The Application of Super Capacitors to relieve Battery-storage systems in Autonomous Renewable Energy Systems

Arjan M. van Voorden, Laura M. Ramirez Elizondo, Gerard C. Paap, *Senior Member, IEEE*, Jody Verboomen, *Member, IEEE,* Lou van der Sluis, *Senior Member, IEEE*

***Abstract*—The utilization of wind and sun as renewable sources causes uncontrollable fluctuations in power generation. Furthermore, the ratio between peak power and average power is high for systems with a limited number of households. In small autonomous renewable energy systems (ARES), energy storage is needed; however, the use of Lead-acid batteries as energy buffers is problematic, since it is not possible to cover fast power fluctuations without dramatically reducing the batteries' life-time. In this paper Super Capacitors are applied to relieve fast changes in the battery storage system. Batteries are used to meet the energy requirements and Super Capacitors are used to meet the instantaneous power demand. At the end of this paper, a sizing method is proposed for the Super Capacitor system.**

***Index Terms*—Autonomous Renewable Energy Systems, Batteries, Control Strategies, Super Capacitors**

I. Introduction

Some research and development sectors visualize that power systems of the coming decades could exist of autonomous, self supplying energy systems with a high penetration of renewable sources [1,2,3]. The drive towards implementing these innovative energy systems is exerted by the liberalization of the power market and the constraints of the greenhouse problems, caused by the exhaust of environmental polluting gasses. The biggest challenge in these systems is to maintain the energy and power balance, especially when the size of the system is small.

In 1997, the Electrical Power Systems Laboratory at Delft University of Technology started a research program to investigate the behavior of autonomous renewable energy systems. For this purpose, a renewable energy laboratory, DENlab, was built to analyze the system integration of renewable energy sources in a limited power scale of 50 kVA, the size of a row of 10 houses. The system layout is depicted in Fig. 1.

This work was partly supported by the Delft University of Technology research Center project: SENECU, dealing with the Sustainable Energy: Extraction, Conversion and Use.

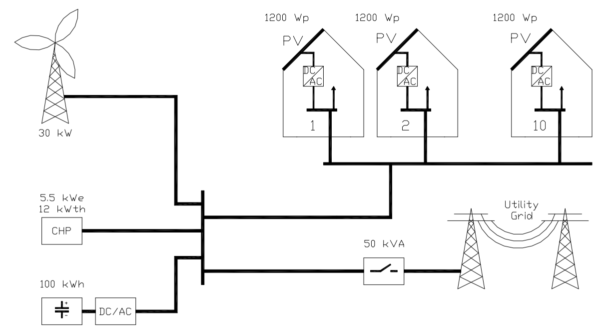


Fig. 1. System lay-out of the renewable energy system

In this system, the generated power is delivered by 120 m^2 solar cells (12 kWp), a wind energy conversion system of maximum 30 kW, and a combined heat and power set of 5.5 kWe. The maximum power demand in this system is 50 kVA. The storage system was initially calculated to be a Lead-acid battery arrangement of 100 kWh (720 V, 140 Ah).

The laboratory model is designed to give a realistic representation of the system. In this laboratory, the wind turbine, the battery system, and the load demand part are replaced with a power electronic counterpart, which allows more flexibility. The control system is programmed in such a way that there is no difference in stationary or dynamic behavior between the laboratory and a real situation. The laboratory model is depicted in Fig. 2.

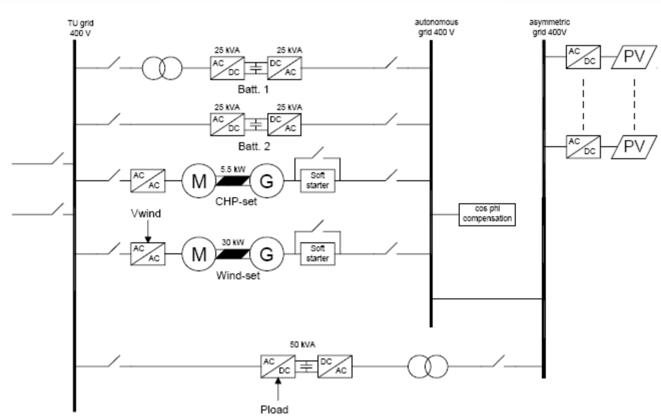


Fig. 2. DENlab model

As shown in Fig. 2, the wind turbine is replaced with a motor-generator-set and controlled by a wind input signal from an anemometer. The battery system is replaced with a bi-directional rectifier that includes the battery characteristics. The overall demand pattern is performed by a back-to-back converter, which returns the demand into the public grid. The pattern of this load demand is made available from a stochastic computer program. More details about this laboratory can be found in [4, 5].

II. Power Mismatch

The power mismatch between generation and demand must be stored or delivered. This section shows the power fluctuations in generation and demand and concludes that the power mismatch varies to a large extent. The power mismatch must be met by the storage system, in other words, the battery storage acts as the system's slack-node, which means that the surplus or shortage of power is equalized by the battery storage. This slack-node approach is valid within the limited power range of the battery capacity and the inverter.

A. Power demand

The rated power of the laboratory model is 50 kVA, which is representative for the maximum load of ten households. For this small system, the ratio between the maximum load and the average load is high. However, when the number of loads increases, the coincidence in load behavior leads to a smoother load curve and a smaller ratio between maximum and average load [6].

$$C = \frac{\text{observed peak power in the group}}{\sum(\text{power pattern})} \qquad (1)$$

$$C = \text{coincidence factor}$$

To connect real loads in the DENlab, in order to represent the power consumption, would be an unnecessary waste of energy. Therefore, a back-to-back converter, which returns the energy back into the public grid, is used to represent the total demand.

A software program based on an inquiry of the demand of many and various types of households, produces the energy demand pattern for a specific number of households [7]. In this inquiry, inhabitants were asked to enumerate the type of equipment installed at their homes and to estimate the time interval at which the different devices are used. The computer program randomizes the large number of acquired data. Finally, by entering the number of households and, when applicable, the specific entries to select the type of households and the number of inhabitants, a weekly load pattern is generated.

B. Wind energy

Buildings and other obstacles produce a lot of turbulences in the wind and lead to fluctuating magnitudes and directions [8-10]. Because of the fluctuations in the wind speed and due to the characteristic of wind speed vs. power (the power curve between 4 and 12 m/s almost depends on the speed to the power of 3), the power produced by a wind turbine in a built-environment is very unstable. Fig. 3 shows an arbitrary measured day pattern of the wind power production, recorded in the DENlab.

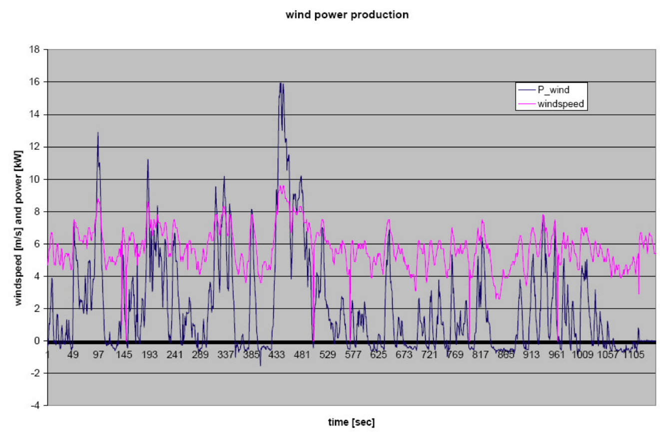


Fig. 3. Wind speed and production

C. Solar energy

Solar cells convert sun-irradiance into electrical power. The intensity of the light depends mainly on the cloud cover and the time of the day. The difference in power production between direct and diffuse light is very large. In Fig. 4, two measured days are depicted. The large power dips are caused by moving clouds. The power reduction can be very fast, as it depends on the speed of the clouds. Days with few fast-moving clouds are particularly bad for achieving a stable power production.

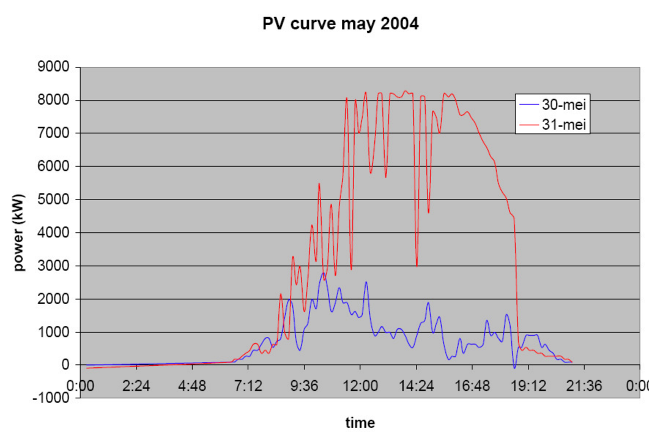


Fig. 4. PV power curves of two days in May 2004

D. Storage power

Like stated before, the difference between generated and demand power is equal to the power exchange with the storage system. It can be concluded from section II. A. - C. that the fluctuations in the battery power result from the sum of the individual solar, wind and demand power variations.

III. BATTERY CHARACTERISTICS

A battery is a widely known component that converts electrical energy into chemical energy or vice versa. In Lead-acid batteries, the charge process leads to a reform of the sulfuric acid of the electrolyte as follows,

$$SO_4 + 2H^+ \Rightarrow H_2SO_4 \quad (2)$$

The net (re)charge reaction on both plates and electrolyte is:

$$2PbSO_4 + 2H_2O \Rightarrow PbO_2 + 2H_2SO_4 + Pb \quad (3)$$

Batteries may be required to supply long-duration energy-type or short-duration power-type loads, depending on their application. Any battery type can be sized to supply short-duration power loads, but high-power battery designs supply them more effectively than others.

The main principle for designing high-power batteries is to consider that these batteries can discharge a high percentage of their stored energy in a short period of time. In contrast, lower-power batteries can deliver more energy but only if they are discharged during a long period of time. This phenomenon is described with the Peukert law.

$$C_p = I^N t \quad (4)$$

where: C_p is the nominal capacity [Ah];
I is the discharge current [A];
N is the Peukert constant;
t is the time of discharge [h].

This law expresses the capacity of a battery in terms of the rate at which it is discharged. As the rate increases, the battery's capacity decreases. For an ideal battery, the constant N would equal one; in this case the actual capacity would be independent of the current. However, for a Lead-acid battery, the value of N is typically between 1.1 and 1.2.

Besides the reduction in remaining capacity, the reduction of the life-time is significant when the battery system operates under high fluctuations. Therefore additional measures should be taken in order to apply the battery in an efficient way to prolong its life. The best way is to split the energy and power needs into two separate components. Lead-acid batteries could be used as energy suppliers, whereas Flywheels and Super Capacitors could be used as power suppliers. In this paper, the use of Super Capacitors is considered to relieve the fast changes in the battery storage.

IV. SUPER CAPACITORS

In literature, the Super Capacitors appear under different names: ultracapacitors (UC), electrochemical double layer capacitors (EDLC) or Super Capacitors (SC) [11]. A SC is an electrochemical capacitor that has an unusually large amount of energy storage capability relative to its size, when compared to common capacitors. These components are of particular interest in automotive applications for hybrid vehicles and as supplementary storage for battery electric vehicles [12]. The first Super Capacitor based on a double layer mechanism was developed in 1957 by General Electronics in a patent using a porous carbon electrode. It was believed that the energy was stored in the carbon pores and it exhibited "exceptionally high capacitance", although the mechanism was unknown at that time.

Electrochemical capacitors (EC) store electrical energy in the two series capacitors of the electric double layer (EDL), which are formed between each of the electrodes and the electrolyte ions. The distance over which the charge separation occurs is just a few angstroms (10^{-10} meter). The capacitance and energy density of these devices is thousands of times larger than electrolytic capacitors.

Super Capacitors have several advantages in relation to batteries:

- Very high rates of charge and discharge;
- Little degradation over hundreds of thousands of cycles;
- Good reversibility;
- Light weight;
- Low toxicity of materials used;
- High cycle efficiency (95% or more).

Their disadvantages are:

- The amount of energy stored per unit weight is considerably lower than that of an electrochemical battery (3-5 Wh/kg for a UC compared to 30-40 Wh/kg for a battery);
- The voltage varies with the energy stored. To effectively store and recover energy requires sophisticated electronic control and switching equipment.

The energy content of a (Super) Capacitor is proportional to the square of the voltage, as shown in the following equation,

$$W_c = \frac{1}{2} C V_c^2 \quad (5)$$

V. Configurations and Control Strategies

The Lead-acid battery – Super Capacitor facility can be arranged in different ways. Two basic configurations are the DC-system and the AC-system. They are depicted in Fig. 5 and Fig. 6.

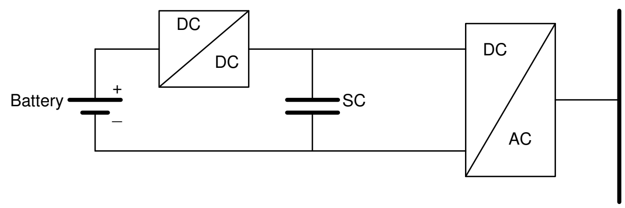


Fig. 5. DC-system configuration

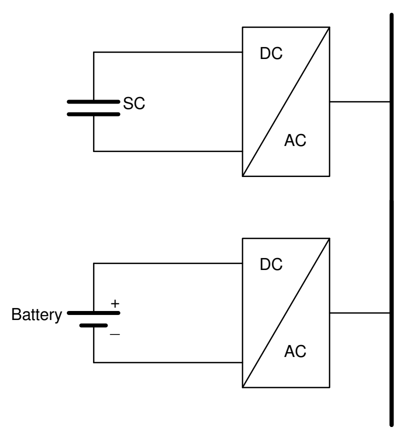


Fig. 6. AC-system configuration

The AC-system provides a better and simpler control of the energy exchange and has a better performance than the DC-system and will therefore be used here.

It should be noted that a DC/AC converter has a limited voltage range at its DC side for a specific AC voltage. In standard converters of 400 V, the DC-voltage may vary between 600 and 740 V. This limits the usable energy content of the Super Capacitor. Because of the quadratic voltage dependency, however, most of the energy is available at the high voltage regions.

To define the properties of the SC-buffer for fast power fluctuations and the battery-buffer for slower energy changes, the following control strategy is developed. As reference voltage for the SC-buffer, the average voltage of 670 V is taken. When balancing power is needed, it will be delivered by the SC, which causes the SC-buffer to drop. At the same time, the battery-buffer provides power proportional to the difference of the actual SC voltage and its reference.

When the balancing power is negative i.e. the production is higher than the demand, both the SC and the battery will be charged in the same way. For fast power changes, the SC will take most of the fluctuations while the battery takes the longer term changes in power. In Fig. 7 the control system is depicted.

The control is a simple integrator controller, where the time constant can be adjusted. In this way, the battery supplies the energy (average power), whereas the Super Capacitor supplies the power deviation from the mean value. The transfer function is experimentally derived.

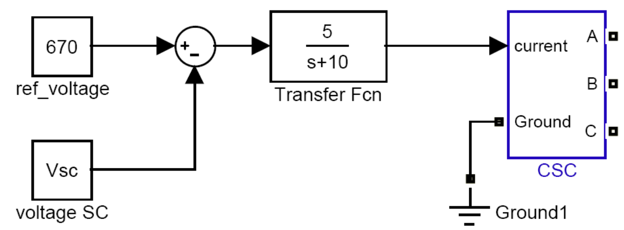


Fig. 7. Control system for battery current

The DC/AC converter, connected to the Super Capacitor bank, acts as a Voltage Source Converter (VSC) that dictates the frequency and AC voltage in the system. This converter is the primary storage system, which mainly responds to sudden energy unbalances.

The DC/AC converter, connected to the battery bank, acts as a Current Source Converter (CSC). It receives the control input from the Super Capacitor voltage difference and mitigates the error-signal in order to fulfill the necessary energy demand of the autonomous system.

VI. Sizing Super Capacitor System

The calculation of the dimension of the Super Capacitor system is always a matter of choice between costs aspects and performance. The higher the capacity of the SC-system, the more constant the battery current will be. Since the cost aspects are ignored in this paper, the following procedure can be followed in order to select the size of the Super Capacitor system for the autonomous energy system application.

- Collect the data of several successive days;
- Calculate the mean value of the power of the total storage system using a moving average filter with a period of half a minute;
- Determine the deviation of the instantaneous power from its mean value (output of the moving average filter);
- Calculate the worst period of that day, in other words, the highest average power in a certain period (absolute value);
- Calculate the required capacity, taking into account the bandwidth of the DC inverter voltage.

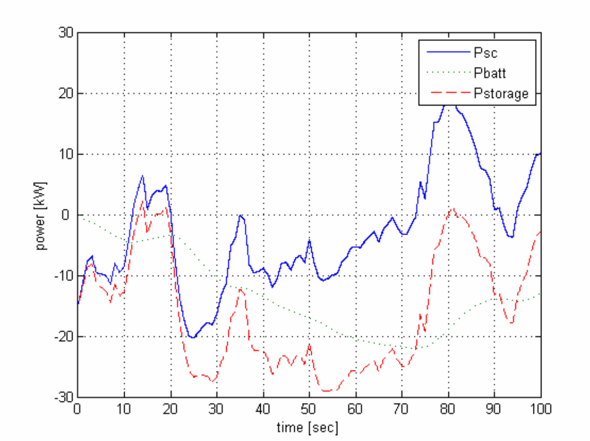


Fig. 8. Power at the storage energy system

In Fig. 8, the power flowing into the storage system is depicted. It can be seen that the storage power is fluctuating in time (bottom fluctuating curve, dashed). The control system with a time constant of 10 seconds and a gain of 5 delivers a smoothed battery current (dotted line). The difference between mean and actual power (upper fluctuating curve) is delivered by the Super Capacitor. In time, the average power of the Super Capacitor is almost zero. By changing the transfer function, other system responses can be realized.

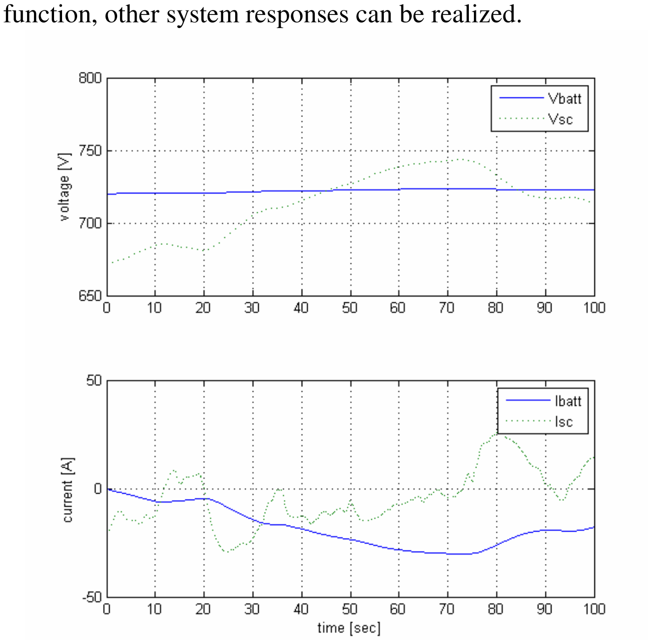


Fig. 9. Voltages and currents in the Battery - Super Capacitor system

Fig. 9 shows the individual voltages and currents of the battery and Super Capacitor system. This curves show that the battery current is smoothed and that the Super Capacitor current is fluctuating around the zero-line. During periods of positive current, the voltage of the Super Capacitor decreases. The rate of decrease depends on the size of the capacitor system and the actual current. The deviation of the Super Capacitor voltage from the reference value controls the battery current.

TABLE I
DATA OF BATTERY AND SUPER CAPACITOR

	Size	Resistance	Voltage
Super Capacitor	C = 10 F	R_{sc}= 10 mΩ	U_{sc} =670V
Battery	E = 100kWh	R_{batt}= 0.1 Ω	U_{batt} =720V

The simulation results have shown a 100 s period, where the maximum energy exchange in the SC is 740.000 Ws. For the calculation of the capacitor's dimension, we assume that the Super Capacitor voltage may vary between 740 and 600 V (maximum to minimum operating voltage of the inverter).

$$E = \frac{1}{2}CV_{\max}{}^2 - \frac{1}{2}CV_{\min}{}^2 = C\left(\frac{1}{2}V_{\max}{}^2 - \frac{1}{2}V_{\min}{}^2\right) \tag{6}$$

$$C = \frac{740.000}{93.800} = 7{,}88 \text{ [F]}$$

From this calculation, it follows that the minimum capacity is 7.88 F. For security reasons, a higher value is chosen, for instance 10 F.

VII. Conclusions

This paper proposes a Lead-acid battery - Super Capacitor system as a solution for energy storage in autonomous renewable energy systems (ARES). It describes and quantifies the occurrence of power fluctuations as a consequence of the usage of renewable energy sources in a small system of 10 households. Batteries are not appropriate to follow the sharp fluctuations, since their life-time is negatively affected. Therefore, the application of only Lead-acid batteries is inadequate for ARES of this power scale.

By splitting the total energy demand, the energy and power requests can be fulfilled by introducing two different types of storage. Super Capacitors are applied to meet the fast changing power demand, while the Lead-acid batteries balance the average energy demand. The integration of the Lead-acid batteries and the Super Capacitor in the storage system is explained.

A way to dimension the Super Capacitor system is also described. In general, the larger the Super Capacitor, the lower is the impact on the life-time of the batteries. It can be concluded that ARES with a storage system as proposed is technically feasible.

References

[1] CIGRE, *Electric Power Systems 2020.* 2003, Joint Advisory Group SC15/E1-JAG 02 TC.2.
[2] *Technologies for Tomorrow*, IEEE Power Engineering Review, 1998. 18(9).
[3] *SmartGrids, vision and strategy for Europe's Electricity Networks of the Future*. 2006, European Commission.

[4] van Voorden, A.M., Paap, G.C., van der Sluis, L. *The set-up of a renewable energy laboratory*. in *IEEE young research conference*. 2002. Leuven.

[5] van Voorden, A.M., Paap, G.C., van der Sluis, L. *The Use of Batteries in Autonomous Renewable Energy Systems*. in *PowerTech 2005*. 2005. St. Petersburg.

[6] Willis, H.L., Scott, W.G., *Distributed Power Generation*. 2000, New York: Marcel Dekker Inc.

[7] Uitzinger, J., *Sepath, simulatie van energievraagpatronen van huishoudens*, SDE, Editor. 2003, IVAM: Amsterdam.

[8] Dutton, A.G., Halliday, J.A., Blanch, M.J., *The Feasibility of Building Mounted/Integrated Wind Turbines (BUWTs): Achieving their potential for carbon emission reduction*. 2005, CLRC Rutherford

[9] Mertens, S., *The energy yield of roof mounted wind turbines.* Wind Engineering, 2003. 27(6): p. 507-518.

[10] Wit, M.H.d., *Wind in de gebouwde omgeving*. 2001, Technische Universiteit Eindhoven.

[11] Smith, T.A., Mars, J.P., Turner, G.A. *Using Supercapacitors to Improve Battery Performance*. in *33th Power Electronics Specialists Conference*. 2002. Cairns, Australia.

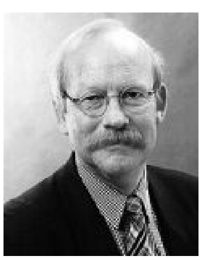
[12] Palma, L., Enjetti, P., Howze, J.W. *An Approach to Improve Battery Run-time in Mobile Applications with Supercapacitors*. in *Power Electronics Specialists Conference*. 2003. Acapulco, Mexico.

Arjan M. Van Voorden was born in Rotterdam, the Netherlands, on April 11, 1972. He received his B.Sc. degree in electrical power engineering from the "Haagse Hogeschool" in June 1995. His thesis project involved cable load calculations on asymmetric cable routes in steady state and emergency situations. This work was done in cooperation with KEMA, The Netherlands. In April 1998, he received his M.Sc. degree in electrical power engineering from the Delft University of Technology. This master thesis project involved autonomous energy supply of houses.

He is currently with the Power System Laboratory at the Delft University of Technology, working on his PhD-thesis: "Power Balancing in renewable energy systems".

Laura M. Ramirez Elizondo was born in San José, Costa Rica on December 12, 1980. On 2003, she received her Bachelor degree in Electrical Engineering at the Universidad de Costa Rica. She obtained a Bachelor degree in Music with a major in piano on August 2005 at the same institution.

From January 2004 to July 2005 she worked as instructor professor at the Department of Power Systems and Electrical Machines of the Universidad de Costa Rica. She is currently working on her thesis as part of her M.Sc. studies in Electrical Power Systems at Delft University of Technology.



Gerard Chr. Paap was born in Rotterdam, the Netherlands, on February 2, 1946. He received his M.Sc. degree from Delft University of Technology in 1972 and his Ph.D. degree from the Technical University of Lodz in 1988.

Since 1973 he has been with the Department of Electrical Engineering at Delft University of Technology. From 1973 to 1985, he was with the Division of Electrical Machines and Drives, where he lectured on the fundamentals and dynamics of electrical machines; since 1985 he has been with the Power Systems Laboratory where he is currently Associate Professor.

Dr. Paap's main research interests include power system transients, dynamics and stability, the large-scale application of renewable energy as well as the dynamics of electrical machines. He is senior member of IEEE.

Jody Verboomen obtained his Master in Industrial Sciences (Electronics) from Groep T Hogeschool in Leuven, Belgium in 2001. He obtained his M.Sc. in Electrical Engineering from the Catholic University of Leuven (KUL), Belgium in 2004.

He is currently working towards a Ph.D. on the application of FACTS and phase shifters in transmission systems in the Electrical Power System (EPS) laboratory of the Delft University of Technology, The Netherlands. His research is funded by SenterNovem, an agency of the Dutch ministry of Economical Affairs.

Lou van der Sluis was born in Geervliet, the Netherlands on July 10, 1950. He obtained his M.Sc. in electrical engineering from the Delft University of Technology in 1974.

He joined the KEMA High Power Laboratory in 1977 as a test engineer and was involved in the development of a data acquisition system for the High Power Laboratory, computer calculations of test circuits and the analysis of test data by digital computer. In 1990 he became a part-time professor and since 1992 he has been employed as a full-time professor at the Delft University of Technology in the Power System Department.

Prof. van der Sluis is a senior member of IEEE and head of the Power System Laboratory of the Delft University of Technology.