factors that can be studied into detail during simulation.**

***Index Terms*—Modeling, Simulation, Wind, Solar, Grid Connection, Grid Synchronisation**

I. Introduction

Grid connected converters are required to transfer harvested green energy from wind and solar systems into the main grid. The importance of the single-phase grid connection for PV and wind power systems should not be underestimated. It is one of the key components when it comes to stable, and efficient power transfer from the solar or wind power system into the grid. Not only grid-synchronization, also EMI problems, harmonic regulations and efficiency are important design issues that have to be solved.

Although it looks fairly simple at first sight, the transfer of DC power from the solar or wind power system to the grid can be categorized into various solutions. Depending on the size of the PV-system and the arrangement of the solar panels, the following combination of solar panels is possible:

Solar Panel:
Parallel and series connected solar cells.
Solar Module:
Parallel and series connected solar cells including bypass diodes.
Solar Array:
Parallel and series connection of solar modules.
Solar string:
Series connection of solar panels.
Solar Multi String:
Parallel connection of solar strings.

The PV inverters are categorized depending on the PV power plant configuration.

50 – 500Watt:
Here mostly one solar panel is used where the inverter is integrated into the solar module. Typically used for feeding on remote locations of Measurement Stations or traffic lights.
500Watt – 2kW:
For small rooftop plants, one solar string is used.
1.5kW – 6kW:
Larger rooftop plants are configured either as solar string or solar Multi String.
6kW – 100kW:
Three-phase grid connection is applied here with solar multi string or arrays.
> 100kW:
Three phase grid connection and central configured grid inverters.

The first grid connected inverters were based on Silicon Controlled Rectifiers (SCR) technology which were also limited in control and came with a high harmonic content, making the use of bulky inefficient filters necessary.
With the introduction of Mosfets for the lower power area and IGBT's for the high power applications, the control of grid side inverters became more advanced.
The primary concern in grid converter design is the efficiency, mainly driven by the high cost of solar energy. This resulted in large variation of PV grid converter. Compared to motor drive inverters, the grid-connected converter is more complex as it includes extra features such as MPP control, and grid synchronization. The power electronics design is more complicated compared to motor drives, because of the grid connection and safety. EMI problems are of special interest especially those associated with leakage currents from the solar panel to the earth.
For electric motor control two-phase and three-phase bridge inverters are the standard technology. However for PV systems different topologies exist, especially for single-phase grid converters.
The first main concern regarding the design of grid connected converters is efficiency, due to the costs of solar produced energy. Secondly, since the lifetime of PV panels typically goes beyond 20 years, also the lifetime of the grid-connected

inverter becomes a design issue. This means extra effort regarding the thermal design. The first attempt to improve efficiency is to remove the transformer, either from the low voltage as from the high voltage side. This improves the total efficiency with 2 to 3 % since core-losses were eliminated.

II. Multilevel Modeling and Simulation

Multilevel modeling and simulation in the field of green and renewable energy is a broad topic. In the first place the systems are very diverse, like wind and solar, but also the physical background of each type of green energy system varies greatly. For the modeling and simulation, this leads to two observations that have to be taken into consideration:

- Physical background of the underlying system
- System or detailed of the model of systems under investigation

First, for example, wind energy requires knowledge on electromagnetic energy conversion, while solar requires knowledge on semiconductor devices. Control in solar systems is mostly a sort of a smart search algorithm that finds the optimum electric load for a solar module, while in wind power systems, the control is clearly dependent on the wind speed. Generally speaking, various technologies are used when working with green energy systems.
Secondly the multilevel character of green energy applications is very clear. The components can de modeled as simple system blocks with clearly defined functions, but on the other hand multilevel models including all details can model them. For example, generator modeling in FEM and detailed semiconductor models in solar modules, compared to the modeling of algorithms in Maximum Power Point controllers. For grid connected converters the multilevel modeling concept is used extensively for the main purpose of making a distinction between the model for the grid converter and the model of the grid synchronization.

III. Solar Power Grid Converters

A. Transformer based PV design

Single-phase grid connection is not as simple as it would look at first sight. Regulation on injected harmonics and the efficiency of the inverter are important factors. Inverters that have a galvanic isolation by means of a transformer have a low efficiency. They are employed in many commercial grid-converters and can be classified as low-voltage side transformer and high-voltage side transformer. The basic topology for a low voltage side transformer based converter is shown in figure 1.

The DC-DC convert is mostly of the type Forward of Flyback, since they provide galvanic isolation through their coupled inductors. Here the transformer is a high frequency device (20kHz) and therefore the volume of transformer is smaller than a comparable low frequency (50Hz) transformer.

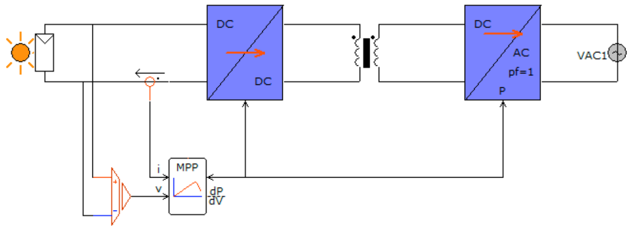

Figure 1: Low Voltage High-Frequency transformer based.

The second approach is to have the transformer at the high voltage sideas shown in figure 2.

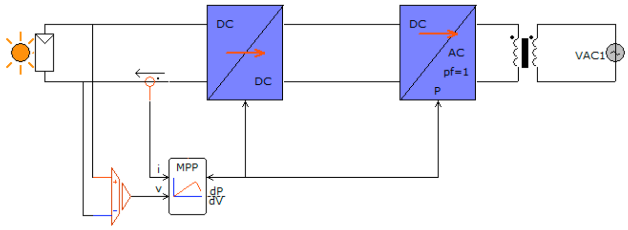

Figure 2: High Voltage Low-Frequency transformer based.

Here the transformer is larger in volume compared to the low-voltage transformer design, because the operational frequency is much lower (50 Hz or 60 Hz).
A typical topology for a low frequency high voltage side transformer based converter is shown in figure 3[Ertl]. Here the boost converter creates a sinusoidal modulated DC voltage that is connected via the coupled inductors to the main grid.

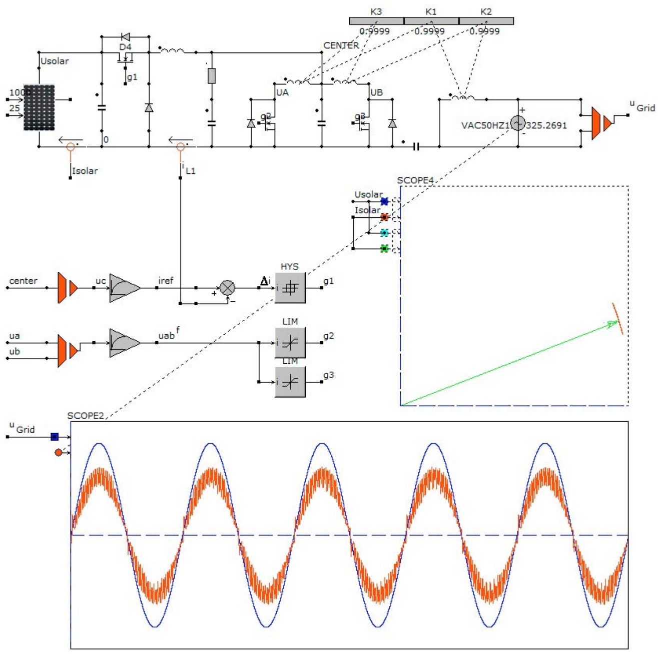

Figure 3: Transformed based design

Although isolation comes naturally with the transformer-based designs, they have a number of disadvantages, from which efficiency is the main drawback.

The main disadvantage of the galvanic isolation is the core-loss in the coupled inductors and therefore the transformer-less grid converters were developed.

B. Transformer-less based PV designs

To overcome the inefficiency of the transformer, a high voltage has tot be generated directly by the solar cells or by a boosting DC-DC converter.
Especially with large solar strings, the generated voltage might be high enough to be used directly without a boosting DC-DC converter. However, keep in mind that a DC-DC converter is still of practical use for the MPP controller, as it gives a stable DC bus voltage for the grid connected inverter.
A second note is on the boosting converter, which has a limited voltage transfer level.

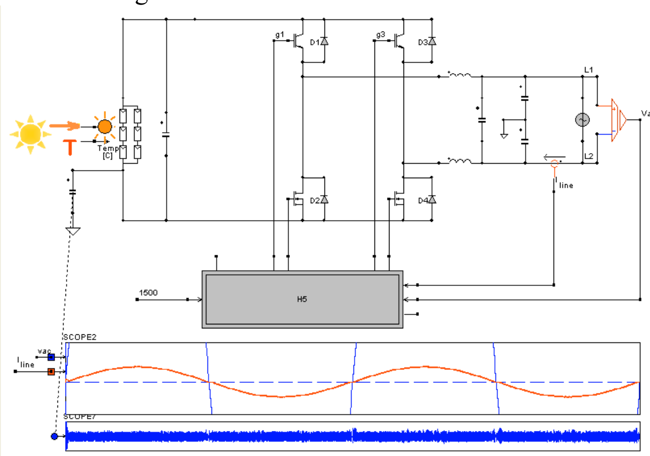

Figure 4: Full Bridge converter

Figure 4 shows a full bridge converter connected to a solar multi string. The output voltage of the solar multi string is such high, that the inverter can directly use it to inject currents into the main grid.

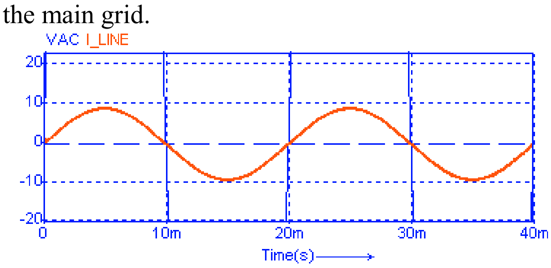

Figure 5: Full Bridge converter Grid injected current

The waveform of the grid-injected current is displayed in figure 5 and shows a low harmonic content. There is however one serious drawback of the full bridge converter, being a leakage current through the solar panels to the earth.

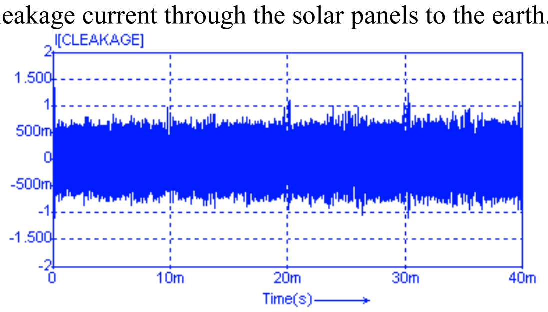

Figure 6: Full Bridge converter leakage current

The leakage current is too large for practical applications. In the transformer based designs this leakage current didn't exist because of the galvanic isolation of the transformer. One method to get rid of the leakage current is the H5 converter [Victor M. et al] as shown in figure 7.

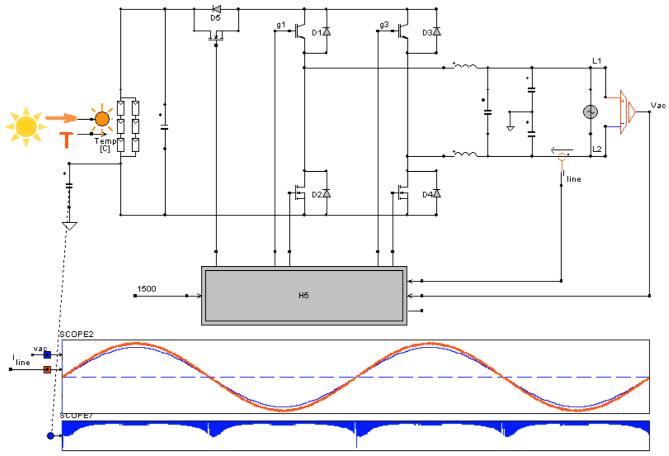

Figure 7: H5 Full Bridge converter

In the H5 converter, an extra switch is included that disconnects the DC input during the zero voltage state of the output of the converter. As result, the leakage current reduces from close to 1Amperes to less 20mA on average, as shown in figure 8. Compared to the leakage current for a full bridge converter as shown in figure 6, this is a remarkable reduction.

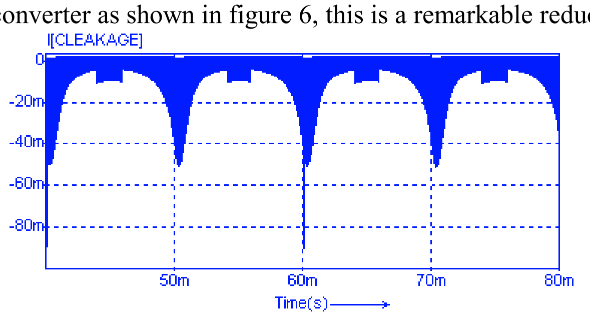

Figure 8: H5 Full Bridge converter leakage current

C. Grid Connect Solar converter with MPP

This example shows the control of a grid-connected solar system. Figure 9 shows the circuit model including the MPP control and grid-connection control.
A detailed second level circuit model that includes load dependent loss and temperature dependency models the solar module. A boost converter that regulates the MPP for the solar module electrically loads the solar module. The boost converter is also modeled as a second level circuit model. The MPP controller is a first level system model that calculates the derivative of the power as a function of the voltage of the solar module. Together with the first level system model for the PI controller, the amount of power harvested by the solar module is maximized. The last part is the grid connection. Here a first level system model for the inverter and control is used. This simulation shows the mixture between the various levels in modeling.

Since all models are connected in a circuit level model, the u-i interactions can be studied as well as the MPP control part. The single-phase grid converter is a very simple system level model that only controls the current delivered to the single-phase grid. In a more detailed study, the complete single-phase inverter with controlling algorithm and modulation strategy as well as grid synchronization could be applied. However for studying the behavior of the MPP controller, this simplified system level model suffices.

Scope 1 in the Caspoc simulation in figure 9, shows the u-i characteristic of the solar module. Small circles indicate the characteristic, while the arrow points to the current point of operation. Scope 2 shows the grid-side current, which is in phase with the grid voltage. Scope 6 shows the amount of power delivered by the solar module and the amount of power delivered to the grid.

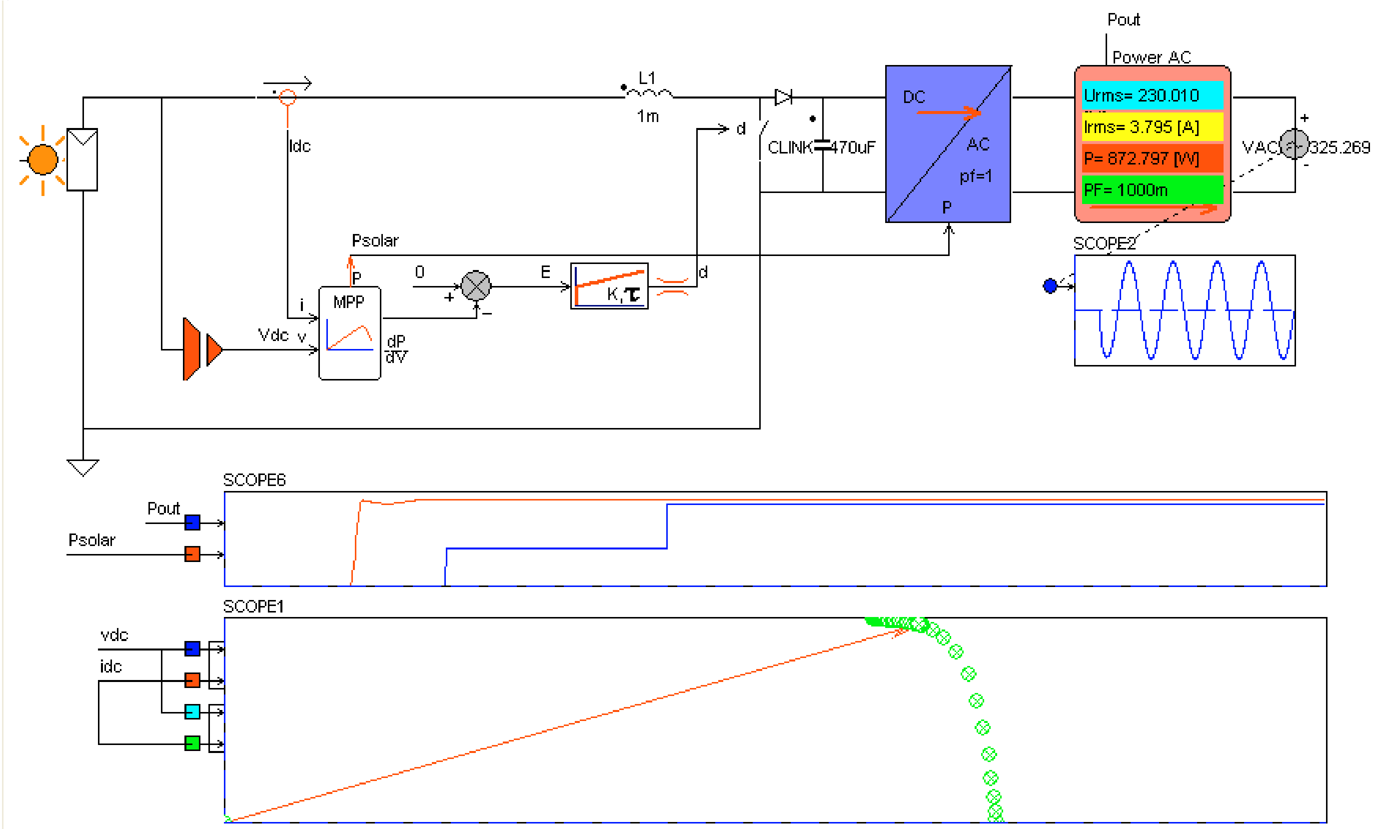

Figure 9:Solar module with boost converter, grid connection and MPP control

IV. Wind Power Modeling

A. Wind Turbine Maximum Power Control

The wind energy example shows an overall system simulation of a wind power system. A more detailed second level circuit model can replace every single component in this first level system simulation. In this example, only the wind speed to rotor angular speed ratio (tip speed ratio [TSR], λ) is modeled in a circuit level model. Also third level component models or even a mix between first, second and third level models would be possible in this type of simulations.

Figure 10 shows a grid connected wind turbine system with optimum power control, modeled in Caspoc. The maximum amount of power a wind turbine can deliver is equal to $k\omega^3$. Therefore the control electrically loads the wind turbine generator such, that it subtracts exactly $k\omega^3$ Watts from the wind turbine and thus keep the system in equilibrium. For varying wind speed, the control directly adjusts the amount of power drawn from the wind turbine generator and also controls the amount of power delivered into the main grid. A second level circuit model models the wind turbine, where the ratio between the wind tip speed and rotor angular speed determines the amount of power the wind turbine can deliver. This model is a minimum requirement when investigating the behavior for varying wind speed. The generator is modeled as a first level system model, as the primary goal is to study the stability of the overall control system. The wind turbine includes the TSR dependent power coefficient $C_p(\lambda,\beta)$, where λ is the TSR and β is the pitch angle of the rotor blades. The characteristic of $C_p(\lambda,\beta)$ is shown in scope 2 in figure 10 and this curve can be specified either by analytical equations, or by a look-up table from measurement results. The amount of mechanical power P_m is displayed in scope 1 as function of the angular rotor speed. Inside the “Maximum Power Control”, the electrical power is calculated and controls the combined system level Generator/Inverter model. The left side of this model is the shaft of the generator, while the right side is the electrical connection to the grid. The remaining scopes in figure 10 show from top to bottom, wind speed and angular shaft speed, grid-side voltage and current, mechanical and electrical power. The scopes clearly show the dependency of the amount of power delivered to the grid on the wind speed.

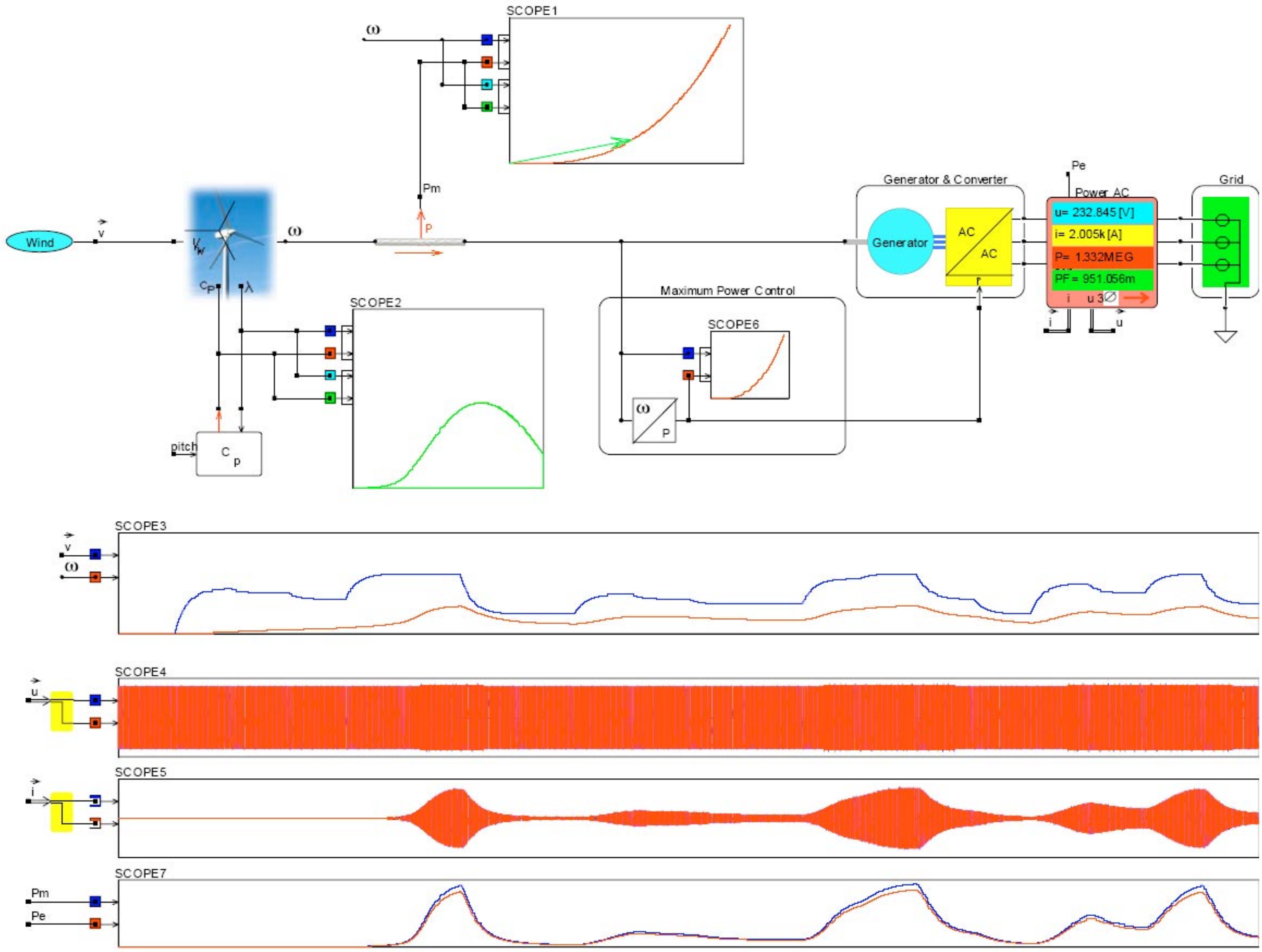

Figure 10: Wind turbine with grid connection and maximum power control

B. Three-phase wind power grid connection

Only the squirrel cage induction machine in a wind generator is capable of delivering power directly to the grid without any power electronics. For control purposes the generator systems of wind turbines and the DC output from the solar modules are connected to the grid via power electronics. The grid connection serves merely two main purposes; scaling and power factor control.

Important when modeling wind power and solar systems are the detailed power electronics converters. Not only the control of the generator via power electronics, but also the calculation of losses of the power electronics has to be modeled in detail. Furthermore the modulation principle has a severe impact on the generation of harmonics on the grid side.

A grid connection could be made using a hysteresis controller. The harmonics produced by the inverter are rather large and unpredictable since the base switching frequency is not fixed.

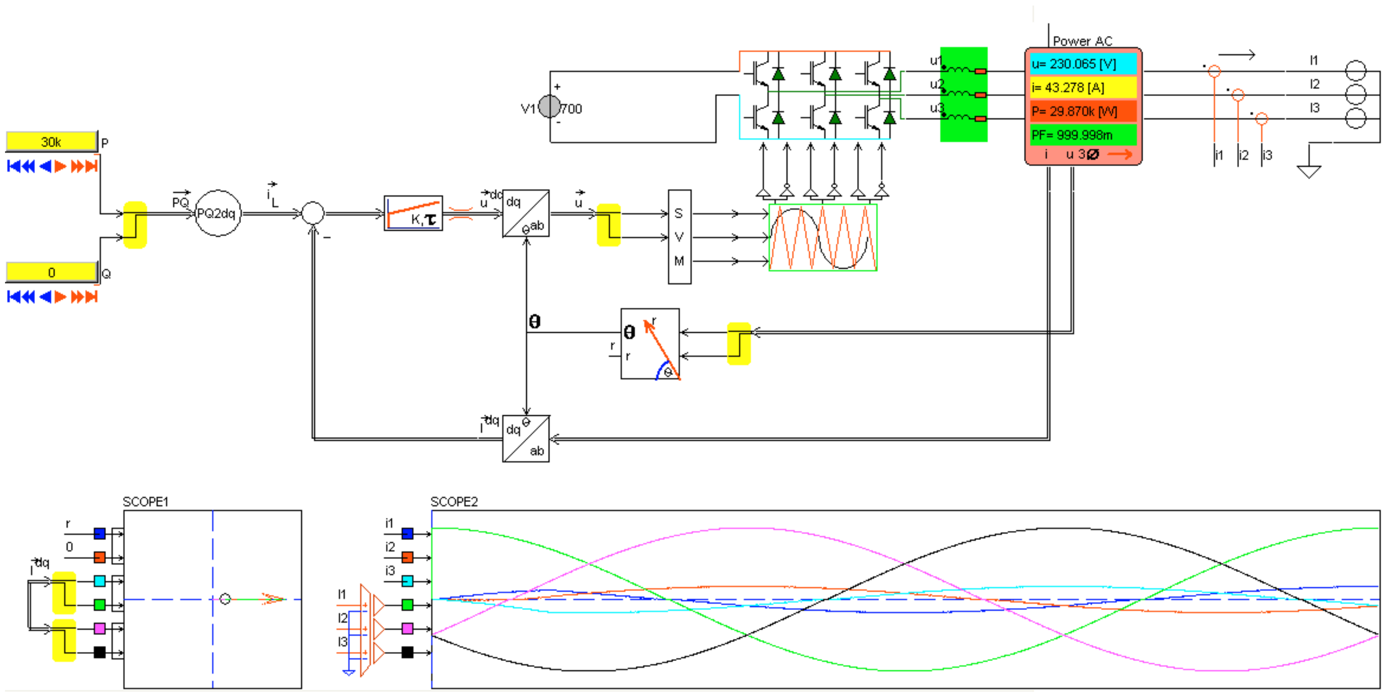

Figure 11: Grid connection with Space Vector Modulation (SVM)

Instead of a hysteresis controller, a PQ controller combined with Space Vector Modulation (SVM) is be used, to generate the three phase current injected into the grid. Here the grid voltages as well as the injected currents are measured and using a PI controller, the error between them is minimized.

V. Conclusions

Multilevel modeling allows the combination of various levels of models to be interconnected. Depending on the required simulation models system models can be employed for overall system behavior and can be interconnected with detailed component models. Concentrating on the minimum required levels in a model reduces overall simulation time and does not overcomplicate the total model.

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