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Smart Grid Research and Development Platform

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Abstract

For several years the Fraunhofer Application Center for Systems Engineering has been running the "ICT-Energy-Lab". It is based on state of the art information and communication technology (ICT) and used to investigate issues of current and future energy supply. Within a funding program of the German federal government the "ICT-Energy-Lab" had been enhanced. This paper outlines the components and research capabilities of the laboratory as well as first results.

Keywords: Smart Grids, Energy management, Distributed Generation, Energy Storage

I. Introduction

In 2006 the Fraunhofer AST – Fraunhofer Application Center System Engineering – in collaboration with the Technical University of Ilmenau planned to establish a laboratory on the field of energy management, energy data management and SCADA systems. It is motivated by the rapid change of the energy systems by increasing distributed generation and the need of control, management and optimization solutions. The implementation process was completed in February 2008 and the "ICT-Energy-Lab" (see Figure 1) was inaugurated.

ICT-Energy-Lab

Figure 1: Logo "ICT-Energy-Lab"

But there was a single flaw. The "ICT-Energy-Lab" did not have any facilities to take influence on. All units (generation plants, consumers) were connected unidirectionally only to provide data of feed-in power or power consumption.

Within a funding program of the German federal government the Fraunhofer AST got the chance to close this gap. The project "Smart Grid Management" was planned to enhance the existing laboratory. Several generation facilities, storage facilities and electrical consumers were installed and embedded in the existing SCADA system. It enables the development and testing of new algorithms and control concepts for distributed generation units and energy storage. Providing a variety of different energy facilities the "ICT-Energy-Lab" in combination with the "Smart Grid Management Demonstrator" is a unique research, development and testing platform of future energy supply.

II. The Smart Grid Management Demnonstrator

A. Components

The SCADA system is one of the major components of the "ICT-Energy-Lab" to aggregate data from various generation plants located at the Fraunhofer Application Center and all over the federal state Thuringia. Storage systems and electrical consumers are also connected to the SCADA system to monitor and control consumption, feed-in and current state of the facilities. The communication protocol IEC60870-5-104 is used to transmit commands and measured data. Several units are embedded by using proprietary protocols which have to be translated to IEC60870-5-104. Investigations on the operation of energy facilities in a virtual power plant are performed by utilization of a self-developed energy management and energy data management system. This software also offers master data management, supplier change management and time series management. It is used by public utilities as well as transmission grid operators. Using grid simulation tools, e.g. DIgSILENT PowerFactory or MATPOWER toolbox at MATLAB (The MathWorks), it is possible to compute the power flow between generation plants and consumption. To establish a Smart Grid and in consideration of an increasing number of distributed generation units these information are required to operate the whole system in an optimal way.

Apart from the software components the electrical facilities play an important role. Within the project different photo-voltaic systems were installed. Three two-axis tracking systems with a rated peak power at approximately 11kW and three rooftop mounted photo-voltaic systems with a rated peak power at 7kW converting solar energy into electrical current. All six facilities are connected via inverters to the local grid. Furthermore the Fraunhofer "Smart Grid Research and Development Platform" has a small scale wind power station with a rated power at 20kW. Contrary to classical design it is build with a vertical axis of rotation (see Figure 2) based on a concrete pylon and 14m high. Thus it is much quieter and independent from the wind direction. The load site is represented by a geothermy pump, a heater battery, electric cars, domestic appliance and a flexible electronic load. Guideline for the electrical consumption of the geothermy pump is the demand of heat within the building containing the experimental equipment. As well the heater battery can be used to heat this building but the electrical load can be influenced directly via the SCADA system to emulate specific load characteristics. Its rated power is about 10kW. The flexible load can also be used to emulate specific load characteristics and in addition it is able to cause disturbances on the grid allowing analyzing their effects on insular grids. The deployed domestic appliance is integrated into a home automation system. This management and control system allows taking an influence on the customer's power consumption.

Figure 2: Wind power station at a rated power of 20kW with a vertical axis of rotation (overall height approx. 21.5m; rotor height 6.6m)

Other vital components of future the Fraunhofer "Smart Grid Research and Development Platform" are several energy storage systems to balance the fluctuating feed-in from the photo-voltaic systems and the wind power station as well as the installed energy consumers. Mid- and long-term storage is realized by a Vanadium redox flow battery which provides a capacity of 100kWh at a rated power of 10kW. The battery is connected to the grid via inverters. In the case of operating in insular grid mode these inverters have to control the insular frequency and voltage via active and reactive power flow in or out of the battery. Additionally two short-term flywheel storage systems at a rated power of 10kW respectively 15kW are available. Although the storage capacity is much lower than at the redox-flow battery these systems are used to compensate power fluctuations, e.g. gusts of wind, at the smart grid very fast providing their rated power over a 15 seconds time period.

Due to the increasing importance of electrical powered mobility the "Smart Grid Research and Development Platform" has two electric city vehicles and a charging station equipped with a measuring system. The vehicles are used to capture realistic driving and usage profiles. In association with the charging station it is possible to analyze the influence of the growing end costumers load caused by electric cars and the influence on the grid state and stability.

PMUs – phasor measurement units – are used in wide area transmission grids to monitor the grid and the power flow over the transmission lines and cables. Within the "Smart Grid Research and Development Platform" PMUs are going to be installed at secondary substations within the distribution grid of Ilmenau. Utilizing a high resolution measuring system new methods and algorithms to ensure respectively to increase power quality, safety and stability will be developed. It also allows fault recording and analyzes.

Also very important are data about the climate conditions. Therefore a weather observatory was installed to capture air temperature, global irradiance, humidity, wind speed and wind direction. These data is used as input parameters for forecast algorithms to predict the power generation from the wind station and the photo-voltaic systems.

B. Realizing the Smart Grid

Investigations on different scenarios of the operation of distributed generation facilities are the main goals of the project "Smart Grid Management". To realize these scenarios a flexible wiring is mandatory. As a consequence it is possible to arrange e.g. wind power generation, redox-flow battery and the flexible electronic load in one insular grid. Figure 3 shows the implemented wiring including switches, the previously described components as well as the ASB – Automatic Switch Box. The main task of this component is to connect the redox-flow battery to the grid and to manage the switching between the operation parallel to the pre-located distribution grid and insular operation. In the case of reconnecting to the public grid phase and magnitude of voltage of the insular grid has to be synchronized to the public grid. This is guaranteed by the applied logic at the ASB.

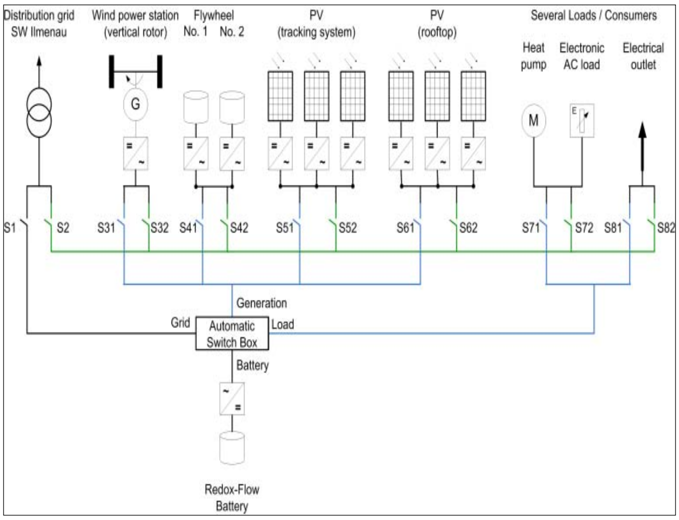

Figure 3: Wiring plan (green: wiring system for grid paralell operation; blue: wiring system for insular operation; black: common wiring system)

As it can be seen every group of generation or consumption facilities is connected via two switches Sna (n from 3 to 8) to the insular grid (a equals 1) and to the public grid (a equals 2). To avoid faults caused by asynchrony between insular grid and public grid it is not possible to close Sn1 and Sn2 at the same time. Switches S1 and S2 are not interlocked.

Opening S1 effects the establishment of an insular grid however a fast balancing between generation and consumption has to be guaranteed e.g. by load control via the flywheel storage systems. Secondary control can be realized by the redox-flow battery and its inverters by providing the lack of energy generation respectively absorbing the excess quantity of generation. Reclosing S1 the ASB starts the synchronization of the insular grid to the public grid and reconnects in state of synchrony.

C. IT network topology

Capturing of measurement data and the operation of the distributed facilities is realized by the SCADA system SICAM230. Like described above it is based on IEC60870-5-104 via IP. A local area network (LAN) connects the centralized SCADA server to the distributed automation and control devices at the "Smart Grid Research and Development Platform". Additionally a wind farm near the city of Erfurt and photo-voltaic systems at the village Kettmannshausen are embedded via a wide area network (WAN) over GPRS connections. To defend the IT network of the "ICT-Energy-Lab" from unauthorized access a gate protection firewall is used.

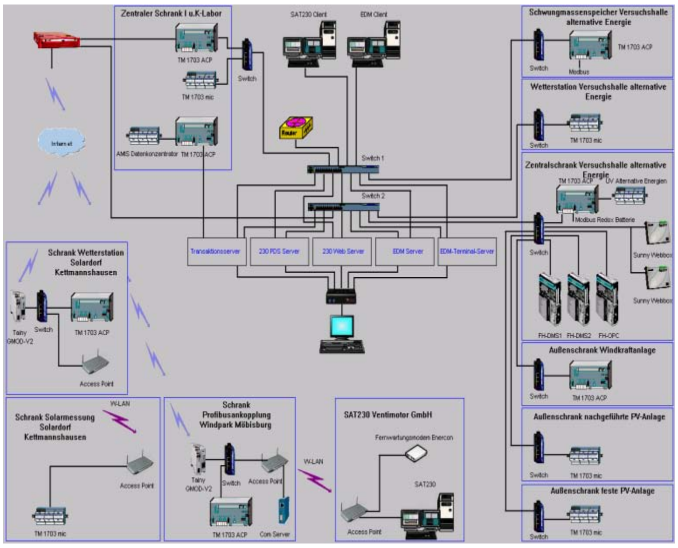

Figure 4: Topology of the IT network connecting the different remote control units of the distributed control system (screen shot from the SCADA system SICAM230 at the "ICT-Energy-Lab")

The distributed automation and control devices manage the communication with the energy facilities utilizing different standardized but also proprietary protocols. OPC[1] is used to connect the redox-flow battery as well as the photo-voltaic systems. The flywheel storage systems are connected via the MODBUS protocol. All other components provide their data respectively receive their commands via analog or digital signals over Input/Output (I/O) components at the distributed automation and control devices.

The process of put the "Smart Grid Demonstrator" into operation has shown that the interoperability of the different systems and protocols is hard to manage. In the future the IEC61850 standard will make it much easier to network the facilities and software modules.

III. Focus at Research & Development

This section outlines the research and development (R&D) interests of the Fraunhofer AST to be investigated utilizing the "Smart Grid Research and Development Platform". Offering a large variety of software and hardware systems on the sector of energy management and distribution the laboratory allows studies on the following issues:

- Simulation analyses on the effects of fluctuating distributed generation on the distribution grid.
- Developing and simulation analyses of new methods and processes for a holistically economic and ecologic optimal operation of energy systems. Very important is the consideration of the grid structure and to detach from the copper-plat view. Apart from fluctuating distributed generation the R&D activities consider about distributed storage systems (mobile and immobile), virtual power plants (VPP) and virtual storage systems realized by Demand-Side-Management (DSM) aiming for an increase of total system efficiency, minimization of CO_2 emission as well as the coordinated operation of distributed feed-in.
- Simulation analyses on an optimal operation of the total system under consideration of the requirements of the liberalized energy markets where information of generation, gird and trading are separated.
- Analyzing and developing the technological requirements at the field of ICT and IT systems for a technological and market orientated integration of distributed generation as well as storage systems.
- Analyzing and developing numerical protection and control algorithms especially for distributed generation facilities.
- Providing a test platform for control system components of commercial providers of control systems.
- Developing strategies and business models for a direct marketing of renewable energy sources e.g. for the operators of wind farms.
- Providing a research, development and testing platform for Advanced Metering Management (AMM) systems as well as e-mobility.

[1] OLE (Object Linking and Embedding) for Process Control based on DCOM specifications by Microsoft; standardized software interface to enable data exchange between different applications

The listing of R&D issues does not claim to be all-embracing but gives a well overview over the possibilities of the “Smart Grid Research and Development Platform” and the “ICT-Energy-Lab”.

IV. RESULTS

A. Data acquisition and integration into the existing ICT-Energy-Lab

As described before the ICT-Energy-Lab is equipped with a SCADA system to control distribution grids normally utilized by small and middle size public utilities. The new constructed systems were integrated into this system to capture the generation, load and further state data. Due to a multitude of different protocols this is one of the major challenges putting the total system into operation. Protocols and measurement values directly transcribed to IEC 60870-5-104 within the programmable logic controllers (PLC) are listed below:

- PROFIBUS DP,
- MODBUS and
- digital and analogue process measurements.

But the integration of the process data captured by the SMA [2] inverters is not suitable via IEC 60870-5-104. The proprietary SMA protocol is not supported by the manufacturer of the SCADA system. To make the data available the OPC interface of the SCADA system is used. For this purpose the data captured by the inverters is send via two-wire line to two *Sunny Webboxes* (also a product of SMA) and provided to an OPC server. The SCADA system acts as a client and communicates with the server for data exchange of measurement values, messages and commands.

A disadvantage of the chosen solution is the high latency period of the signals complicating respectively making grid control impossible. Applying other communication protocols or solutions for the integration is necessary. One approach suggested by the manufacturer of the SCADA system is to implement the transcription of the proprietary SMA protocol to IEC 60870-5-104 directly into the PLC.

To be able to evaluate the experiments and test series respectively to create a data pool for future analyzes it is essential to archive the measured data. The measurement equipment captures and transmits spontaneous values i.e. changes of values are transmitted to the SCADA system. Packing these data to 1-minute mean values before storing them at a data base is a good compromise between resolution and quantity of data (memory requirements). In particular cases as well as for short periods of time the capturing interval can be set to 1-second spontaneous values. At this a limitation on single values or components of the smart grid at the R&D platform is useful. Meeting the demands of experiments and research works are enabled.

a) Redox flow battery

A multitude of parameters are captured for the core of the Smart Grid Demonstrator, the redox flow battery. But this paper concentrates on the state of charge (SoC) as well as relevant DC values like battery voltage, charge and discharge current.

Figure 4 shows the characteristics of the inverter power, the battery voltage and the state of charge of a test run to evaluate the behavior of the redox flow battery. It is obvious that charging and discharging conducting totally different. At a SoC of about 75% the charging power begins to decline. If the SoC reaches 90% a further charging is almost impossible and a conservation of the SoC occurs. However, the discharge power remains constant until reaching a SoC of 20%.

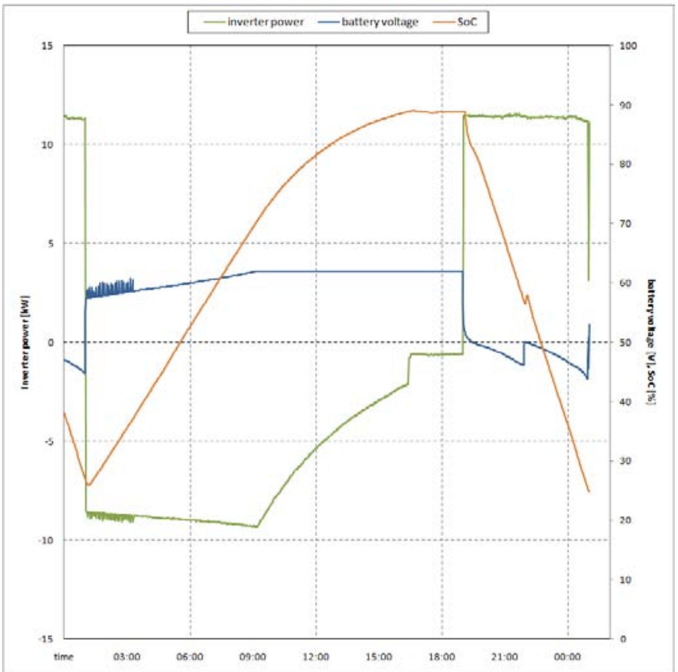

Figure 5: Charge and discharge characteristics of the 100kWh redox flow battery

Charging and discharging are influenced by setting charging respectively discharging currents at the inverters. A direct setting at the battery management is not appropriate at the moment. To charge the battery a maximal charging current is set and the battery management calculates the optimal charging current in dependence on the SoC of the battery.

In conflict with the charging process it is possible to set an active current as well as a reactive current at the discharging process. Ancillary services, e.g. voltage control via reactive power fed-in, supplied by this kind of storage systems are enabled.

b) Photovoltaic systems

At present the measured values at the photovoltaic systems (PV systems) include the information captured by the inverters. In spite of utilizing inverters from a single manufacturer the provided data and possibilities of setting parameters vary from system to system significantly. Reason for this are the various types of inverters to fit the rated power of each system. But fed-in power, Mpp voltage, AC and DC currents as well as general status and error messages are provided by every PV system. On the basis of the measured values so far, archived as

[2] SMA Solar Technology AG; manufacturer of solar inverters and monitoring systems; Kassel/Niestetal; Germany

1-minute mean values, the marked fluctuating character of photovoltaic generation is indicated.

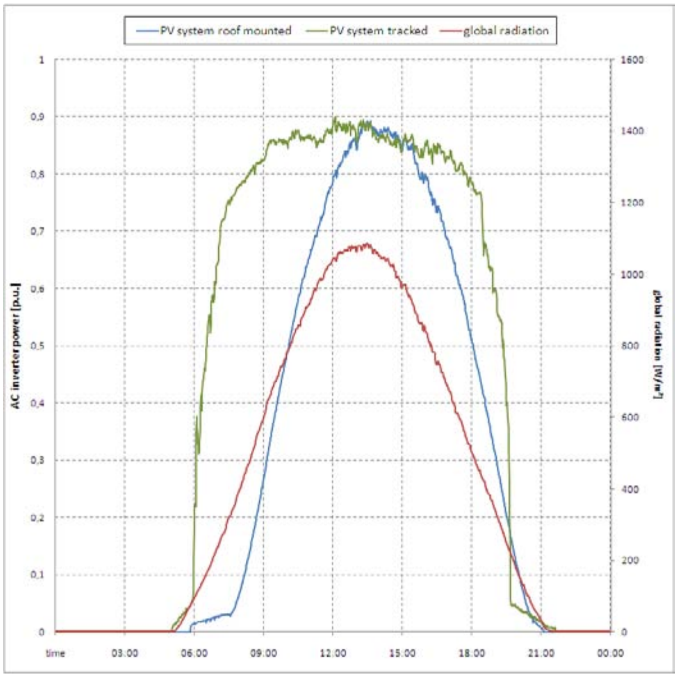

Figure 6: measurement data from static roof mounted and tracked photo voltaic systems (optimal weather conditions)

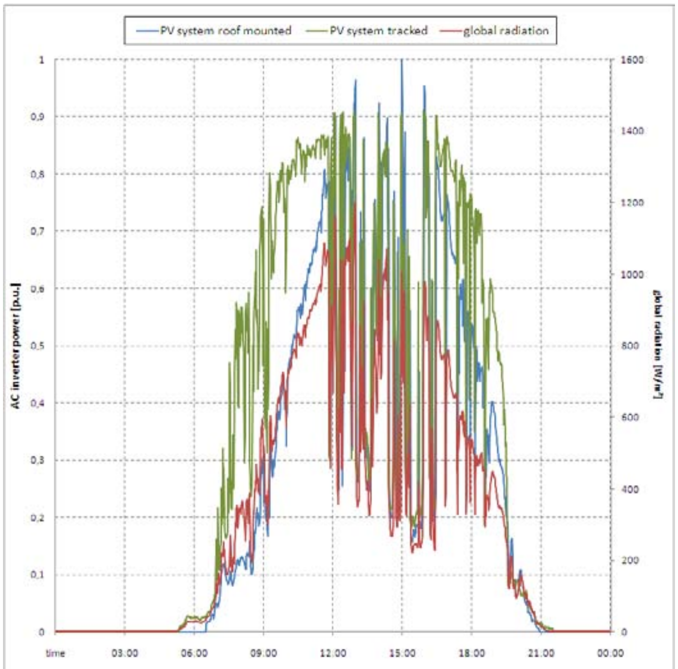

Figure 7: measurement data from static roof mounted and tracked photo voltaic systems (unsettled weather conditions)

Figure 6 shows the PV fed-in of a roof mounted system and a tracking system at an almost ideal day, that means a day with optimal weather conditions. The fed-in of day with unsettled weather conditions, e.g. a cloudy day, is presented in Figure 7. As it can be seen the power fed-in of the PV system varies around 70% pertained to the rated power within one minute. Distribution grids with a large penetration of PV fed-in facing a serious challenge handling the fluctuating grid load. Next to the AC power the figures visualize the global radiation (Red graph) measured by the weather station at the R&D platform.

It is obvious that the tracked PV system reaches much earlier its rated power then the static roof mounted PV system (see Figure 6). Additionally shadowing effects in the early morning and late afternoon, majorly at the tracked PV system, are indicated. The data of the roof mounted PV system in comparison with the global radiation proving the system not to be justified to the south. The maximum value of fed-in has a time delay to the maximum of global radiation.

c) Electric vehicles

The two electric vehicles are in use since November 2009. To charge these vehicles a charging station at the outdoor area of the technical building and several electrical outlets for charging inside the technical building are available. Smart meters are use to measure the charging curves of the vehicles and appliances connected to the charging stations and delivers time series with 15-minutes power mean values. The measured data from the smart meters is directly imported to the energy management system and is available for further analyzes and investigations.

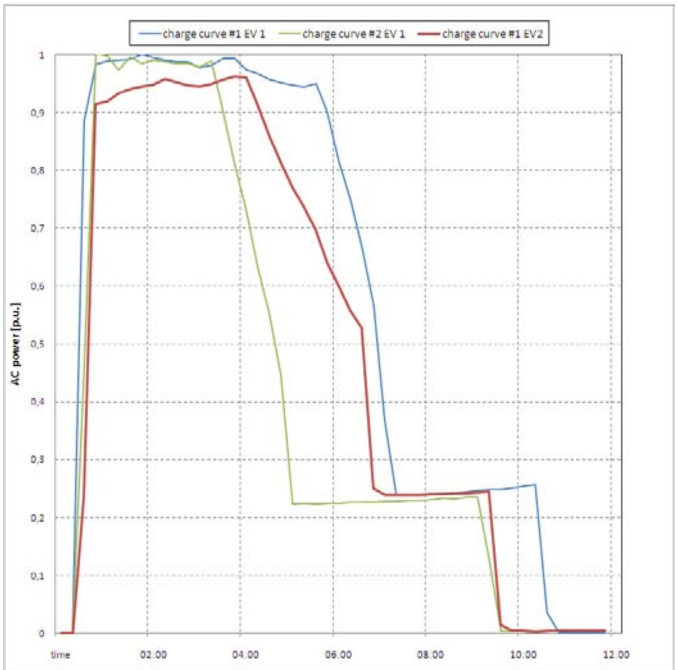

Figure 8: charge curves of electric vehicles (EV)

Various charge curves of the two electric vehicles are shown in Figure 8. The qualitative characteristic is all the same but the maximum charging power and the period of charge depends on the present state of the vehicles, e.g. the SoC of the battery as well as the battery voltage or battery temperature. All these facts have to be considered at the integration of electrical vehicles to the distribution grid.

B. *Modelling and simulation*

Based on the measured data and by means of the available component description a simulation model of the Smart Grid Platform is created. It has to emulate the real behavior of the Smart Grid Platform in an accurate way and serves as basis for further research work in the field of Smart Grid. Universal model approaches for a large number of the deployed components are described in the technical literature. Challenges of the modeling are the special conditions to be factored e.g. shadowing effects caused by objects in the surrounding area of the PV systems or the combination of inverters of different manufacturers at an insular grid respectively a grid connected to public supply.

A first approach deals with a simulation model for quasi-steady analyzes with a temporal resolution of one minute. The implementation of the model is realized by utilization of MATLAB/Simulink (see Figure 9). After implementing the parameter models a parameter fitting for single assets based on the measured data is performed. The measured data are descended from the recordings of the regular operation of the assets, e.g. PV systems and wind power station, or are captured at special test scenarios developed for specific assets.

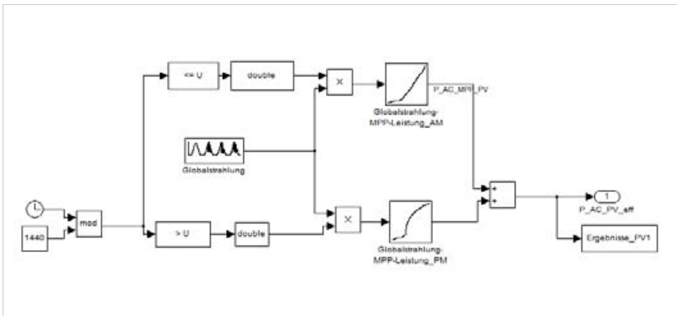

Figure 9: MATLAB/Simulink model of the photovoltaic AC power characteristics of a single PV system

C. *Development of operation strategies*

By means of the Smart Grid Platform the important research topic of developing operational strategies for distributed generation units, consumers and storage systems is in the focus of investigations. Solutions will be realized by implementation of control algorithms into the PLC components. Utilizing the SCADA system setpoint values can be set and different deposed strategies can be chosen. All operational relevant processes running on the highly available PLC components and the less critical processes running on personal computers is the major advantage of this procedure.

First of all concentrating on the rationing of the energy storage systems to guarantee the energy supply of the laboratory building the research work aims the minimization of energy consumption from the public grid. Continuing that work the evaluation of insular grid operation and investigations on the requirements on different types of inverters embedded to the same grid will be performed. Furthermore the embedding of smart meters in terms of connection to an energy data management system (EDM) is investigated and communication tests are analyzed.

V. Conclusion and Outlook

In 2009 the „Smart Grid Research and Development Platform“ was planned and implemented and is a completion of the ICT-Energy-Lab like mentioned before at this paper. The start of putting the Smart Grid Platform into operation was in the first quarter of 2010 and is still in progress. First investigations and research work at single components has been done. Information and communication technology (ICT) is a vital part of realizing the smart grid the Smart Grid Demonstrator provides an ideal platform for this research topic.

The project started with the implementation of an efficient data acquisition as basis for the modeling of the total system as well as first successful experiments operating at insular grid mode. Next steps will be the roll out of phasor measurement units (PMUs) at the distribution grid of the *Stadtwerke Ilmenau GmbH (SWI)* and its connecting substation to the gird of the *Thüringer Energienetze GmbH (TEN)*.

Later on further R&D work is planned on the following topics:

- enhancement of the simulation model on short-term simulation under consideration of the short-term models of single components,
- implementation of the operational strategies for an optimal grid operation of the smart grid,
- realization of a distributed energy management system,
- integration of the PMU data into the SCADA system and
- implementation of grid simulations based on the captured data and information.

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