Measurement and Remote Monitoring for Virtual Synchronous Generator Design

M. Albu, J. Diaz, V. Thong, R. Neurohr, D. Federenciuc, M. Popa, M. Calin

***Abstract*— The future power system will integrate widely distributed energy resources (DER) interfaced by power electronics units, which may cause a reduction of the system inertia, resulting in non-compatibility with existing control algorithms and settings. Additional rotational-inertia can be provided to the system if many DER units combined with relative small storage units operate like virtual synchronous generators (VSG). This paper presents the measurement layer and the associated monitoring campaign needed for a VSG design and operation.**

Keywords- Virtual Synchronous Generator, Monitoring, Stationarity, Remote access, Synchronized measurements

I. INTRODUCTION

Traditional power systems operation considers for both steady state conditions and dynamic responses adequately developed control algorithms which aim at regulating large synchronous machines with high inertia. With an increasing share of dispersed energy resources (DER) in the electrical energy portfolio mainly at distribution level, the generation layer changes and incorporates distributed generation (DG) characteristics. DER units interfaced by power electronics having no inertia translate in fast answer to any change in the system. In addition, the power generation share from large synchronous generation units may be reduced following renewable-based energy policy; economic and technical reasons also count as most of the conventional generation units cannot operate at power values lower than a technology-dependent minimum. This causes in a reduction of the system inertia, resulting in higher frequency variations in normal operation and in cases of severe disturbances [1, 2].

A solution towards stabilizing such a power system within the limits of presently available system control strategies is to provide additional virtual rotational inertia. Principally, this can be attained by adding short-term energy storage to any DER-based unit together with an intelligent control of the power electronics interface to the grid. The resulting unit is meant to operate like a virtual synchronous generator (VSG), emulating inertial answer to system changes (either during transients or on short time intervals, in the order of tens of minutes).

The idea of a virtual synchronous machine is put into practice in the VSYNC project [3-6]. In order to successfully demonstrate the VSG concept, a significant part of work is allocated to the laboratory set-up and experimentation, including testing various control techniques operating on different types of short-term storage systems. The field operation of large and small VSG systems is demonstrated [7, 9] in two distribution networks, one located in Romania and one in the Netherlands.

This paper aims at describing the measurement layer of the field test in Cheia, Romania, designed as to provide a demonstration for the VSG concept.

The demonstration site of a 100 kW VSG in Romania is currently in operation and the algorithms have been developed based on a 1 year on-site measurement campaign. One of the goals is development of the power exchange with the grid as based on the change of frequency in the point of connection of the VSG.

II. CONFIGURATION OF VIRTUAL SYNCHRONOUS GENERATOR

For the field testing phase, a versatile converter platform (Fig. 1) was acquired from Triphase in Leuven, Belgium [8]. It contains two three-leg converters, allowing the use of one three-phase four-leg grid-connected AC-DC converter, two bidirectional DC-DC converters and one bidirectional DC-DC convertor for connection of a DC source (in our case an emulated DER unit).

The VSG available measurements include the inverter output currents, the DC link voltage, the filter capacitor voltages, the grid voltages and the currents flowing towards (or from) the grid. These measurements are connected to the equipment printed circuit board (PCB) and communicated to the Linux server using an Ethernet connection. Using Ethernet communication, certain data available in the control algorithm can be communicated to another inverter cabinet or to any other computer which has an Ethernet connection. This way, measurement data and monitoring could be performed by periodically collecting all requested data (frequency estimate, grid voltage magnitude and/or waveform, currents, active and/or reactive power exchanged with the grid) and store it.

This work is a part of the VSYNC project funded by the European Commission under the FP6 framework with the contract No: FP6 – 038584 (www.vsync.eu).

M. Albu, R. Neurohr M. Popa and M. Calin are with Dept. if El. Engineering, Politehnica University of Bucharest, Spl. Indep. 313, 060042 Romania (albu@ieee.org; ralf.neurohr@gmail.com; mihail.popa@ieee.org); V.V. Thong is with 3E, Vaartstraat 61, B-1000, Brussels, Belgium (thong.vuvan@3e.eu); J. Diaz is with Ufe, Germany (javier.diaz@ufegmbh.de). D. Federenciuc is with SC Electrica SA, str. Grigore Alexandrescu, nr. 9, sector 1, Bucureşti, Romania (dumitru.federenciuc@electrica.ro)

978-1-4244-7374-8/10/$26.00 ©2010 IEEE

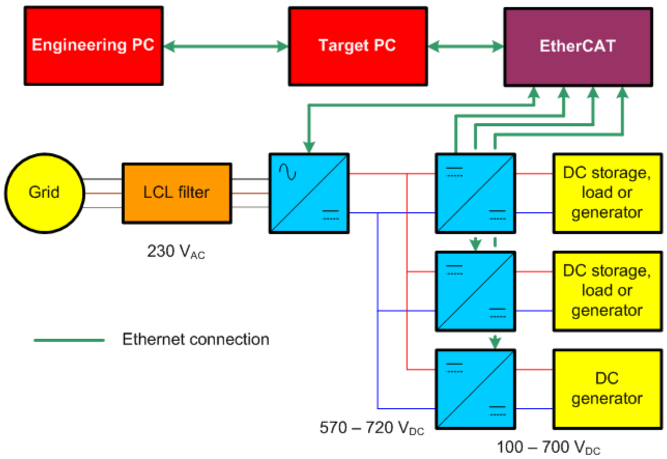


Fig. 1. Schema of Triphase's converter, 100 kW

A dedicated control unit (Target PC) runs the model being tested, and directly controls the IGBT reference pulse-width modulated (PWM) signals. The model being tested is developed on a so-called Engineering PC and then compiled and uploaded to the Target PC.

The VSG application runs as basically to provide a bi-directional exchange of active and reactive power with the grid. It mediates the active power exchange with a storage unit which in our case is a battery bank selected accordingly to an algorithm presented in [10] and is composed of 180 cells, providing 100Ah. A critical input parameter of the VSG algorithm is the SOC (State of Charge) which has to be maintained in a band around the selected nominal value (in our case 80%). In case of persistent need for power exchange, a separate control algorithm drives the averaged SOC back to its nominal value.

The entire process is based on frequency measurement and takes into account the frequency band centered on 50 Hz value, this is determined as a function of the frequency measurement resolution, power network properties (local short circuit power) and maximum available power to be exchanged with the grid.

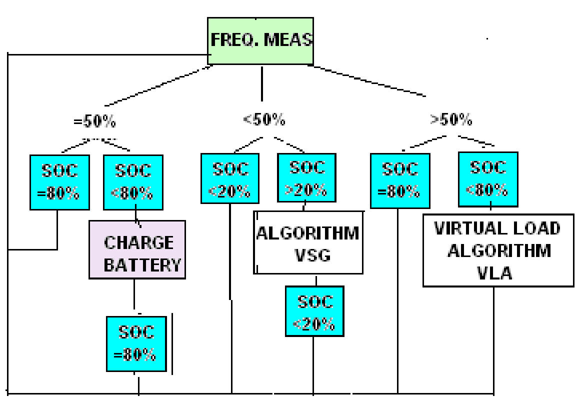


Fig. 2. The basic algorithm for energy exchange with the grid.

Figure 2 shows the two basic functions of the algorithm: the virtual synchronous generator (VSG) mode, when the state of charge (SOC) is between 20 and 80% (these values are correlated with the type of storage technology – in our case lead-acid batteries); and the virtual load (VLA) mode, active during the periods with excess of energy in the system.

The control algorithm starts by comparing the network frequency to the system value (50Hz) an, following the SOC of the available energy source, is selecting between the VSG and the VL algorithms. The VSG algorithm has as input variable the rat of change of frequency (ROCOF) in the PCC. Both frequency and ROCOF maximum admissible deviations are dependent from the network power transfer in the PCC and structure on a geographic area compatible with the VSG maximum transfer energy. This justifies the need of performing intensive monitoring campaigns. However, the available equipment for such measurement tasks is of limited accuracy. For example, the half-period determined with the MOT has a resolution of 0,01 ms, corresponding to an associated uncertainty of minimum 0.1% which results in a frequency uncertainty of comparable value. While most of the frequency variations in Cheia span within 0.1 Hz one cannot set a band below 0. 05 Hz for initiating the VSG algorithm. The requirements for the VL algorithm are less critical, as usually the operation in VL regime has a longer time constant associated – and comprises two phases: firstly SOC is checked and, if below 80% than the battery charging module is activated; when the battery is fully charged, the energy is redirected to a resistor. A nonlinear load can be also emulated as to provide a local voltage control.

III. FIELD TEST SITE

The VSG field test site is located in a distribution network substation in Cheia, about 140 km North of Bucharest. This substation supplies mainly residential load. It is a weak low voltage system with expected severe voltage variations at the point of common coupling. The VSG is connected to a reserved feeder at the 0.4 kV side of the substation. Detailed schematic of the power section of the VSG in Cheia is presented in Fig. 3.

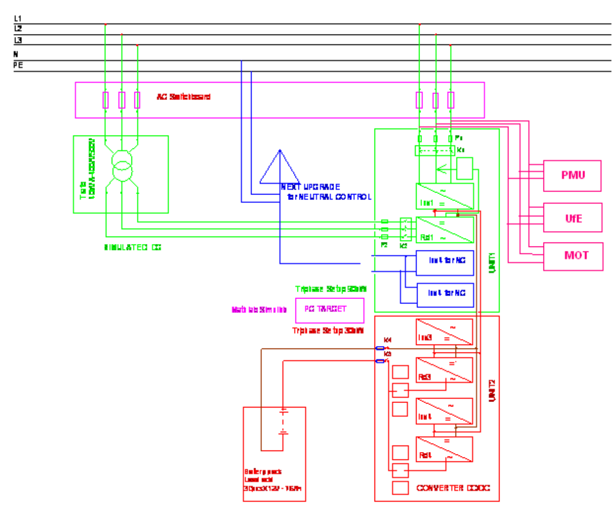
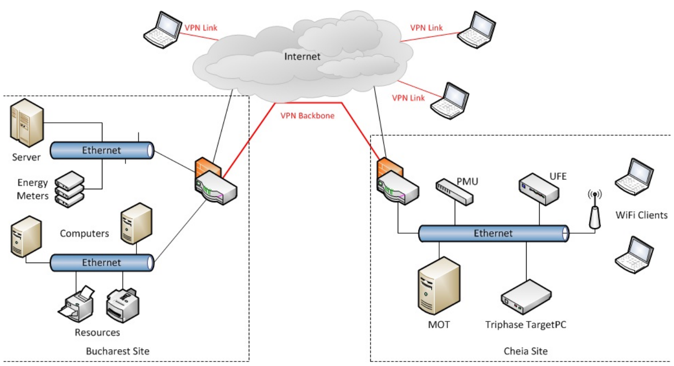


Fig. 3. Configuration of field test set-up of VSG in Cheia, Romania.

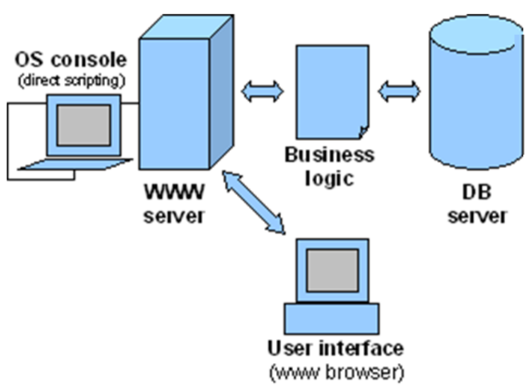
IV. Voltage and Frequency Monitoring

In order to monitor frequency and voltage variations at the point of common coupling (PCC), an extensive monitoring campaign was initiated in 2008. The rate of change of frequency was also monitored during a one year measurement campaign [11].

A communication facility is set up to provide a remote access to the installation and to gather monitored data (Fig. 4a). It also allows uploading and running remotely various VSG control algorithms, according to a predefined schedule derived from bandwidth constraints. Fig 4b shows the associated data base configuration.



a)



b)

Fig.4. Monitoring set-up in Cheia. (a) communication layout (b) voltage monitoring database.

Three independent measurement units: a voltage quality monitoring device, in use for more than 5 years for monitoring purposes in Romania (MOT), a waveform monitoring device manufactured by one of the VSYNC project partners (UFE) and a phasor measurement unit (PMU) are installed successively (Fig. 4a) to acquire voltages and currents directly at the PCC. The voltage level in the PCC allows direct use of the input channels of the three measurement devices without instrument transformers. All three units provide autonomy in data management and can handle a permanent connection to the Internet. With appropriate credentials to a dedicated virtual private network (VPN) connection, data can be retrieved using simple web-applications.

Fig. 5. Frequency variation for 60 minutes MOT registration in April 2009

MOT (Voltage monitoring equipment) monitors continuous half-cycle-rms voltage waveforms registration [12]. From acquired data the frequency will be also derived (Fig. 5) and aggregated according to the IEC 6100-4-30. It has a RS232 interface for communication with the local PC and autonomous software for data and disk space management, together with and FTP enabled data download. Figure 6 shows MOT internal blocks.

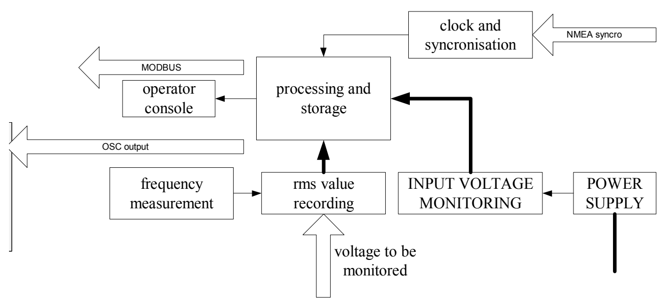


Fig. 6. MOT internal blocks

The UFE monitoring equipment [13] is a PC-based system (hardware and software) able to record voltage and current waveforms. It consists of a small-inexpensive laptop computer and a high quality data acquisition card (and corresponding sensing elements). The result is a versatile four-channel recording system at 16 bits/44.1 kHz resolution. The channels can be used for voltage (maximal 270 V) or current (20A and 200A, provided by the on-site selection of probes range) monitoring. It uses an Ethernet interface for communication. Internet technologies were used and applications programmed in order to perform several tasks that allow a friendly, secure and reliable use of the system and the data, for example: Browser-based-GUI (Graphical User Interface) for data access and display; VPN for secure remote connection; and NTP (Network Time Protocol) for clock synchronization.

Since May 2010, a phasor measurement unit (Arbiter 1133 Power Sentinel Arbiter Systems, [14]) is connected to duplicate the voltage and currents monitoring in PCC. Information on voltage and current waveforms are broadcasted

(VPN connection). In fig. 7 the frequency variation during 5 s is illustrated.

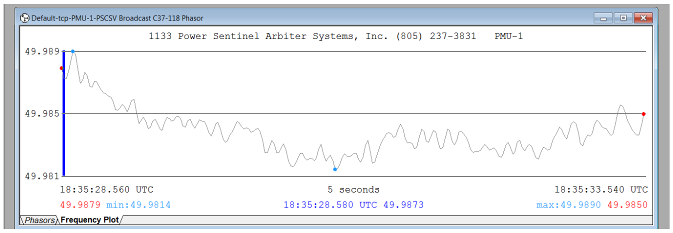


Fig. 7. Frequency variation in July 2010, as recorded by the PMU

The system is permanently connected to the Internet, such that all data can be visualized on-line or downloaded remotely. Presently a High Speed Downlink Packet Access (HSDPA) link through a 3G modem is used, performing an intelligent data packet routing, together with an Advanced Encryption Standard (AES) encrypted VPN connection. The authentication is based on Public – Private Digital Key Pair Infrastructure. Due to low bandwidth (until the foreseen upgrade in October 2010 with a dedicated communication channel) data cannot be replicated on the fly with the database hosed by the MicroDERLab server in Bucharest. A schedule has been created in order to avoid transfer bottlenecks and MOT data replication agent runs every night when the VSG application tests are not in progress. As a result, the MOT values in the database are delayed one day.

Due to the geographic isolation of Cheia, the only internet connection available for the moment is a radio link over the mobile telephone system. In the area there are two internet service providers available, one of them offering Wideband Code Division Multiple Access (WCDMA) in their network and therefore higher data transfer rate. Unfortunately their access point is far away and the signal strength drops below -50 dB.

Maximum transfer rate achieved through this link is about 1.8 Mb/s which equates to 225 kB/s. However the provider offers wider bands in areas closer to their Access Point where the data rate may reach 7.2 Mb/s (~900 kB/s) for Downlink and 1.8 Mb/s (225 kB/s) for Uplink by using HSDP access. Comparing the above data rates, our connection in Cheia can be categorized as a low-mid bandwidth connection.

The requirements of an internet link for transferring data are following:

- Quick Internet access from local hosts of the local area network (LAN) in Cheia (sporadic data bursts of 50 ~ 70kB/s)
- VPN traffic generated by the UFE Device (continuous); the data rate is currently being measured
- Microderlab VPN traffic (continuous) used to tunnel the following services between Bucharest and Cheia: (i) communication between the Triphase RT-Target PC in Cheia and the other computers in Bucharest and/or abroad; (ii) communication between the PMU device in Cheia and the host computers performing the requests (in Bucharest or abroad); (iii) data replication between the local MOT storage and the Microderlab Database located in Bucharest. Fig. 8 illustrates the daily Internet link usage for the above needs.

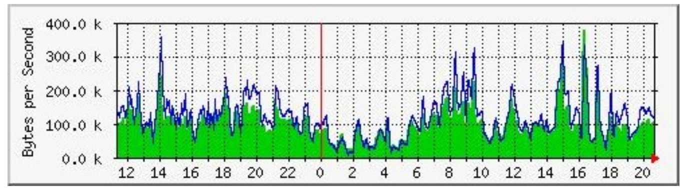


Fig. 8. Daily Internet link usage for VSG project in Cheia / (including voltage and frequency monitoring)

As long as no public IP address has been assigned by the Provider in Cheia, the connections from Internet clients to the Triphase RT-Target PC and to the PMU cannot be routed directly to the monitoring site, but to our router in Bucharest which then routes the packets through VPN to Cheia. Future plans include the acquisition of a public IP address for the Cheia connection and probably an external 3G antenna. Since a new service provider is announced to appear on the local market in Cheia offering Fiber Channel access we will also take into consideration switching over to its high speed services.

V. Measurements For VSG Designing Purposes

For Virtual Synchronous Generation design purposes and later for assessment of the contribution done by the VSG an appropriate measurement system was required. A remote measurement and monitoring system was implemented. The system should be not only to allow easy access for all project partners but also to provide accurate and reliable measurements in a convenient data format. There is not the perfect measurement instrument, for that, three different system (MOT, UFE, PMU) were used, each one having its pros and cons. It was found out that regarding frequency measurement the PMU has an overall higher accuracy (see figure 7), however due to the reporting format (10 points/second), one cannot accurately compute the rate of change of frequency as required by the VSG algorithm.

When capturing electrical disturbance, the UFE equipment performs quite good (see figure 8 a-e), due to its high A/D resolution and sampling frequency.

At the time of getting statistics of voltage and frequency including time variations the MOT gives accurate values quickly (see figure 5) and helps the selection of the variable limits in the control algorithm.

Images, spreadsheets and waveforms are the measurement data formats that can be retrieved with these three instruments; for instance, measurement data can be used in simulation and modeling software tools.

As mentioned, an objective of the VSYNC project is to demonstrate the VSG concept. After successful demonstration of the VSG concept, further researches on coordination of DER with VSG functions are required. Here synchronization of measurements becomes a critical issue and therefore time synchronization features will be demanded from the instruments.

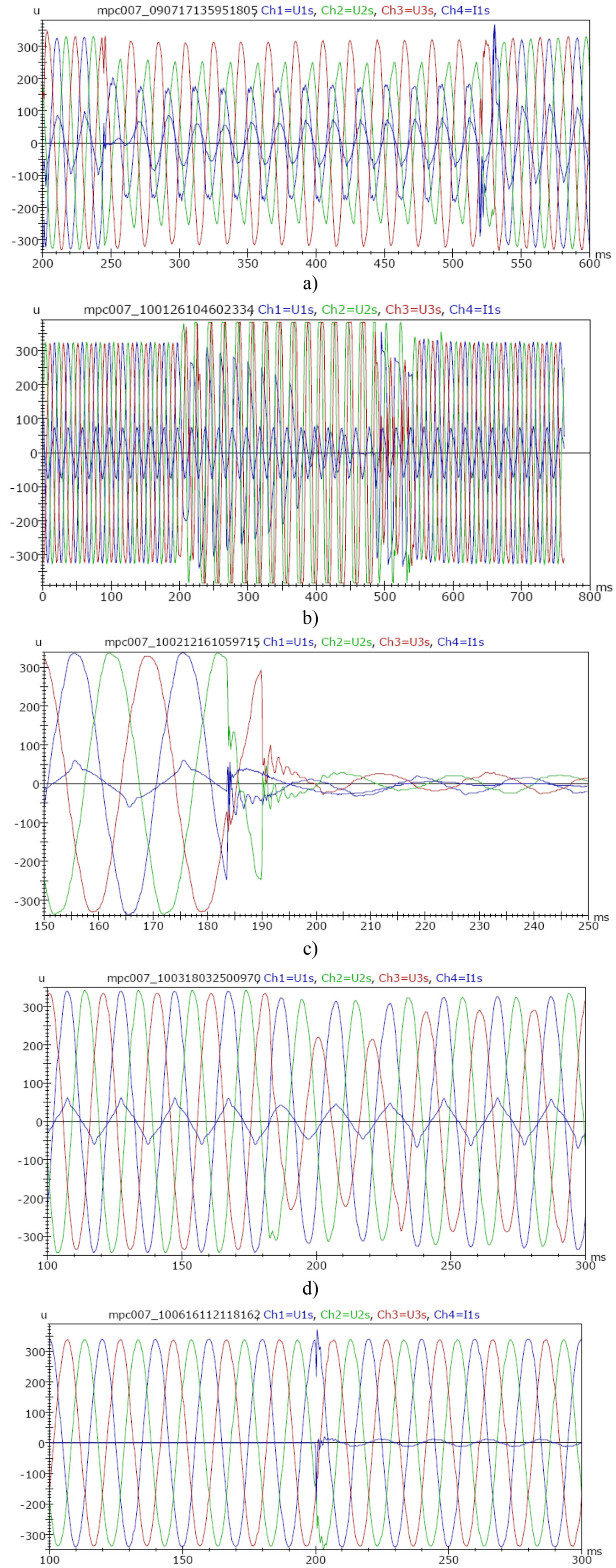


Fig. 8. Waveforms acquired by the UFE device; (a) 300ms unbalanced dip; (b) single-phase fault; (c) three phase fault; (d) unbalanced 40 ms voltage dip; (e) VSG operation

VI. CONCLUSIONS

In order to devise efficient VSG control algorithms, a-priori information on the voltage and frequency variation in the field test connection bus bar needs to be acquired and pre-processed. Due to the collaborative work, a web-based solution for accessing the measurement data was designed. An accordingly designed data base able to deal with huge volumes of data is functional for more than one year.

VII. REFERENCES

[1] Vu Van T., Van Dommelen D.M., Belmans R.: “Penetration level of distributed energy resources with anti-islanding criteria and secure operation of power system," 2006 IEEE Power Engineering Society General Meeting, Montreal, Canada, June 18-22, 2006; 7 pages.

[2] Vu Van T.: “Impact of distributed generation on power system operation and control,” K.U.Leuven, ESAT-ELECTA, Promotor: R.Belmans & D.Van Dommelen, Assessor: Driesen J., ISBN 90-5682-717-0/UDC 621.315+621.316, May 29, 2006; 163 pages.

[3] VSYNC project – Virtual Synchronous Machines (VSG's) For Frequency Stabilisation In Future Grids with a Significant Share of Decentralized Generation. http://www.vsync.eu (accessed 30/10/2008).

[4] J. Driesen, K. Visscher, Virtual synchronous generators, 2008, Proceedings of the IEEE PES Meeting, 20-24 July, Pittsburgh, PA, USA

[5] K. Visscher, S.W.H. de Haan, "Virtual synchronous machines for frequency stabilisation in future grids with a significant share of decentralised generation", 2008, Proceedings of the CIRED SmartGrids conference, 23-24 June, Frankfurt, Germany.

[6] K. Visscher, "VSYNC, The Virtual Synchronous Generator concept", (http://www.vsync.eu/fileadmin/vsync/user/docs/20080728-VSYNC-General_presentation.pdf)

[7] S. de Haan, K. Visscher: “Modelling and control of virtual synchronous machines,” internal project report, August 2008 (14 pages)

[8] Triphase: http://www.triphase.com/

[9] V. V. Thong, A. Woyte, M. Albu, M. Van Hest, J. Bozelie, J. Diaz, T. Loix, D. Stanculescu, K. Visscher: “Virtual Synchronous Generator: Laboratory Scale Results and Field Demonstration,” IEEE PowerTech conference, Bucharest,Romania,2009

[10] M. Albu, D. Creangă, A. Nechifor, and N. Golovanov, Storage Selection for DG applications containing Virtual Synchronous Generators, Proc. of the PowerTech 2009, Bucharest

[11] M. Albu, R. Neurohr, D. Apetrei, I. Silvas, D. Federenciuc, “Monitoring voltage and frequency in smart distribution grids. A case study on data compression and accessibility,” Proc. IEEE Power and Energy Society General Meeting, Minneapolis, MN, USA, July 2010

[12] MOT Operating Console, http://www.felix.ro/cd-ice.en/pdf/consola.pdf.

[13] UfE Grid Simulator & Grid Recorder System. Description of the System, Umweltfreundliche Energieanlagen GmbH, Lübeck, Germany, www.ufegmbh.de, viewed on 25.11.2009

[14] Arbiter Systems, 1133A Power Sentinel, www.arbiter.com, viewed on 20.06. 2010