VIRTUAL SYNCHRONOUS MACHINES (VSG'S) FOR FREQUENCY STABILISATION IN FUTURE GRIDS WITH A SIGNIFICANT SHARE OF DECENTRALIZED GENERATION

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ABSTRACT

In October 2007 the European project "VSYNC" started with project co-ordinator Energy research Centre of the Netherlands (NL) and partners Technical University of Eindhoven (NL), Delft University of Technology (NL), Catholic University of Leuven (BE), Universitatea Politehnica Bucuresti (RO), Fundación LABEIN, 3E NV (BE), UfE Umweltfreundliche Energieanlagen Handelsgesellschaft mbH (DE), Electrica SA (RO), and Continuon NV (NL). This paper describes the project and some preliminary results.

INTRODUCTION

In electricity grids the frequency of the generated voltage is stabilized by a combination of the rotational inertia of synchronous generators in the grid and a controller acting on the rotational speed of a number of major synchronous generators.

When in future decentralized non-synchronous generation units replace a significant part of the synchronous power generation capacity, the total rotational inertia of the synchronous generators is decreased significantly. As a consequence the rate of change of the rotational speed of the synchronous generators due to changes in their net load will become much higher than at present. This causes large frequency variations that can end up in an unstable grid and frequent blackouts.

PROPOSED SOLUTION

A way for short term stabilization of the frequency of the grid is to add virtual inertia to the distributed generators. This principle has been investigated theoretically by a number of authors [3-5] for the wind case where only the rotational inertia of the wind turbine is used. Here the existing power electronics converter is combined with a suitable control mechanism.

For distributed electricity generators without some means of energy storage, e.g. photovoltaic systems and micro CHP, there is no virtual inertia [2]. However a virtual inertia can be attained for any distributed electricity generator by adding a short-term energy store, combined with a suitable control mechanism for the power electronics converter, to the distributed generator, as depicted in Figure 1.

In this way distributed generators can behave like "Virtual Synchronous Generators" (VSG's) during short time intervals, and contribute to stabilization of the grid frequency by diminishing fast fluctuations in the net loads of the synchronous generators.

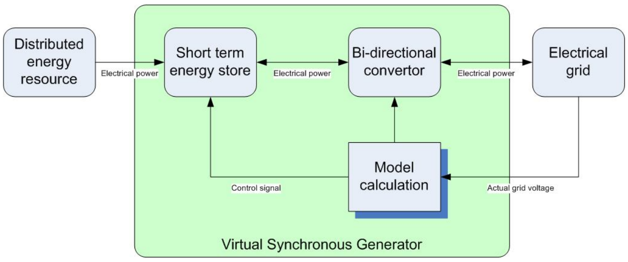


Figure 1 Principle of a Virtual Synchronous Generator (VSG)

SCOPE OF THE WORK

The principle of the Virtual Synchronous Generator can be applied either to single distributed generators, or to groups of distributed generators. The first application may be more appropriate to individual owners of distributed generators, whereas the second application is more economical and easier to control from the point of view of the network operator.

If successful, the project delivers prototypes of Virtual Synchronous Generators that are in the pre-market phase and can provide a cost effective solution to grid stability problems in areas where distributed generation is becoming significant.

The following characteristics can be implemented:

- Prevent electricity grid instability and blackouts due to large short term frequency variations caused by decentralized generation.
- Retain safety in fault situations of an electricity grid with any given share of decentralized generation.
- Lay down a basis for intentionally islanding of low voltage area's with decentralized generation.

Operation principle of VSG's

In a future grid where a large portion of centralised generation is replaced by many small decentralised generators, many VSG's may together behave like one large rotating mass. This invokes short lasting power exchanges between grid and VSG energy stores counteracting changes in frequency and voltage. It is expected that this results in a reduction of variations in frequency and voltage and some time is gained for fault clearance due to the slower response of power system.

Instability scenarios

In the current stage of the project, instability scenarios [1] are devised concerning:

1) Primary Balancing
2) Safety & Security Of Supply
3) Reconnection Of Micro grid

These will be used for testing VSG algorithms in simulations and in a laboratory environment. The results will provide a basis to put the VSG concepts proposed into hardware for a field test in The Netherlands and in Romania.

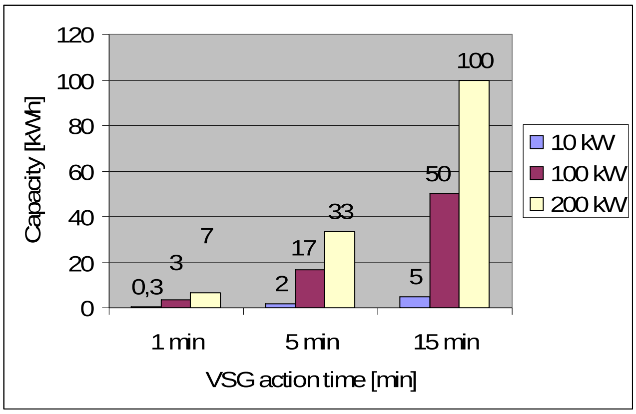
But in order to do this all, VSG algorithms have to be developed first. In the following, a few idealised VSG algorithms are worked out from basic concepts.

VSG IMPLEMENTATIONS

Implementations of the VSG concept as depicted in Figure 1 will mainly differ in the choice of short term energy store and the model calculation chosen. Therefore in the following the focus is on the energy store capacity and the model for the virtual rotating mass, and not on the electronic power converters in Figure 1.

Energy store capacity

It is anticipated that during an instability a VSG should contribute to network stability (this is, to inject or absorb power) during time intervals ranging from several grid frequency periods through tens of minutes. The smallest time interval complies with the reaction time of safety circuits, which lies in the order of tens of milliseconds. The largest time interval complies with the characteristic time interval of economic dispatch at central generators, which is about 15 minutes. This rather large time interval enables VSG's to take part in intentionally islanding of micro grids. An estimate for the energy to be stored in the VSG then is obtained by choosing a nominal (maximum) VSG power. As a VSG should be able to inject or absorb power, the energy store in the VSG should be operated at about 50% of its nominal capacity in a stationary situation.



Graph 1 Minimum energy store capacity in kWh as a function of VSG action time, for nominal VSG powers of 10, 100 and 200 kW.

From this the the minimum amounts of energy to be stored are given for a range of VSG nominal powers are calculated, as shown in Graph 1.

Virtual rotating mass relations

The energy E contained in a rotating mass with rotational inertia J is a function of its angular frequency ω as follows:

$$E = 0.5 \cdot J \cdot \omega^2 \tag{1}$$

Therefore, the mechanical power delivered to the rotating mass by its surroundings is the time derivative of this relation. In a virtual rotating mass both the rotational inertia J as the angular frequency ω may be a function of time. For the (virtual) mechanical power P_{mech} delivered to the rotating mass by its surroundings we thus get:

$$P_{mech} = \frac{1}{2} \cdot \frac{d}{dt} J(t) \cdot \omega(t)^2 + J(t) \cdot \omega(t) \cdot \frac{d}{dt} \omega(t) \tag{2}$$

In the VSG set-up as depicted in Figure 1, the power injected to the grid must be the negative of the virtual mechanical power in relation (2). Therefore, if the angular frequency ω of the VSG rises, then power is absorbed from the grid and injected to the energy store.

In order to enhance grid stability, each VSG algorithm must be devised such that it counteracts grid frequency changes. Further, as the rotating mass is virtual and in reality is a control algorithm, the power absorbed from the grid equals the power injected to energy store, resulting in:

$$P_{store} = -P_{grid\_injection} = P_{mech} \tag{3}$$

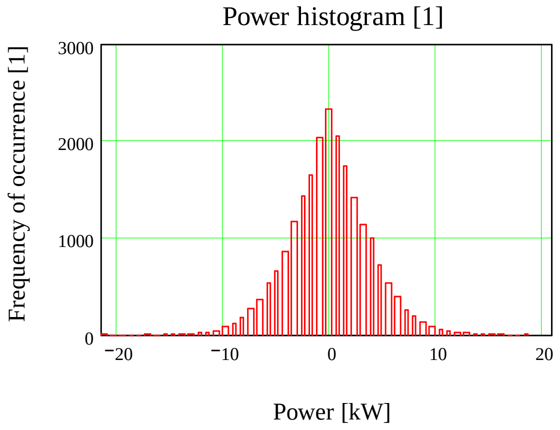
Ideal frequency-following VSG at normal operation

As an estimate to how a single VSG may function in a power network, the power exchange with the grid of an ideally frequency-following VSG is calculated. For the sake of simplicity of the present analysis is assumed that the decentralised generator is switched off. In case the rotational inertia is constant relation (2) changes into:

$$P_{mech} = \omega_{grid} \cdot J \cdot \left(\frac{d}{dt} \omega_{grid}(t) \right) \tag{4}$$

From this relation and actual grid frequency data an estimate of the virtual rotational mass parameter needed for VSG operation can be derived. From the Dutch system operator TenneT a grid frequency plot of 10 April 2008 (24 hrs, sample time 4s) was obtained. From this frequency data under normal operation it follows that the maximum of the grid frequency change is about 1 Hz per minute and the RMS value is about 0.2 Hz per minute. Suppose the nominal VSG power is 10 kW at grid frequency 50 Hz. Then it follows from (4) that the virtual rotating mass J_{rot} equals:

$$J_{rot} = 608\, kg \cdot m^2 \tag{5}$$

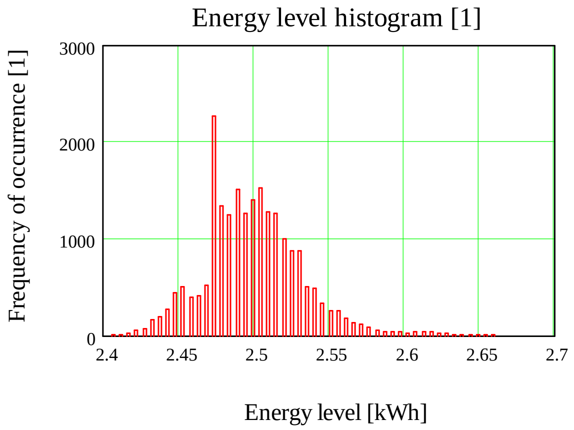


Graph 2 Power histogram of a 10 kW ideally frequency-following VSG on 10 April 2008 (24 hrs, sample time 4s)

Based on the grid frequency data under normal operation obtained from TenneT, from relations (4) and (5) the VSG power was calculated. Graph 2 shows the power histogram for this day. In the VSG model in Figure 1, this power is actually subtracted form the energy store, and delivered to the grid in order to counteract frequency changes.

From Graph 2 it is concluded that under normal operation the histogram of power exchange between the VSG energy store and the grid is symmetrical, and that occasionally power peaks up to two times nominal power (about +/- 20 kW). It can be concluded that this VSG algorithm may contribute to grid frequency stabilisation continuously.

By means of time integration of the VSG power exchange, the variation in the energy level of the VSG energy store is obtained. In Graph 1 the energy level histogram is plotted for a 5 kWh energy store that is operated around a 50% stationary level of 2.5 kWh.

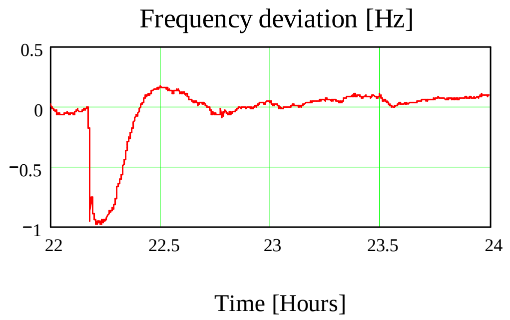


Graph 3 Energy level histogram of a VSG energy store of 5 kWh operated around 2.5 kWh stationary energy level on 10 April 2008 (24 hrs, sample time 4s).

From Graph 3 it is concluded that under normal operation only about 8% (0.2 kWh) of the maximum charging or discharging capacity (2.5 kWh) of the energy store is used.

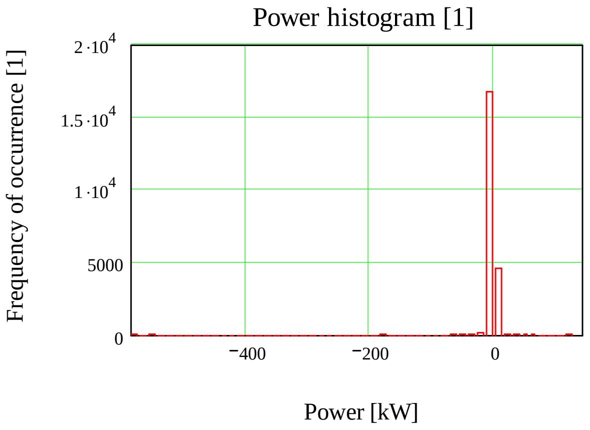
Ideal frequency-following VSG at contingency

It is interesting to see how the ideal frequency-following VSG would respond to a contingency in grid frequency. Dutch grid operator Tennet provided a grid frequency plot of 4 November 2006 (24 hrs, sample time 4s), when a major event in the grid frequency occurred just past 22:00 hours as given in Graph 4. The response of an ideal frequency-following VSG to this event is depicted in Graph 5.

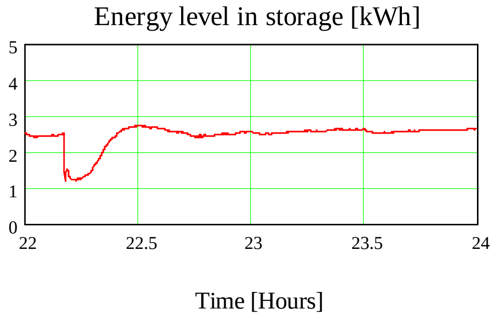


Graph 4 Grid frequency contingency situation on 4 November 2006 (sample time 4s).

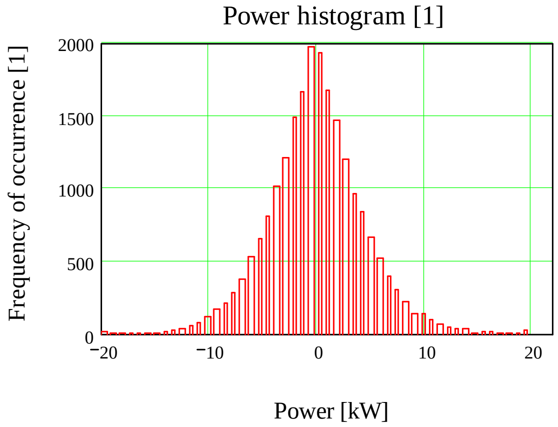
From Graph 5 it is concluded that for this situation the maximum power peak is more than 60 times nominal VSG power. Please note that in Graph 5 due to the high power peaks during the frequency fall the wide central peak (as in Graph 2) is condensed into a few large occurrence peaks. In practice, the VSG power is limited to e.g. two times nominal power during short time intervals and to the nominal power for continuous operation. Applying this limitation the power histogram and storage energy level change to the situation in Graph 7 and Graph 8.



Graph 5 Power histogram of an ideal frequency-following VSG for the contingency on 4 November 2006 (24 hrs, sample time 4s).

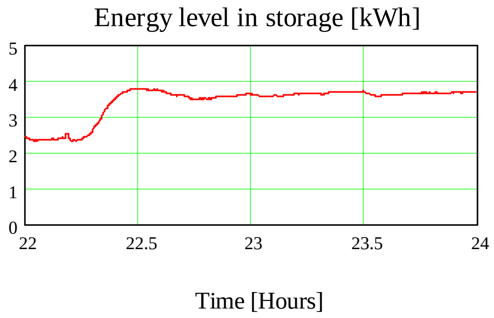


Graph 6 Storage energy level for ideal frequency-following VSG for the contingency on 4 November .



Graph 7 Power histogram of a power-limited frequency-following VSG for the contingency on 4 November 2006 (24 hrs, sample time 4s).

The effect of the power limitation of the VSG appears to be that the initial steep frequency drop is largely ignored, and only the subsequent more gradual frequency rise is counteracted by the VSG. Due to the presence of many VSG's in a future power system this initial frequency drop may be flattened.



Graph 8 Storage energy level for a power-limited frequency-following VSG due to the grid contingency on 4 November

CONCLUSIONS AND FURTHER RESEARCH

The operating principle and potential application of the Virtual Synchronous Generators (VSG's) under development in the European VSYNC project are described. A first ideal frequency-following VSG control algorithm is investigated. It is shown that this VSG algorithm may contribute to grid frequency stabilisation continuously. In case of a contingency in grid frequency the initial steep frequency change is largely ignored by the system because of its power limitation. However, when many VSG's are present in a future power system this initial frequency drop may be flattened. This remains to be investigated in the project.

ACKNOWLEDGMENTS

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