Sophisticated research and development station for control of grid connected distributed energy sources

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Abstract—**A sophisticated research and development station for control of the grid connected distributed energy sources have been developed at the Faculty of Technical Sciences. This research station should allow researchers to investigate the influence of grid connected converter control on the grid conditions and vice versa. Additionally, the control of the grid connected converter during grid disturbances can be investigated. In addition to its R&D features, this station will present students with the possibilities to get high quality knowledge in the respected area. This paper aims to present the research potential of the station, while displaying some of the many versatile features gained by the introduction of the grid emulator.**

Keywords - distributed energy resource; grid connected converter; grid emulation; research and development station;

I. Introduction

In order to achieve sustainable development of the society in the future, it is necessary to address one of the key features that follow the development – energy demand. Energy market in the future, concerning the rather rapid increase in demand, will have to develop and adapt to more decentralized power system. The distinction between consumer and supplier is going to become less apparent, as renewable energy sources are integrated in the distribution grid. This allows for utility grid "clients" to alter its nature from consumer to supplier, and vice versa, depending on its current energy demand and generation capacity. In addition, with introduction of energy storage this alteration in nature can be postponed and made when energy prices are higher and it is more beneficiary for the grid connected subject to act as a supplier rather than consumer.

By the same token the development in the automotive industry is bringing forth ever so progressive inclusion of electrical vehicles in the transportation system, consequently leading to increase number of vehicles connected to the grid. The nature of the electrical vehicle and its possibility to run in V2G mode or G2V mode also provides the opportunity for it to behave as a source or as a load while connected to utility grid.

The basis of the sustainable development of the society therefore lies within the ideas and features proposed by the smart grid technology. However, with improvement of efficiency, reliability, economics, and sustainability of energy supply in mind, smart grid introduces imminent increase in number of grid connected converters. In such a number the influence of the converters on the grid power quality becomes a serious issue. Additionally, reduced power quality of the grid influences other converters, which in return influence the grid power quality even more. In that regard, developing adequate control for the grid connected converter is very important. These control algorithms, in addition to being able to actively participate in sustaining the grid power quality, have to be able to operate under different grid faults. Testing such an algorithm can prove to be a difficult task, especially due to the fact that grid fault appearances are relatively rare, and it is not rational to induce them potentially causing instability in the distribution network.

To accommodate the need for such a particular testing, Chair of Power Electronic and Converters, at Faculty of Technical Sciences, has put together a sophisticated research and development station for control of grid connected distributed energy sources. The station consists of cutting edge high-tech tools for development and testing of control algorithm of grid connected systems. The components allow for testing of these systems under various grid conditions in both operating regimes.

Another benefit of such a system is that it will serve as an educational tool for MSc and PhD students where they will get high quality knowledge in the area of grid connected distributed energy sources. Consequently, this will allow students to compete with other skilled individuals in the field [1]. The setup also includes a high level of versatility, allowing for a full control of the grid side converter, machine side converter, DC bus parameters, multi-phase machines etc.

This paper looks to present this sophisticated research and development station for control of grid connected distributed energy sources developed at the Faculty of Technical Sciences. Together with the description of basic elements of the research station, the paper will present possibilities for grid condition variations. There exist, but a few, experimental stations such as this one, that accompanies such level of versatility and modularity, and with its functionality it should position itself as a top tool for research and development of control algorithms.

II. RESEARCH AND DEVELOPMENT STATION DESCRIPTION

Basis of this research station is an advanced laboratory setup for control of electrical drives [1]. The laboratory setup presented in Ref. [1] is expanded and adapted to include a grid connected converter topology. In addition to the grid connected converter, grid emulator is integrated in the system to allow variable grid conditions.

As it is presented, the laboratory setup consists of the state of the art hardware in the field of electrical drives and control. Its modularity allowed for simple integration of a grid emulation system, with no noticeable change to the system. The basis of the system remains highly modular dSPACE hardware with modified industrial converters [2, 3, 4]. Versatility of the setup is increased by adding grid emulator to the grid side converter [5].

Fig. 1 shows the block diagram of the research station with included basic control elements. The actual outlook of the system is presented in Fig. 2, showing the grid connected topology and grid emulator separately. The focus of this system is to observe the behavior of grid side converter under different operating conditions.

A. *Control Hardware*

dSPACE is a highly modular, highly sophisticated control system hardware, which allows for a fast developing and testing of control algorithms. Major advantage of this control hardware is that it minimizes the development time and cost, while opening up a large number of possibilities of control optimization [2]. It consists of different control boards (modules) described in details in [1] and [6]. Control boards DS1006 (processor board), DS5101 (DWO board), DS2004 (A/D board), DS3001 (encoder board) and DS2201 (Multi I/O board) are used for the control of the complete research station. Fig. 3 shows all basic modules of a dSPACE hardware.

B. *Power Converters*

Power converters represent the basis for any modern renewable energy system, and thus is an integral part of the research station such as this one. Standard industrial converters are an obvious choice, since they are generally very robust, but they lack in the area of controllability especially for the laboratory testing. To overcome this, these converters are equipped with Interface and protection card (IPC), developed at Aalborg University [7].

The converter with the integrated IPC card is shown in Fig. 4. It is clearly intended to allow the user full operational control of the inverter switches, while maintaining its predominant quality of a highly reliable industrial converter. Another important quality of standard industrial drive is that it has relatively small packaging. This, together with the full controllability of the system allowed by the IPC, clearly shifts the edge towards using this solution for laboratory testing.

Some more details on the power converters can be found in the references [1], [3] and [4].

In contrast to the experimentation done in [1], with proper selectors and switch manipulation, one of the converters

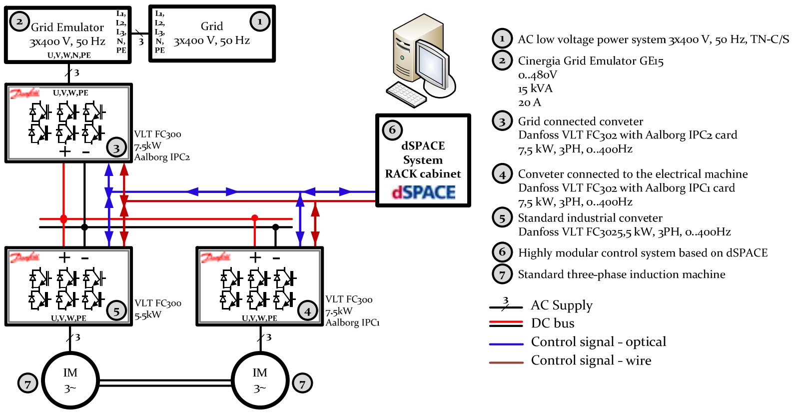


Figure 1. Block diagram of a research station

Figure 2. Physical overview of the system and the grid emulator

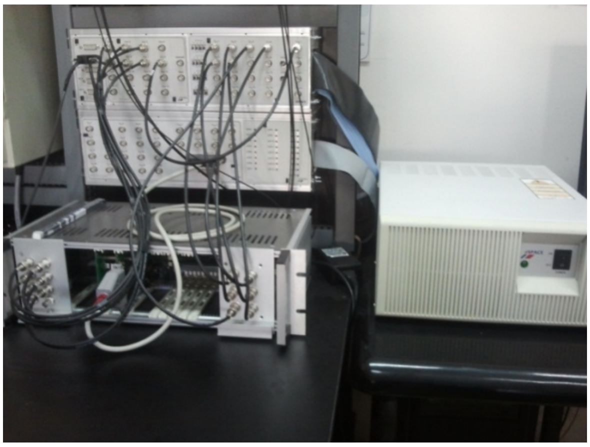


Figure 3. dSPACE based control hardware

Figure 4. Standard industrial converter with integrated IPC card

with an IPC card is connected to the grid at its active end, thus playing the role of a grid connected converter in renewable energy sources application.

C. Grid Emulator

To fully understand operation of grid connected converter it is necessary to observe its behavior not only under normal grid conditions, but also during faults, and different power quality conditions. To allow this kind of experimentation setup described in [1] needs to be complemented with a device capable of altering grid operating conditions. In addition, since the grid connected converter can act as a load, as well as the supplier to the electrical grid, this device should have possibility of bidirectional power flow. This is a highly valued feature, since it will allow for testing the grid connected converter both as an active rectifier, and as an inverter depending on the power flow. With that in mind, such a device would fit in well, with the modular versatile concept, this sophisticated and modern research station is trying to implement.

Grid emulator is a product of CINERGIA, a company which specializes in state of the art digital control of customized power electronics solutions. The device based on controlled power electronic converters capable of emulating the grid conditions. Modern design and powerful control features allow for a wide range of different operating regimes. Presented grid emulator is fully capable of a bidirectional power flow, which can be concluding by observing the block diagram in Fig. 5. It can be concluded that the basis for grid emulator is a Back-to-Back grid connected converter controlled by the separate DSP at the input and the output side. Control algorithms based on resonant control are employed for both the input and the output AC side. These control algorithms allow each harmonic to be controlled independently, consequently generating or suppressing it at a given set-point value. A large number of sensors are integrated for measurement of necessary parameters to achieve desired output parameters of the emulated grid. A 12 bit analogue to digital conversion with digital processing allows high resolution output up to 0.1 % paired with a high stability of the system [5]. Additional elements including filters, protection and switching equipment are present.

User has the possibility to operate the grid emulator using a PC software, digital I/O ports, analogue I/O ports, RS485 connector and associated protocol, CAN bus and standard RJ45 connector and MODBUS protocol. It is also possible to control the grid emulator using local touchscreen 3.2″ panel. The control of the grid emulator using local panel is very limited, without possibility to generate faults.

In additions to generating different type of grids, grid emulator is specially designed to also emulate their common faults and disturbances [5]. At the output side, grid emulator can produce three-phase grids with voltages ranging from 0 to 480 V, and frequencies from 40 to 400 Hz. Total distortion of these voltages (without including harmonic generation) is less than 0.5 %. Furthermore, voltage amplitude and phase referent value can be set independently for each phase, thus making it possible to create a non symmetrical three phase system (either by amplitude or by phase).

When non-ideal grid conditions are discussed, usually voltage harmonic distortion is considered. Grid emulator is fully capable of generating full range harmonics for orders up to 15^{th} for grids frequencies of 50 Hz (60 Hz). Any harmonic in that range can be set to any amplitude (with regard to maximum output voltage) independently for any phase. In addition to the harmonic spectrum that can be set for constant operating regime, harmonic sequence can be set as a grid fault. Harmonic sequence represents a run through, or cyclic repetition, of several different reference values of harmonic spectra. To test the fault ride through of the grid connected converter, grid emulator is capable of generating various types of voltage dips, over and under voltage disturbances, frequency variation and variable grid impedance.

While maintaining the desired output grid emulator always consumes sinusoidal current from the grid (with distortion less than 2%). Input side also has an optional control for the reactive power supplied by the grid emulator on the grid side. Table I shows the basic characteristics of a grid emulator integrated in the research and development station. The grid emulator acquired by the Faculty of Technical Sciences is a three-phase 15 kVA model, with a possible 13.5 kW of active output power.

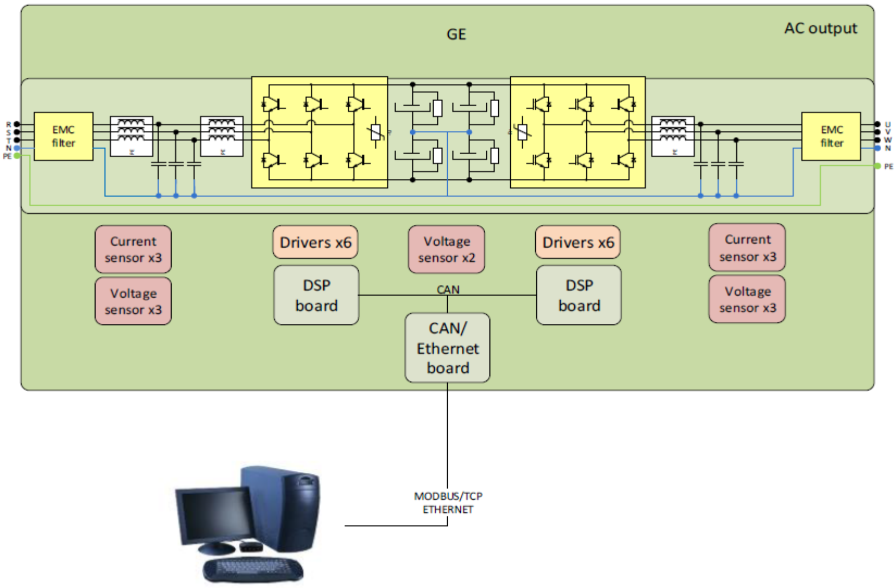


Figure 5. Block diagram of a grid emulator taken from grid emulator operating instruction

TABLE I. GRID EMULATOR BASIC CHARACTERISTICS

GE 15		
Feature	**Description**	**Value**
Input voltage	Rated	3 x 400 V (with neutral and earth)
Input Voltage range		+15 % / -20%
Input AC current	Rated	20 A
Input Frequency		50/60 Hz
Power Factor		1
Efficiency	At full load	> 92 %
Overload		125 % for 10 min 150 % for 60 sec
Output voltage	Phase-Phase	0-480 V
Output AC current	Single-Phase	0-20 A
Output Frequency		40 - 400 Hz
Harmonic content	Per Phase	1^{st} - 15^{th}
Faults	Voltage dip Over and Under Voltage Frequency variation Flicker Harmonic sequence	
Measurements	Input Power Output Voltages Output Currents Output Power Temperatures	
Protection	Over Current and Over Voltage Short circuit Over temperature	

III. IMPLEMENTATION AND EXPERIMENTATION SOFTWARE TOOLS

For the fast prototyping systems, the implementation of the control algorithm must be equally as fast. The new approach to development of control algorithms is recognized as Total Development Environment (TDE). This concept allows for a full visual block-oriented programming of dynamic real time systems. TDE has been reported in a large number of papers and it is hard to distinguish who was the pioneer and where TDE was mentioned firstly [7, 8, 9, 10]. The principles of TDE introduction to the particular laboratory setup is described in [1]. The main advantage of TDE is that the programming method is highly modular and fairly easy to comprehend. This makes the research station ideal tool for beginner, as well as experienced users. Implementation and experimentation tools for the grid connected converter control are Matlab/Simulink and Control-Desk respectively.

The addition in the control is the introduction of CINERGIA software for control of grid emulator. Even though the grid emulator can be controlled through several different protocols, even directly from the dSPACE system (thus implementing it in TDE), software tool for control of grid emulator provides very good functionality. Main advantage of the software is its easy to use nature. The overview of the control software is given in the Fig. 6. The software allows for a control of grid parameters on the output side, with a control option of reactive power injection at the input side. All of the measured values are available to be observed by the control software as well. In addition to control of voltage parameters in the stationary regime, software allows for voltage parameters during all of the mentioned faults to be set up and generated.

Figure 6. Grid emulator control software

IV. EXPERIMENTAL EXAMPLES

In addition to the research oriented at electrical drives and control shown in [1], the presented station without grid emulator has been used to investigate the grid connected converter behavior to some extent. Results achieved are shown in [11], where current controller parameter influence on power quality was investigated. With addition of the grid emulator, the research can be expanded to investigate the influence of the grid conditions on control quality and power quality issues of the grid connected converter.

These experimental results aim to demonstrate the possibilities and the versatility of the grid emulator. The measurement was carried out using Chauvin Arnoux power quality analyzer. The tests were done with the open circuit output side of the grid emulator. To establish a base point, the output reference was set at 230 V, with no phase shift. In addition, no disturbance has been activated for the first test. It can be observed from the Fig. 7 that the output signal is almost ideally sinus waveform. Total harmonic distortion for this particular case is less than 0.5 %, thus we can consider this mode of operation an idealized stat of the grid voltages.

In order to fully demonstrate the possibilities of generation of the voltage with a certain harmonic content, set-point values for the voltage harmonic content for every phase of the three-phase system is set independently. Waveform of the voltages with desired harmonic content is shown in Fig. 8. By comparison of the spectrum with the reference values entered into the control software, it can be concluded that grid emulator has almost ideal matching between the reference and the output harmonic content. It is also apparent that this grid emulator can emulate any harmonic content of the voltage, thus the power quality issues of the grid connected converter can be further investigated. Furthermore, it can act as an ideal network, any classical network (by adopting the standard harmonic content of the grid voltages), or any other type of network with different harmonic content of the voltages. This last part is particularly interesting in case of grid connected converters running in an isolated network, i.e. islanding mode.

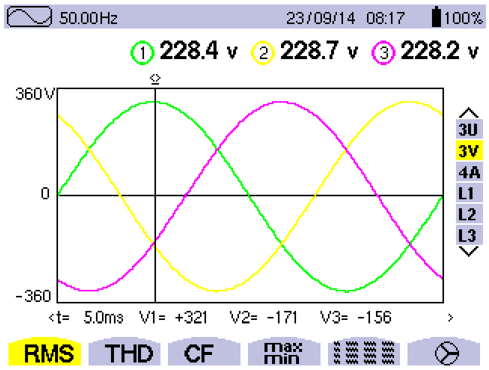


Figure 7. Emulated grid voltages

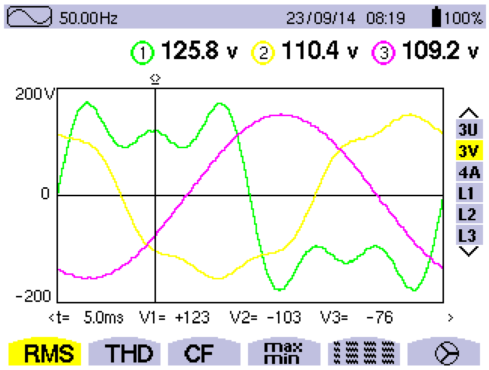
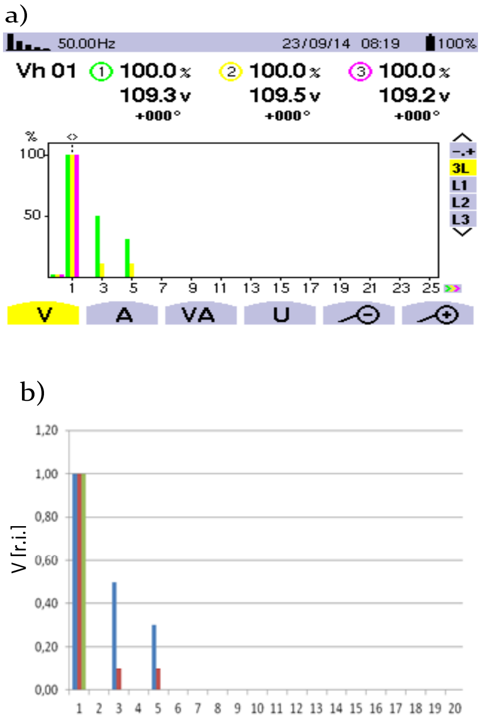


Figure 8. Emulated grid voltages with harmonic content

a)



b)

Figure 9. Harmonic content of emulated grid voltages (a) and reference values (b)

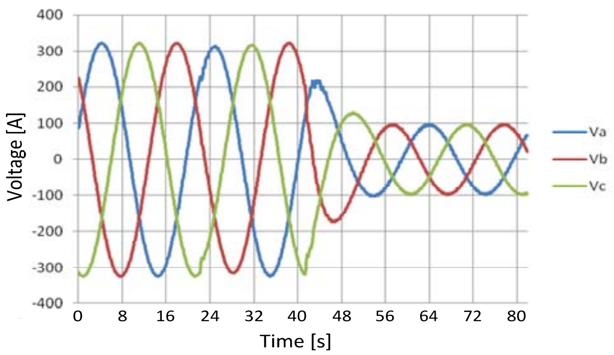


Figure 10. Symmetrical voltage dip

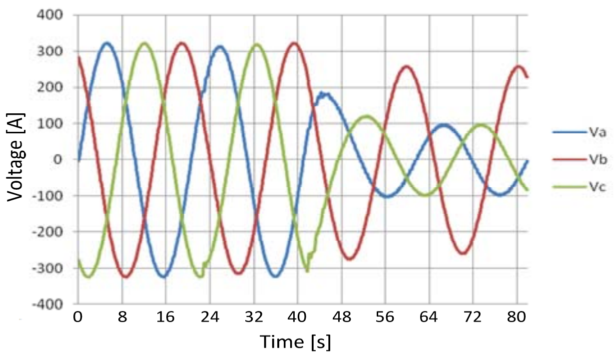


Figure 11. Asymmetrical voltage dip

In order to investigate the behavior of the grid connected converter and its associated control algorithm during faults, grid emulator needs to be able to generate faults like voltage dips. Figs. 10 and 11 show the voltage dip emulated by the grid emulator. The set-point value for the voltage, during the voltage dip shown in Fig. 10, has been set at 30 % for all three phases and the length of the disturbance is set at 3 periods of the waveform. As it can be seen in Fig. 10 the voltage dip has been emulated successfully. To demonstrate the versatility of the emulator, an asymmetrical voltage dip has been emulated and the result is shown in the Fig. 11. It is shown that every voltage can be controlled independently, allowing for a large number of possibilities when testing the grid connected converter during disturbances. For the test shown in Fig. 11 two phases have the voltage set-point at 30 %, where as one has the set-point at 80 %. In addition to these, successful test have been carried out in generating flicker, as well as generating harmonic sequence disturbance.

V. CONCLUSION

As the number of the grid connected converters increase in the future, it will become necessary to study the influence of the grid connected converter on the power system. In addition to this research area, the influence of grid conditions on the operation of the grid connected converters will be investigated as well. Together with those, future converters will have to operate under different grid disturbances. In order to prepare for the research in those areas at the Faculty of Technical Sciences, Chair of Power Electronic and Converters has developed a sophisticated research and development station for control of grid connected distributed energy sources. This research station is an expansion of the highly modular advanced laboratory setup for control of electrical drives. With the introduction of the grid emulator, this research station becomes more than capable of reproducing any desired grid conditions, without influencing the actual power system. As it has been shown, the sophisticated research station is a versatile tool for research, development and testing the grid connected converter control algorithms, under varying grid conditions. In addition to its R&D features, this station becomes a great tool for educating young scientists in the area of grid connected distributed energy sources.

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