A system for dispersed generator participation in voltage control and primary frequency control

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Abstract—When the amount of power that is generated by dispersed power sources becomes a significant part of the total generated power, the control of grid voltage and frequency may become a problem, because ever less centralized power plants for voltage and frequency control remain. Therefore, a method is proposed to let dispersed power sources participate in voltage control and primary frequency control. The method is specifically meant for dispersed sources that are connected to the power system via a power electronic interface, such as photovoltaic systems, variable speed wind turbines and fuel cells. The method takes advantage of the possibilities to control the active and reactive current of the power electronic interface independently, within limits imposed by the prime mover and the converter rating. Theory, simulations and experimental results obtained with a scaled model are presented. Both simulations and experimental results show qualitatively that dispersed generators can help to stabilize voltage and frequency.

Index Terms—Voltage control, frequency control, power system control, wind energy, solar energy, power generation control, dispersed generation.

I. INTRODUCTION

As a result of increasing environmental concern efforts are made to generate electricity from renewable sources such as wind turbines, photovoltaic panels, and bio-fuel cells. Most dispersed generators are characterized by a relative small scale and geographical spread. Up to this moment, the amount dispersed or renewable energy integrated into large-scale electrical power systems only covers a small part of the total power system load.

Dispersed generators hardly ever take part in voltage and power (or frequency) control of the grid. If a disturbance occurs, the generators are disconnected, amongst others to avoid islanding, and are reconnected when normal operation has been resumed. Thus the power balance and voltage are maintained by controlling the large power plants. This is possible, as long as penetration of dispersed generators is still low.

With current operating practices, neither the load nor the dispersed power generators contribute to controlling and stabilizing the power system, while the power generated by dispersed generators depends heavily on the availability of the renewable source [1-7]. When the penetration of dispersed generators increases significantly, it will no longer be possible to run a power system by only controlling the large-scale power plants. Also the practice to disconnect dispersed generators in case of disturbances can no longer be maintained as this will make the problem worse because of loss of more power.

In this paper a method is proposed to enable dispersed generators to participate in the voltage control and frequency control of a power system through the power electronic converter that connects them to the grid. Modern power electronic dc-ac converters are capable of fast control of the output voltage with respect to amplitude, frequency and phase.

In section II, the investigated system will be described. The basic concepts will be reviewed. In section III the proposed method of control and the associated models will be described. In section IV experimental results will be compared with simulation results.

II. SYSTEM DESCRIPTION AND MODELING

The considered system consists of categories of components as shown in Fig. 1:
- controlled generators in centralized power stations
- uncontrolled dispersed generators like wind parks
- time varying active and reactive loads;

The qualifications ‘controlled’ and ‘uncontrolled’ refer to the controllability from the viewpoint of voltage and frequency control in power systems. Strictly spoken, dispersed generators can either be controlled or uncontrolled. However, for the time being they are considered as a separate category and initially (in Section II.A) they are considered as non-controllable. In section II.B the controllability is addressed.

![Fig. 1. Considered simplified power system with controllable, non-controllable and dispersed generators](image)
A. State of the art dispersed generator with grid connection

The general model of a typical dispersed generator system is shown in Fig. 2 and it consists of two parts: a prime mover (such as a photovoltaic array, a battery cell etc., Fig. 2a or the generator of a wind turbine, Fig. 2b) and a power electronic converter that converts the voltage available from the prime mover (dc or variable frequency ac) to ac that is conform to the grid [10,11]. Nowadays, converters are controlled in such a way that they behave as a negative load. The power that is supplied to the grid is determined by the power that is available from the prime mover. The power is mostly delivered at constant reactive power, or at unity power factor [1]. Active and reactive power are not controlled on the basis of grid frequency or voltage. Often the converter simultaneously controls the current at the input side such that optimum power is extracted from a renewable prime mover.

![Fig. 2. Dispersed generator systems a) photovoltaic systems, battery systems or fuel cells; b) variable speed wind turbines, flywheel storage systems](image)

1) State of the art Power/frequency primary control

For stable operation of an electric power system, a balance between generated power and consumed power is required. An unbalance between generated and consumed power will be reflected in a change in the kinetic energy of the rotating machines connected to the network. This results in a changing speed and grid frequency, which is observed by all power stations in the network.

The controllable generators have to stabilize the frequency [10,11]. An observed increase of the frequency will lead to a reduction of the fuel injection as shown in Fig. 3.

![Fig. 3. Droop line of controllable power plant n. A change in frequency from \( f_1 \) to \( f_2 \) leads to a reduction of prime power \( P \).](image)

After a load change \( \Delta P \) the frequency will also change until a new equilibrium is obtained between generated power and load. When the number of non-controllable generators increases, the number of controllable generators \( N \) will probably decrease and consequently the frequency deviation will become (too) large for a given load change \( \Delta P \) and a given gain of the individual power stations.

2) Voltage control

Each controllable generator controls the voltage at its terminals or a near node by injecting or consuming reactive power [1,2]. To determine whether reactive power should be supplied or consumed, the voltage at the controlled node is measured. When the terminal voltage is too low, reactive power generation is increased. When it is too high, reactive power generation is decreased. In synchronous generators, the reactive power generation is controlled by changing the current through the field winding by adapting the field voltage. The device that controls the field current based on the measured terminal voltage is called the excitation system.

![Fig. 4. Principle of voltage control](image)

B. Power electronic interface

Modern power electronic converters of the ‘voltage source’ type are assumed. These converters can convert dc to variable frequency ac (inversion) and need a relatively small inductor \( L_s \) in series with the ac connection to limit high-frequency currents that are caused by the switching process. On the grid side a voltage source converter can be modeled as a controllable ac voltage \( v_s(t) \) with series inductance \( L_s \) (Fig. 5). The inverter can generate a more or less sinusoidal voltage \( v_s(t) \) at the output, of which the amplitude, frequency and phase of the fundamental are fully controllable.

III. Proposed method of control

A. Participation in voltage and frequency control

As pointed out in section II.A.1 the frequency will change in response to a load change according to Fig. 3. One of the objectives of the research presented here, is to let the dispersed generators participate in the frequency control such that dispersed generators also take part in a frequency control.
According to (1), this will result in a smaller power change of the other controllable generators and thus in a smaller frequency change of the system, as the total number of controllable generators $N$ is increased.

The output voltage phasor $V_s$ of the inverter is fully controllable within certain limits imposed by the magnitude of the DC-link voltage $V_{dc}$. This implies that – within certain limits - the voltage across $L_s$ can be set to any value too, which means that the current $I_s$ and thus the power flow to the grid can be controlled according to:

$$I_s = \frac{V_s - V_e}{j\omega L_s} \quad \text{(1)}$$

It is obvious from (1) that active and reactive current can be controlled through $V_s$.

**B. Mathematical model**

It is necessary that the active and reactive component of the output current can be controlled independently. For that purpose, all currents $i(t)$ and voltages $v(t)$ are transformed to a rotating d-q frame that rotates in synchronism with the grid voltage $v_g$. This transformation yields space phasors that are constant in the stationary state and if the transformed waveforms are pure sinoids:

$$
\begin{bmatrix}
x_a \\
x_b \\
x_c
\end{bmatrix} = C_{abc,\alpha} \cdot \begin{bmatrix}
x_a \\
x_b \\
x_c
\end{bmatrix} \quad \text{with} \quad C_{abc,\alpha} = \begin{bmatrix}
\sqrt{2} & -1 & -1 \\
\sqrt{3} & \sqrt{6} & -\sqrt{6} \\
0 & 1 & -1
\end{bmatrix} \quad \text{(2)}
$$

$$
\begin{bmatrix}
x_d \\
x_q
\end{bmatrix} = C_{\alpha,\alpha}^{-1} (\theta) \cdot \begin{bmatrix}
x_a \\
x_b
\end{bmatrix} \quad \text{with} \quad C_{\alpha,\alpha}^{-1} (\theta) = \begin{bmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{bmatrix}
$$

The combined transformation $C_{abc,\alpha} C_{\alpha,\alpha}^{-1}$ will further be denoted by $C_{d\alpha/\alpha}$ and the space phasors are in bold typeface. The transformations eventually result in d and q components, where $i_d$ is the active current, which is in phase with the voltage $v_s$, the reactive current is represented by $i_q$.

The primary frequency control is implemented by the proportional controller as shown in the block $f$-control in Fig. 5, which generates a setpoint for $i_q$. The voltage control is implemented by the block V-control in Fig. 5, which generates a setpoint for $i_d$. These controllers will be described in more detail in the next section. In the next block ‘current control’ these setpoints are transformed to a setpoint for $v_d(t)$, as $v_d(t)$ directly affects the current $i_d(t)$ according to:

$$i_d(t) = \frac{1}{L_s} \int [(v_s(t) - v_g(t))] \, dt \quad \text{(3)}$$

The function of the current controller is to calculate the reference $v_{d\text{ref}}(t)$ for the voltage $v_d(t)$, such that the values of $i_d$ and $i_q$ are indeed realized.

**C. Controllers**

The objective of the frequency control is to change the real power of the renewable generator on basis of a frequency deviation.

$$\Delta P_f = k_{g,\text{inv}} \Delta f \quad \text{(4)}$$

Where $k_{g,\text{inv}}$ is the ‘governor’ gain of the inverter of the renewable generator. The real power of the renewable generator $P_f$ follows from the d-component of $V_g$ and $i_d$:

$$P_f = \sqrt{3}/2 \, V_{g,\text{dc}} \, i_d$$

so (4) can be rewritten as:

$$\sqrt{3}/2 \, V_g \, \Delta i_d = k_{g,\text{inv}} \Delta f \quad \text{or} \quad \Delta i_d = \frac{k_{g,\text{inv}}}{\sqrt{3}/2 \, V_g} \Delta f = k_d \Delta f \quad \text{(5)}$$

where $V_g$ is assumed more or less constant and where, for brevity, the constant $k_{g,\text{inv}}/V_g$ is replaced by $k_d$. This control law (5) is implemented by the proportional controller as shown in Fig. 6a. The reference $i_{d,\text{ref}}$ is finally obtained by adding $\Delta i_d$ to the signal $I_{set}$, which is the setpoint for the operational current of the renewable generator, given the availability of the primary energy source. When participation in frequency control is desired or necessary, it is be possible to have some control margin to increase the generated power. To this end, the value of $I_{set}$ should be set to a value that is slightly below the value that corresponds to maximum power extraction from the renewable source. Decreasing the real power in case of a frequency increase is of course not a problem.

The block V-control in Fig. 6b implements the voltage controller. The frequency and voltage controllers generate set points for $i_d$ and $i_q$. The function of the current controller is to set $v_s$ to such a value that the values of $i_d$ and $i_q$ are indeed realized. In Fig. 6c a simplified version of the current controller is shown. Based on the difference between the actual value $i_d$ and the reference value $i_{d,\text{ref}}$, a reference for the inductor voltage $V_{q,\text{ref}}$ is obtained via a PI-controller, as the inductor voltage will cause $i_d$ to change. This inductor voltage is added to the actual grid voltage $v_{g,\text{dc}}$ to get a new reference $V_{q,\text{ref}}$. In the same way a reference $V_{d,\text{ref}}$ is generated. The reference $V_{d,\text{ref}}(t)$ is finally obtained by applying the transformation $C_{d\alpha/\alpha}^{-1}$ to $V_{d,\text{ref}}$ and $V_{q,\text{ref}}$. In the
simulations and experimental setup the current controller is slightly more complicated as there is cross coupling from $v_{sd}$ to $i_{sq}$ and from $v_{sq}$ to $i_{sd}$ which is, however, neglected here for clarity.

$\begin{align*}
v_{Lq,ref} & = \frac{1}{s} + k_s k_1 s^2 v_{gq} + k_3 s_{ref} v_{Ld,ref}^{3/2} \frac{1}{C_{sd}^{-1}} s_{ref} v_q,ref \\
i_{q} & = i_{q,ref} + f_{k_d} + i_{d,ref} + k_2 s \frac{1}{C_{sd}^{-1}} s_{ref} v_q,ref \\
i_{d} & = \frac{1}{s} + \frac{k_1}{s} + k_2 s \frac{1}{C_{sd}^{-1}} s_{ref} v_q,ref
\end{align*}$

Fig. 6. Controllers. a) frequency controller ($k_d=2.5$, corresponding to 862 W/Hz); b) voltage controller ($k_v=20$); c) current controller ($k_1=0.5$, $k_2=100$)

IV. RESULTS

A. Simulation results

The system as shown in Fig. 1 was modeled in the Power System Blockset of Matlab Simulink™ to investigate the proposed method of control. The standard Simulink SG model was used with parameters given in the appendix. The generator was equipped with standard frequency control. For the inverter, a dedicated model was used that generated pulse width modulated voltages $v_s$ based on a signal $v_sref$ (see Fig. 5). The internal switching frequency was set at 5 kHz and a line inductance of 5mH was used.

The power level of the dispersed generator was chosen at about 20% of the power of the central generator, representing a fair degree of penetration. The absolute power levels were selected close to the power rating of the experimental systems to enable comparison. The real powers of the synchronous generator and the dispersed generator for rated voltage and frequency were 40 kW and 7 kW respectively without upper and lower limits on the actual power.

1) Control signal response

Prior to investigating the closed-loop response of the system, the open-loop response of the system to steps in $i_{d,ref}$ and $i_{q,ref}$ was investigated.

Fig. 7 shows the real power $P_{INV}$ that is generated by the inverter INV (representing a renewable generator) and the synchronous generator SG (representing a central power station) after a step in $i_{d,ref}$ at $t=0.1s$. The figure also shows that rise time after the step is about 30 ms. Fig. 8 shows the response of $Q_{INV}$, $P_{INV}$ and $Q_{SG}$ to a step in $i_{q,ref}$. From Fig. 7 and Fig. 8 it can be concluded that $P_{INV}$ and $Q_{INV}$ can be controlled independently.

![Fig. 7 Simulation: Real and reactive power from inverter (INV) and synchronous generator (SG) after a step in $i_{d,ref}$ from 20 to 35A at t=0.1s at constant load. Note that the small oscillations do not occur in practice, but are caused by the applied method of power measurement in Simulink](image)

Fig. 8 Real and reactive power from inverter (INV) and synchronous generator (SG) after a step in $i_{q,ref}$ from 0 to 50A at constant load.

2) Frequency control

The performance of the method of frequency control was verified by investigating the response of the system to a stepwise change in the power of the load with frequency control both ON and OFF. In Fig. 9 the initial load is 45kW+21.8kVar. At $t=0.1s$ the load is stepwise increased with 20kW+9.7kVar ($\cos \phi =0.9$). Fig. 9 shows that with f-control OFF the drop in frequency is about 5Hz and with f-control ON the drop is reduced to about 4 Hz, which is in accordance of the droop setting of both sources. This is also reflected in Fig. 10 and Fig. 11, which give the power of both generators. With f-control OFF the extra load power is completely supplied from SG (increases from 37kW to about 57 kW) while the inverter power remains constant at about 8 kW. With f-control ON the inverter power increases from 8 to 12 kW so that the power of the SG generator does not have to increase that much resulting in a smaller drop in frequency. For all cases concerning the frequency control
behavior, the voltage control on the SG was ON and on the voltage control on the DG was OFF.

Fig. 9 Simulation: Frequency after a stepwise increase of the load from (45kW+21.8kVAR) to (65kW+31.5kVAR) at t=0.1 s. Lower line: f-control OFF; Upper line: f-control ON.

3) Voltage control
The performance of the method of voltage control was verified by investigating the response of the system to a step change in the active power of the load. The step change in load was implemented by connecting additional resistors and inductors. During these experiments the synchronous generator had a constant excitation current ('manual excitation control' [10]). Fig. 11 shows the resulting power and Fig. 12 shows the voltage after this step in the load with v-control OFF (f-control ON). The bus-voltage immediately drops from 230V to 215V due to the increased voltage drop across the reactance of the SM and the bus-voltage continues to decrease afterwards. The continued voltage reduction can be clarified from Fig. 13, which gives the real and reactive power supplied from the SM. After the load step, the real and reactive power of the SG increases with the same amount, while the power of the inverter hardly changes. As a consequence the frequency will gradually drop and so will the EMF of the SG, which leads to a continued reduction of the voltage.

The reduction in voltage across the load results in a reduction in real and reactive load power and this stops the frequency from dropping further. A new balance is reached after several seconds (not shown). With v-control ON the voltage is restored to its initial value within 0.5 s (Fig. 12). The restoration of the voltage is caused by a sharp increase in reactive power that is generated by the inverter as shown in Fig. 13 as the generator reactive power decreases. With v-control ON the bus voltage is maintained at its nominal value, so in the stationary state the load power is higher than with v-control OFF.

This method of voltage control is currently applied in several large offshore wind farms.

Fig. 10 Real power of SG (upper trace) and INV (lower trace) after increasing the load from (45kW+21.8kVAR) to (65kW+31.5kVAR) with f-control OFF

Fig. 11 Simulation: Real power of SG (upper trace) and INV (lower trace) after increasing the load from (45kW+21.8kVAR) to (65kW+31.5kVAR) with f-control ON

Fig. 12 Simulation: Rms voltage after increasing the load from (45kW+21.8kVAR) to (65kW+31.5kVAR) at t=0.1 s. Lower line: v-control OFF; upper line: v-control ON
B. Experimental verification

1) Set up

To simulate model was validated in the laboratory using the experimental set-up shown in Fig. 14. The experimental set-up represented a simple grid, one central power station, one decentralized power station and a variable load.

A SG driven by a separately excited dc-motor was used to represent the central power station. For the f-control experiment a resistance was inserted in the armature circuit of the dc-motor to simulate the prime mover droop characteristic. The decentralized power station consisted of simulated renewable source (DC supply) that was coupled to the grid via a voltage source inverter. The decentralized generator was equipped with the proposed frequency and voltage controller, which could be turned on and off for comparison. To be able to operate the system at rated frequency (50 Hz), the grid voltage would be 230/400V. This would require a DC supply of at least 550V, which was not available. For practical reasons, the ac voltage was therefore reduced to about 140/240V and consequently the base frequency to about 30Hz because of the Volt/Herz ratio of the SG. The load consisted of an inductance and a variable resistor of 10-40 Ohm. The control system was implemented in a DSP system with TI320C40.

2) Experimental verification of v-control

Fig. 15a and b show the bus voltage with v-control OFF and ON respectively. The resistance in the armature circuit was removed an f-control was OFF. The figure confirms the simulation results and shows that the bus voltage is stabilized by the v-controller. Fig. 15c shows the stabilization is due to generation of reactive power by the inverter.
3) Experimental verification of f-control

The measured droop line of the system (see section IIA) for different gain setting of the renewable generator $dP_{inv}/df$ is shown in Fig. 16. The figure shows that the f-control has a small but obvious effect on the droop of the system. The effect is relatively small because the power rating of the inverter is about 20% of the power of the system.

![Fig. 16 Experimental: Measured droop line of the system for different gain settings ($dP_{inv}/df$) in software of the inverter f-control](image)

**V. APPENDIX**

**TABLE I**

<table>
<thead>
<tr>
<th><strong>Parameter</strong></th>
<th><strong>Symbol</strong></th>
<th><strong>Value</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal power generator</td>
<td>$P_{SG,nom}$</td>
<td>40 kW</td>
</tr>
<tr>
<td>Number of poles</td>
<td>$N$</td>
<td>4</td>
</tr>
<tr>
<td>Mutual inductance in d axis</td>
<td>$L_{dm}$</td>
<td>13.7 mH</td>
</tr>
<tr>
<td>Mutual inductance in q-axis</td>
<td>$L_{qm}$</td>
<td>11.0 mH</td>
</tr>
<tr>
<td>Stator leakage inductance</td>
<td>$L_{ss}$</td>
<td>1.44 mH</td>
</tr>
<tr>
<td>Stator resistance</td>
<td>$R_s$</td>
<td>0.26 Ω</td>
</tr>
<tr>
<td>Field inductance</td>
<td>$L_{f}$</td>
<td>2.1 mH</td>
</tr>
<tr>
<td>Inertia constant</td>
<td>$J$</td>
<td>2.4 kgm²</td>
</tr>
<tr>
<td>Nominal power inverter</td>
<td>$P_{inv,nom}$</td>
<td>7 kW</td>
</tr>
<tr>
<td>Line inductance of inverter</td>
<td>$L_a$</td>
<td>5 mH</td>
</tr>
</tbody>
</table>

**VI. ACKNOWLEDGEMENT**

The work presented in this paper was the core of the master project of Sydney Wijnbergen that he performed in 2001. Rob Schoevaars is acknowledged for the extensive technical support that he gave during the project.

**VII. CONCLUSIONS AND RECOMMENDATIONS**

A method is proposed for connecting dispersed generators with a power electronics interface to a grid in such a way that they participate in primary frequency control and voltage control. The method is based on independent injection of active or reactive power via the power electronic interface between renewable source and grid. The active and reactive power generation is derived from the measured frequency and voltage. The method has been qualitatively verified experimentally for a small system. This showed that the proposed control method works according to expectation and is both statically and dynamically stable. During step changes in the load, the transients damped in about 1 sec, depending on the controller settings.

The method has been demonstrated for a simplified grid, where both the central power stations and the dispersed sources are each represented by only one unit. The models should be extended to investigate the coordination of power and frequency control of the multiple dispersed units.

**VIII. REFERENCES**