EUROPEAN TRANSACTIONS ON ELECTRICAL POWER
Euro. Trans. Electr. Power 2006; **16**:507–521
Published online in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/etep.113

Contribution of DG units to primary frequency control

J. Morren*,†, S. W. H. de Haan and J. A. Ferreira

Electrical Power Processing, Delft University of Technology, The Netherlands

SUMMARY

The increasing penetration of distributed generation (DG) in the electricity grid will result in a reduction of the number of connected conventional power plants, which are nowadays responsible for control of the electricity network frequency. Currently DG units do not contribute to frequency control. With increasing penetration of DG it will become necessary, however, that they also contribute to frequency control. A significant part of the DG units are connected to the grid by a power electronic converter. It is possible to implement additional control in this converter to let the DG unit contribute to frequency control. In this paper it is investigated how these controllers can be implemented and it is analysed how large the contribution of several types of DG units can be. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS: frequency control; stability; distributed generation

1. INTRODUCTION

Due to a number of developments in electrical power systems, such as liberalisation and deregulation an increasing number of small generators will be connected to the grid. The connection of these distributed generation (DG) units will drastically change the operation of the electrical power system.

Nowadays the grid frequency is controlled by the conventional power plants. The goal of the frequency control is to maintain the synchronous operation of the synchronous generators in the system and to maintain the power balance.

The response of the synchronous generators to a change in power balance and the resulting frequency deviations can be split up in three phases.

In the first phase, following a deviation in the power balance, the rotor of the synchronous generators will release or absorb kinetic energy and as a result the frequency will change. The response is determined by the dynamics of the system and will be called ‘inertial response’.

When the frequency deviation exceeds a certain limit, controllers will be activated to change the power input to the prime movers. This is the second phase, the primary frequency control.

When the power balance is restored, there will be still a steady-state frequency deviation. In the third phase, secondary frequency control, the frequency will be brought back to its nominal value.

*Correspondence to: J. Morren, Electrical Power Processing, Delft University of Technology, P.O. Box 5031, 2600 GA Delft, The Netherlands.
†E-mail: JohanMorren@ieee.org

Contract/grant sponsor: SenterNovem.

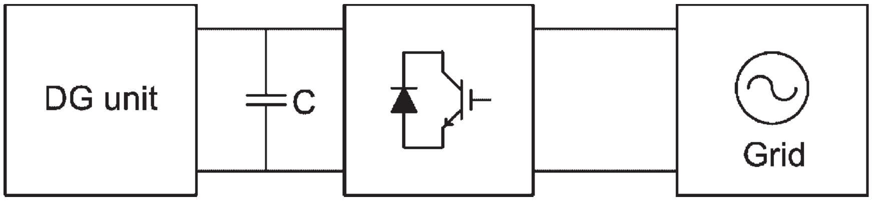


Figure 1. Basic blocks of a distributed generation (DG) system.

A significant part of the DG units will be connected to the grid with power electronic converters, as shown in Figure 1. This gives these generators a behaviour that is fundamentally different from the conventional generators. Some types of DG units supply a dc current (fuel cells, solar cells), which is converted to ac by the converter. They are 'inertia-less' and have no direct relation between power and frequency. Other types of DG unit are based on machines (wind turbines, micro turbines), but the converter decouples their rotational speed from the grid frequency to make variable speed operation possible. And therefore they also do not have the direct relation between their inertia and the grid frequency. So, all these DG units will not contribute to the inertial response. A control loop can be implemented in some cases however, to give these DG units a 'virtual inertia' [1].

So far, DG units also do not contribute to primary control. With an increasing penetration level of DG units, assuming that they (at least partly) replace conventional generation, frequency control will become more difficult. It might, therefore, be required that DG units contribute to primary and secondary frequency control.

In this paper it will be investigated if DG units can contribute to primary frequency control, how large their contribution can be, and which additional control should be implemented. The paper starts with a short review of classical frequency control. This is followed by an investigation of the different DG units with respect to their capabilities to increase their power. In a case study at the end of the paper the additional controllers that are needed are described and it is shown that DG units can contribute to primary frequency control.

In this paper only the contribution to primary control will be considered. Contribution to inertial response and secondary frequency control is not taken into account.

2. CONVENTIONAL FREQUENCY CONTROL

In this section conventional frequency control will be shortly discussed. After a drop in network frequency conventional power plants will immediately release energy from their rotating mass. The energy stored in this rotating mass is given by:

$$E = \frac{1}{2} J \omega_{\mathrm{m}}^2 \tag{1}$$

with J the inertia of the machine and ω_{m} the rotational speed of the machine. In electrical power engineering often the so-called inertia constant H is used, which is defined as:

$$H = \frac{J \omega_{\mathrm{m}}^2}{2S} \tag{2}$$

with S the nominal apparent power of the generator. The inertia constant has the dimension time and gives an indication of the time that the generator can provide nominal power by only using the energy stored in its rotating mass. Typical inertia constants for the generators of the large power plants are in the range of 2–9 seconds, depending on the type of power plant in which they are used and on the nominal rotational speed [2].

In the period immediately following a disturbance, the frequency deviation is dependent on the inertia of the system. When the frequency deviation exceeds a pre-defined threshold value, the primary frequency controllers of the conventional power plants will react. The further frequency deviation depends on the droop, the primary control reserve and the deployment time. The droop gives the additional power that is supplied as a function of the frequency deviation. The droop D_{pf} is without dimension and generally expressed as a percentage:

$$D_{\mathrm{pf}} = \frac{-\Delta f / f_{\mathrm{n}}}{\Delta P_{\mathrm{G}} / P_{\mathrm{Gn}}} \times 100\% \tag{3}$$

Two different droop characteristics are shown in Figure 2. From this figure also the definition of the primary control reserve can be seen. It is the range of a generator from the working point prior to the disturbance to the maximum power, at which the generator can provide primary control. The primary

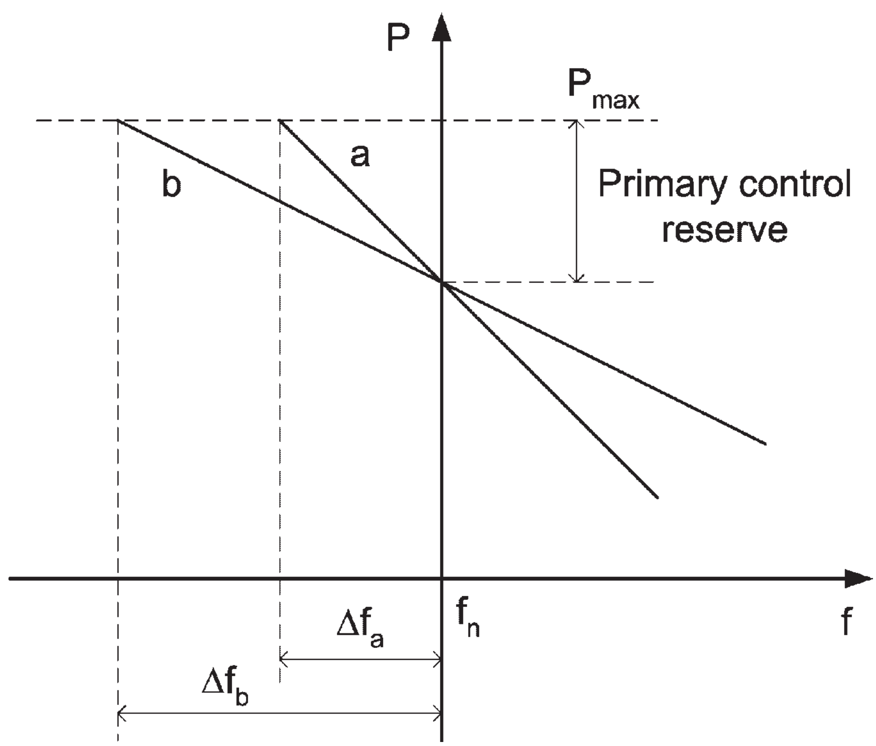


Figure 2. Different droop characteristics.

control reserve will be denoted by Δk. The deployment time is the time that the generator needs to increase its output power.

3. PRIMARY CONTROL RESERVE OF DG UNITS

3.1. Introduction

In order to be able to analyse the influence of an increasing percentage of DG on frequency control it is necessary to know the basic properties and capabilities of each of the DG units. Especially important are the inherent behaviour during frequency deviations, the ability to increase stationary power and the dynamics associated with it. This section describes the characteristics of the different DG unit types. Three types will be considered:

- Wind turbine
- Micro turbine
- Fuel cell

Other types of DG unit will not be considered as they have no power electronic converter, because they are used on a very limited scale only, or because they have no possibility at all to increase their output power.

3.2. Wind turbines

3.2.1. Introduction. The first type of DG unit that will be considered is a variable speed wind turbine. The power that is supplied depends on the wind, which is not controllable. Therefore wind turbines cannot participate in primary frequency control. The large blades of the turbine give this type of DG unit a significant inertia however. The kinetic energy stored in this rotating mass can be used to contribute, for a short time, to primary frequency control. A control loop is required however, as the rotational speed of the turbine is decoupled from the grid, to enable variable speed operation.

3.2.2. Controller. Variable speed wind turbines have a speed controller, which has the task to keep the optimal tip speed ratio λ over different wind speeds, by adapting the steady state generator speed to its reference value. This reference value is normally obtained from a predefined power-speed curve as shown in Figure 3. For low wind speeds the generator speed is kept at a fixed low speed and for wind speeds above the rated speed the speed control loop prevents the rotor/generator speed from becoming too large by progressively pitching the blades in order to limit the aerodynamic power.

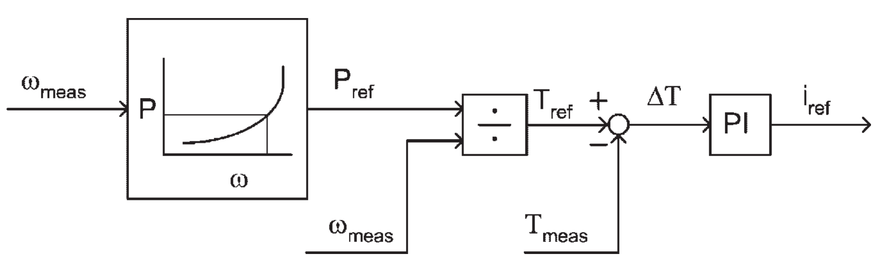


Figure 3. Speed controller.

The reference torque is obtained from the pre-defined static P-ω characteristic. The error between the actual and the reference torque is sent to a PI controller, which gives a setpoint for the current controller of the turbine. In another loop, which is not shown here, also the pitch angle of the turbine will be controlled. The output of the speed controller is the reference torque for the rotor current controller of the DFIG.

3.2.3. Kinetic energy. The energy stored in a rotating mass is given by Equation (1) and the corresponding inertia constant by Equation (2). Typical inertia constants for the generators of the large power plants are in the range of 2–9 seconds [2]. Typical values for wind turbines have roughly the same value: about 2–6 seconds [3]. This implies that introduction of wind turbines in the grid does not necessarily reduce the amount of kinetic energy that is available.

The kinetic energy of a wind turbine consists of the kinetic energy stored in the blades and the kinetic energy of the electrical generator. The inertia of the turbine blades will be much higher than that of the electrical generator. The latter will have a much higher rotational speed however, which will also result in a large amount of kinetic energy.

So far it is assumed that the wind turbine operates at maximum power. The kinetic energy stored in the rotating mass of the wind turbine depends on the rotational speed, as can be seen from Equation (1). With variable speed wind turbines, the rotational speed depends on the wind speed and therefore the kinetic energy that is available will also depend on the wind speed.

3.2.4. Primary control reserve. Variable speed wind turbines are controlled to capture as much power as possible from the wind. Therefore wind turbines do not have a primary control reserve and are not able to contribute to primary frequency control in the classical way. The kinetic energy stored in their inertia gives the turbines the possibility, however, to support primary frequency control for a short period. One particular advantage of variable speed wind turbines is that, unlike thermal power stations, they can increase their output power almost instantaneously. This is an important feature, as will become clear later on.

3.3. Micro turbines

Micro turbines are small gas turbines with power levels up to several hundreds of kilowatts. Essentially micro turbines can be considered to be small versions of conventional gas-fuelled generators. The important differences, however, are that they run at much higher speeds and are connected to the grid with a power electronic converter.

The micro turbines that will be considered are high-speed single-shaft units with the electrical generator on the same shaft as the compressor and turbine. The speed of the turbine mainly is in the range of 50 000–120 000 rpm. The electrical generator is mostly a permanent magnet synchronous machine. A power electronic converter is needed to connect the generator to the grid. The generators and converters that are used are quite conventional and will not be further described here.

As a simple approximation most gas turbines can be modelled as a first order transfer function:

$$G_{\mathrm{gt}}(s) = \frac{k_{\mathrm{mt}}}{\tau_{\mathrm{mt}} s + 1} \tag{4}$$

The values for the time constant τ_{mt} that can be found in literature vary considerably.

As long as the micro turbine is not running at full power, it can participate in primary frequency control. How much the output power can be increased will depend on the primary control reserve,

Δk_{mt}, of the micro turbine. The maximum possible increase in power ΔP_{mt}, at a certain moment, can then be defined as:

$$\Delta P_{mt} = \Delta k_{mt} P_{mt,nom} \tag{5}$$

with $P_{mt,nom}$ the nominal power. The speed with which the output power can be increased will depend on some typical time constants of the gas turbine. The rate of power increase dP_{mt}/dt, can be defined as:

$$\frac{dP_{mt}}{dt} = \frac{P_{mt,nom}}{\tau_{mt}} \tag{6}$$

with τ_{mt} the time constant of the micro turbine. Note that this equation only gives a rough approximation.

3.4. *Fuel cell*

Fuel cells are electrochemical devices. Systems for stationary power applications generally consist of three main parts; a fuel processor (reformer) which converts fuels such as natural gas to hydrogen, the fuel cell itself, where the electrochemical processes take place and the power is generated and the power conditioner, which converts the dc voltage and current to ac and makes connection to the grid possible.

Fuel cells consist of a positive (anode) and a negative (cathode) electrode and an electrolyte. Fuel is supplied to the anode and oxidant to the cathode. The fuel is electrochemically oxidised on the anode, while the oxidant is electrochemically reduced on the cathode. The ions created by the electrochemical reactions flow between the anode and the cathode through the electrolyte, while the electrons resulting from the oxidation at the anode flow through an external circuit to the cathode, completing the electric circuit [4].

The electrical response time of fuel cells is generally fast. It is mainly associated with the speed at which the chemical reaction is capable of restoring the charge that has been drained by the load. Most fuel cells have a reformer however, which generates the hydrogen that is necessary for the electrochemical processes. Mostly natural gas is used by the reformer. The processes in the reformer change rather slow, because of the time that is needed to change the chemical reaction parameters after a change in the flow of reactants. This will limit the speed with which fuel cells can change their output power. This process typically has time constants of ~ 10 seconds. Only when there is some form of hydrogen storage, the fuel cell can increase its power faster.

The capability of fuel cells to contribute to frequency control depends on how much and how fast the output power can be increased. The maximum possible increase in power at a certain moment will depend on the primary control reserve, Δk_{fc}, of the fuel cell at that moment. The maximum possible increase in power ΔP_{fc}, at a certain moment, can therefore easily be defined as:

$$\Delta P_{fc} = \Delta k_{fc} P_{fc,max} \tag{7}$$

with $P_{fc,nom}$ the nominal power.

The speed with which the output power can be increased will depend on some typical time constants of the fuel cell and the (eventual) reformer. The rate of power increase dP_{fc}/dt, can be defined as:

$$\frac{\mathrm{d}P_{\mathrm{fc}}}{\mathrm{d}t} = \frac{P_{\mathrm{fc,nom}}}{\tau_{\mathrm{fc}}} \tag{8}$$

with τ_{fc} the time constant of the fuel cell, which will be a combination of the delays in the reformer and the fuel cell itself. Note that this equation only gives a rough approximation.

3.5. Summary: complementary responses

Three different DG units have been described in this paragraph, with specific emphasis on their ability to increase their output power when necessary. Some complementary responses can be noted. Fuel cells, on one hand, can increase their output power, but the speed with which this can be done is limited by the reformer. Wind turbines, on the other hand, can only supply additional power for a short period. They can increase their output power very fast however. In this way, fuel cells and wind turbines can be complementary to each other.

4. CASE STUDIES

A case study has been done to show the ability of DG units to contribute to frequency control. The results are shown in this section.

4.1. Simulation setup

The case study is performed on a model of a small network that consists of a conventional synchronous generator, wind turbines, fuel cells, micro turbines, and loads. A simplified model of the network is shown in Figure 4.

4.1.1. Conventional power plant. The conventional power plant is modelled as a synchronous machine driven by a reheat steam turbine. The synchronous machine is modelled as a three winding representation in dq coordinates. Damper windings have not been taken into account. With the generator convention adopted the machine equations are given by:

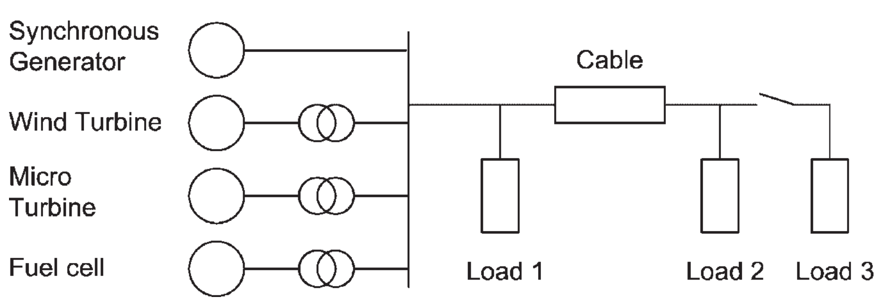


Figure 4. Case study network.

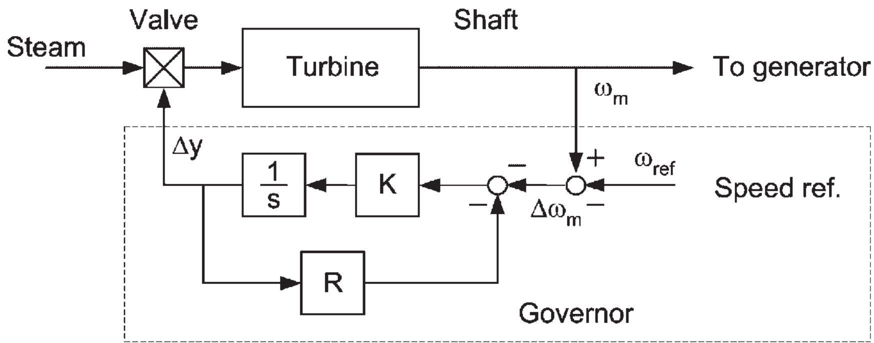


Figure 5. Governor.

$$
\begin{aligned}
L_d \frac{\mathrm{d}i_d}{\mathrm{d}t} + L_{\mathrm{mf}} \frac{\mathrm{d}i_{\mathrm{fd}}}{\mathrm{d}t} &= -u_d - R_{\mathrm{s}} i_d - \omega_{\mathrm{s}} L_q i_q \\
L_{\mathrm{md}} \frac{\mathrm{d}i_d}{\mathrm{d}t} + L_{\mathrm{f}} \frac{\mathrm{d}i_{\mathrm{fd}}}{\mathrm{d}t} &= u_{\mathrm{fd}} - R_{\mathrm{fd}} i_{\mathrm{fd}} \\
L_q \frac{\mathrm{d}i_q}{\mathrm{d}t} &= -u_q - R_{\mathrm{s}} i_q + \omega_{\mathrm{s}} (L_d i_d + L_{\mathrm{md}} i_{\mathrm{fd}})
\end{aligned}
\tag{9}
$$

with L_d, L_q, L_{md}, L_{mf}, L_{f} the synchronous machine inductances and R_{s} and R_{fd} the stator and field winding resistance respectively and ω_{s} the grid frequency. For the voltage regulator and exciter a so-called type 1 model from Reference [5] is used.

Primary frequency control is performed by the speed governor shown in Figure 5, which increases or decreases the steam flow to the turbine, depending on the frequency error $(\omega_{\mathrm{m}} - \omega_{\mathrm{ref}})$.

The prime mover has been modelled as a reheat steam turbine, based on the second-order transfer function that is given in Reference [6]

$$
H_{\mathrm{ST}}(s) = \frac{1 + sF_{\mathrm{HP}}T_{\mathrm{RH}}}{(1 + sT_{\mathrm{CH}})(1 + sT_{\mathrm{RH}})}
\tag{10}
$$

with:

T_{CH} = time constant of main inlet volumes and steam chest = 0.3 seconds
T_{RH} = time constant of reheater = 7.0 seconds
F_{HP} = fraction of total turbine power generated by high-pressure section = 0.3

4.1.2. Wind turbine. Models of a 2.75 MW variable speed wind turbine with doubly fed induction generator are used. A detailed description of the wind turbine model can be found in Reference [7].

Normally the controllers of variable speed wind turbines try to keep the turbine at its optimal speed in order to produce maximum power. The controller gives a torque setpoint that is based on measured speed and power, see Figure 6. The torque setpoint is an input for the converter control that realises the torque by controlling the generator currents. An additional controller is implemented that can adapt the torque setpoint as a function of the deviation of the grid frequency Δf, see Figure 6. The support to

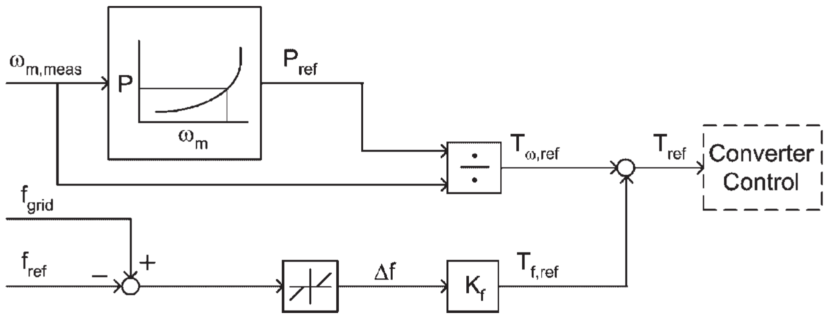


Figure 6. Wind turbine controller; upper branch: wind rotor control, lower branch: frequency control support.

primary frequency control is proportional to K_f where this latter loop is activated when the grid frequency exceeds certain limits.

4.1.3. Micro turbine. The electrical system of the micro turbine consists of a permanent magnet generator and a back-to-back converter. The generator-side converter controls the generator current in order to regulate its speed. Models of permanent magnet generators and power electronic converters are well known and will not be given here. They can, for example, be found in References [7] and [8].

The gas turbine is simply modelled by a first order transfer function, as described by Equation (4). The time constant of the turbines is based on Reference [9]. In order to let the micro turbine contribute to primary frequency control, an additional control loop is implemented. It is similar to the one shown in Figure 6 for wind turbines.

4.1.4. Fuel cell. A model of a solid-oxide fuel cell (SOFC) has been used. The 100 kW model and its parameters are based on Reference [9]. The fuel cell is connected to the grid with a three-phase voltage source converter. A control loop with a certain droop constant has been implemented on the system, in order to let it contribute to primary frequency control.

4.2. Frequency control with DG mix

The case study investigates how three types of DG unit can work together to contribute to frequency control. As an event, load 3 in Figure 4 will be turned on. This implies an increase in required power of 10%. The most important parameters are given in Table I. It can be seen that the total power of the network is rather small. They have been chosen in this way in order to be able to see a significant contribution of DG units, without the necessity to model and simulate a large number of DG units.

Table I. Parameters for case study: frequency control with DG mix.

Parameter	Value	Parameter	Value
$P_{\mathrm{sm,nom}}$	100 MW	P_{load1}	10 MW
$P_{\mathrm{wt,nom}}$	11 MW	P_{load2}	90 MW
$P_{\mathrm{mt,nom}}$	4.5 MW	P_{load3}	10 MW
$P_{\mathrm{fc,nom}}$	4.5 MW		

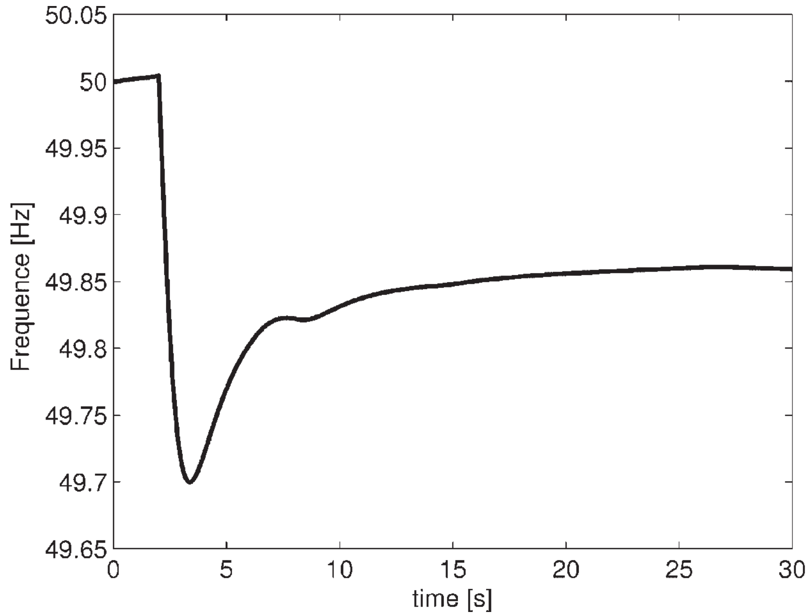


Figure 7. Grid frequency following a disturbance.

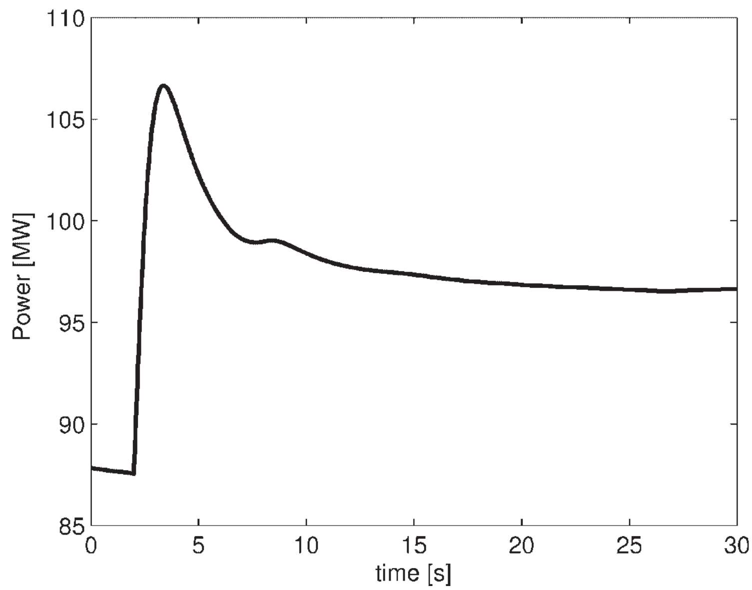


Figure 8. Power supplied by synchronous generator (representing conventional power plant).

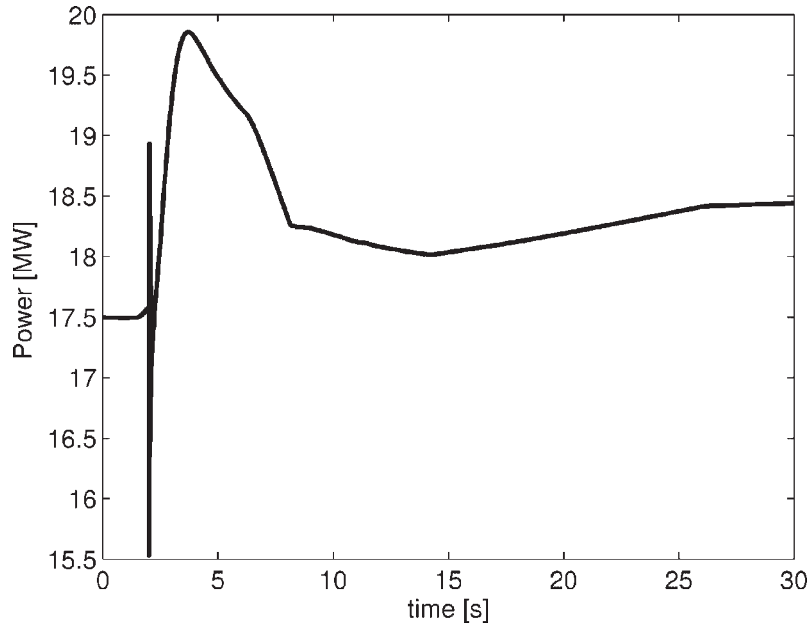


Figure 9. Power supplied by all DG units together.

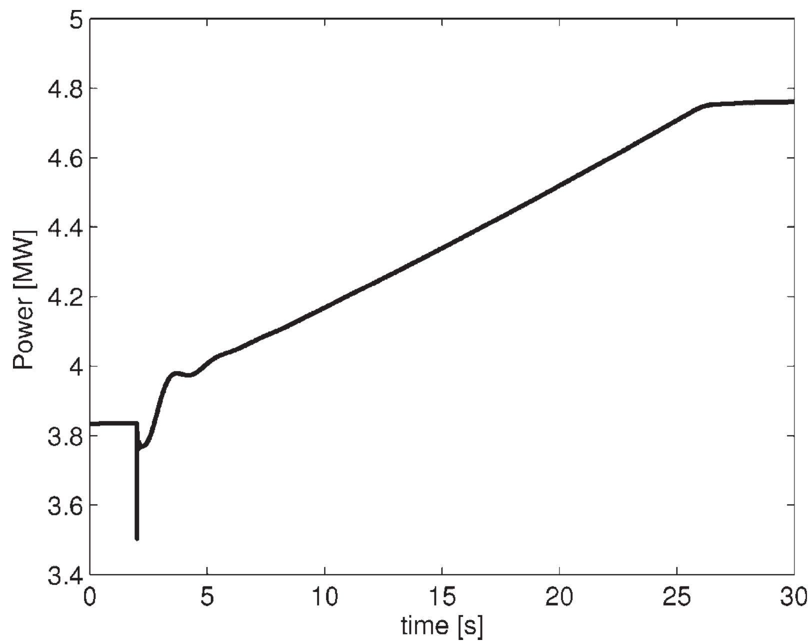


Figure 10. Fuel cell power.

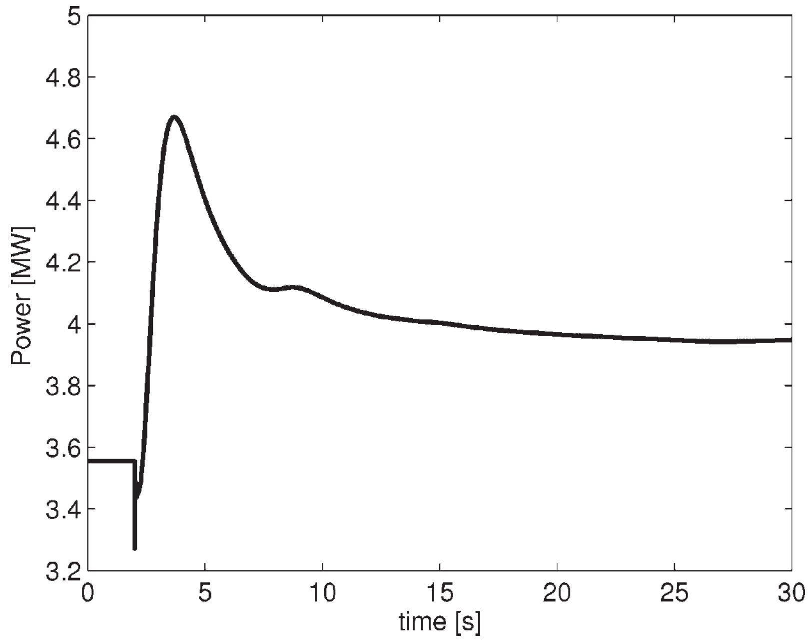


Figure 11. Micro turbine power.

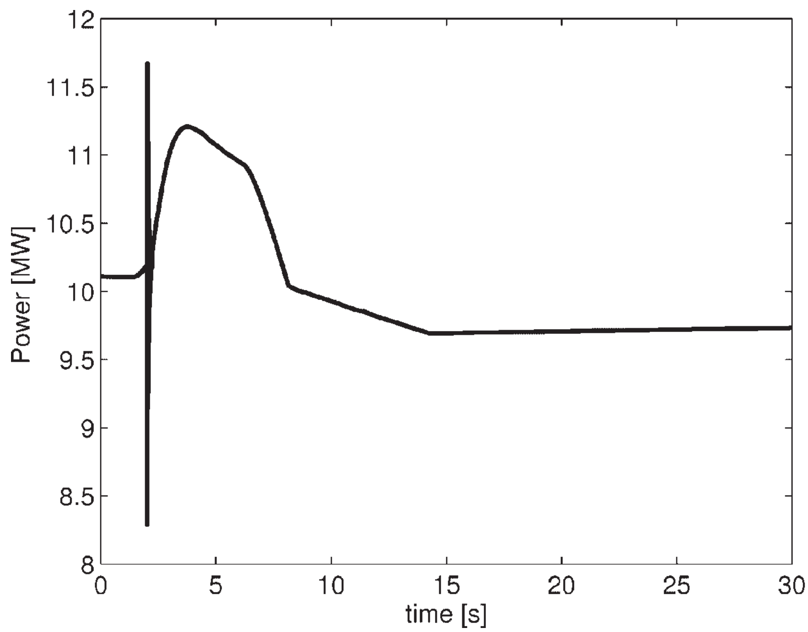


Figure 12. Wind turbine power.

The frequency response of the network is shown in Figure 7. After falling to 49.7 Hz the frequency restores a bit, due to primary frequency control, to ~49.85 Hz. As a result of the drop in frequency the synchronous generators and the DG units will increase their output power. Figure 8 shows the power supplied by the synchronous generator. The combined power of all DG units together is shown in Figure 9.

The peak increase of the synchronous machine output power is almost 20%. That of the combined DG units is with 13% a bit lower. The steady-state increase of the DG units is with about 6% also lower than that of the synchronous machine (~9%).

The output power of the fuel cell, micro turbine and wind turbine are shown in Figures 10, 11 and 12 respectively. It can be noted that the response of the fuel cell is rather slow. This can also be seen from the combined response in Figure 9. The output power of the wind turbine will drop after finishing the contribution to inertial response and frequency control. This can be seen from Figure 12. How large the drop is, can be determined by the controller. The smaller the drop is, the longer the period will be that the power is below its normal value.

5. CONCLUSION

The increasing number of DG units in the grid will make frequency control more difficult. To avoid large frequency deviations DG units will have to contribute to frequency control. To make a contribution of DG units possible, they should be able to increase their output power.

Additional controllers are described, which are needed to let the DG units contribute to primary frequency control. It has been concluded that the possibilities of some DG units are complementary to each other (fuel cell and wind turbine). To obtain a good contribution to primary frequency control it is therefore needed to have a mix of different DG unit types.

In a case study, it has been shown how DG units can contribute to primary frequency control. It has further been investigated how different types of DG unit can work together.

6. LIST OF SYMBOLS AND ABBREVIATIONS

Symbols

E	kinetic energy
f	frequency
f_{n}	nominal frequency
F_{HP}	fraction of total power generated by high-pressure section of steam turbine
$G_{\mathrm{gt}}(s)$	transfer function of gas turbine
i_d, i_q	d-axis and q-axis stator current
i_{fd}, u_{fd}	field current and voltage, transposed to stator winding
J	inertia
K_{D}	droop constant
k_{fc}	utilisation factor of fuel cell
k_{mt}	utilisation factor of micro turbine
L_d, L_q	d-axis and q-axis stator inductance
L_{f}	field winding inductance
L_{md}, L_{mf}	stator and field mutual inductance
s	Laplace operators

P_{fc}	fuel cell power
P_{G}	generator power
P_{Gn}	nominal generator power
P_{mt}	micro turbine power
P_{sm}	synchronous machine power
P_{wt}	wind turbine power
R_{s}, R_{fd}	stator and field winding resistance
S	apparent power
T_{CH}	time constant of main inlet volumes and steam chest
T_{RH}	time constant of reheater
v_d, v_q	d-axis and q-axis stator current
λ	tip speed ratio
τ_{fc}	time constant of fuel cell
τ_{mt}	time constant of micro turbine
ω_{m}	mechanical rotational speed
ω_{s}	electrical rotational speed

Abbreviations

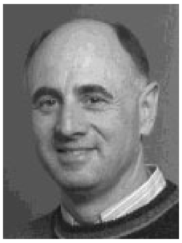
DG	distributed generation
PI	proportional integral

REFERENCES

1. Morren J, Pierik JTG, de Haan SWH. Inertial response of variable speed wind turbines. *Electric Power Systems Research* 2006; (in press). DOI:10.1016/j.epsr.2005.12.002
2. Grainger JJ, Stevenson WD. *Power System Analysis*. McGraw-Hill: New York, 1994.
3. Knudsen H, Nielsen JH. Introduction to the modelling of wind turbines. In *Wind Power in Power Systems*, Ackermann T (ed.). John Wiley: Chicester, 2005; 525–585.
4. Brouwer J. Fuel cells. In *Distributed Generation*, Borbely A-M, Kreider JF (eds). CRC Press: Boca Raton, 2001; 151–184.
5. Anderson PM, Fouad AA. *Power System Control and Stability.* Iowa State University Press: Iowa, 1977.
6. Kundur P. *Power System Stability and Control*. McGraw-Hill, Inc.: New York, 1993.
7. Pierik JTG, Morren J, Wiggelinkhuizen E, de Haan SWH, van Engelen TG, Bozelie J. *Electrical and control aspects of offshore wind turbines II (Erao-2), Vol. 1: Dynamic models of wind farms*, Technical report ECN-C–04-050, ECN, 2004, June 2004.
8. Morren J, Pierik JTG, de Haan SWH. Voltage dip ride-through of direct-drive wind turbines. In *Proceedings of the 39th International Universities Power Engineering Conference (UPEC 2004)*, Bristol, UK, 6–8 September 2004.
9. Zhu Y, Tomsovic K. Development of models for analyzing the load-following performance of microturbines and fuel cells. *Electrical Power Systems Research* 2002; **62**:1–11.

AUTHORS' BIOGRAPHIES

Johan Morren received his M.Sc. degree in electrical engineering in 2000 from the Delft University of Technology. Currently, he is a research assistant at the Electrical Power Processing group of the Delft University of Technology. He worked on different projects regarding the grid-connection of renewable energy sources. Since 2002, he is working towards his Ph.D. on the power electronic aspects of grid integration of distributed generation units.



Sjoerd W. H. de Haan received his M.Sc. degree in applied physics from the Delft University of Technology, The Netherlands, in 1975. Currently, he is associate professor of Power Electronics at the Delft University of Technology, where he has been since 1995. His current research covers electric systems for renewable energy sources and pulsed power supplies for various applications.

J. A. (Braham) Ferreira was born in Pretoria, South Africa, and received his B.Sc. Eng., M.Sc. Eng., degrees and Ph.D. in electrical engineering from the Rand Afrikaans University, Johannesburg, South Africa. In 1981, he was with the Institute of Power Electronics and Electric Drives, Technical University of Aachen, and worked in industry at ESD(Pty) Ltd. from 1982 to 1985. From 1986 until 1997 he was at the Faculty of Engineering, Rand Afrikaans University, where he held the Carl and Emily Fuchs Chair of Power Electronics. Since 1998, he is professor at the EEMCS Faculty of the Delft University of Technology in The Netherlands. Professor Ferreira is the transactions review chairman of the IEEE IAS Power Electronic Devices and Components committee, and served as chairman of the IEEE Joint IAS/PELS Benelux chapter and the CIGRE SC14 national committee of the Netherlands. He is also member of the IEEE PESC AdCom, and member of the executive committee of the EPE Society.