Grid Inertia Supporting by Energy Storage Inverters

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Abstract: - The new approach to increase the amount of inertia in power system with dispersed renewable generation and energy storage inverter is proposed. The inverter capability to deliver frequency support is presented and analyzed. The basics of the new method are in the inverter modulation scheme related to the generation of the inverter reference voltage through a specific delay line. Derived results are verified by Matlab-Simulink simulation results, comparing two cases, one with increased generator inertia and the other with energy storage inverter employed as proposed.

Key-Words: - energy storage integration, power-frequency control, grid inertia, inverter control

1 Introduction
Disturbances in an interconnected power system lead to frequency deviations in the grid. In the period immediately following a disturbance, the frequency deviation is primarily characterized by the amount of inertia in the system. This system inertia is often considered to be of curtail importance when it comes to power imbalance. In such cases the kinetic energy of rotating masses of synchronous generators and turbines will inject or absorb kinetic energy into or from the grid to depress the frequency deviation. This initial reaction of the power system to a disturbance is called inertial response of the system. It can be described as a stabilizing effect in response to a change from the equilibrium condition in the power system. Such an inertial response has long been treated as given in power systems due to the prevalence of synchronous generators.

The integration of renewable resources (both generation and storage technologies) in power grid, however, gives rise to new problems. Because renewable energy sources are mainly connected to the grid through inverters [1], [2], an inertial response is not inherently provided, and different responses can be designed, not necessarily of classical inertial type [3]. With the increasing penetration of renewable energy resources, the overall inertial response of the system is decreasing due to electrically decoupled renewable generators from the grid [4], [5].

With the implementation of an additional control path an inertia-like response can be emulated and frequency control is possible [6], [7]. The additional power for the control branches is provided by internal power sources as well as external energy storage devices [4]-[7]. These power systems have different characteristics in terms of bandwidth and saturation limits and in order to account for these characteristics, modern control designs have to be developed [8]-[10].

The paper presents the initial analysis of the influence of inverter connected energy storage on small disturbance stability of power system. It demonstrates the influence of improved inverter voltage control on system stability within the frequency range of electromechanical oscillations.

2 Inverter Control
The main cause of frequency change in power system is unbalance between production and
consumption of electric power. In the case of balance between production and consumption of electric power, the voltage waveform at the point of common coupling between inverter and power system is of constant frequency. But if there is unbalance in system and either the consumption is larger than production or vice versa, the voltage frequency will change in time. Energy provided to the grid form stored kinetic energy of rotating generators in the grid is given with (1):

\[
2(J) \frac{\partial P}{\partial t} = \omega_1 \Delta \omega
\]

A dedicated MATLAB/Simulink model is developed to examine this change [11].

In the proposed algorithm the common coupling voltage waveform is processed. Average period of a given voltage is estimated for the last 100 periods and defined as \(T_{av100}\). Then the processed voltage waveform is shifted in time for \(T_{av100}\) and is further used as the inverter reference voltage.

If system is in balance and production and consumption of power are equal, the voltage waveform of current period of voltage will match the inverter reference voltage and there will be no energy flow from inverter to the grid as shown in Fig. 1 a).

But, if there is a loss of some of produced energy, frequency of voltage waveform will decrease and waveforms of two voltages will not match each other. Phasor diagram reference voltage of inverter, when the system is not in balance, is presented in Fig. 1 b). Amplitude of the voltage is designated as \(E_{F1}\) and power angle is defined as \(\delta_1\). Waveform of actual voltage in system has new amplitude designated as \(E_{F2}\) and the new power angle \(\delta_2\). Both voltages are shown in Fig. 1 b) as well the phase difference between them. The energy flow between the inverter and power system can be determined with (2):

\[
P_{av} = \frac{E_{F1} \cdot E_{F2}}{X_c} \sin(\delta_2 - \delta_1)
\]

The difference between the actual period of the voltage \(T\) and \(T_{av100}\), defined as \(\Delta T_{av100}\), is calculated by (3):

\[
\Delta T_{av100} = T - T_{av100}
\]

Blok diagram of calculation of average derivation of frequency is given in Fig 2.

![Fig. 2 Block diagram of calculation of difference between current period of voltage and the average period of last 100 periods of voltage](image)
If we define the actual waveform of a grid voltage as (4):

\[ v_{grd}(t) = E_{f1} \sin(\omega t) \]  

and the inverter voltage waveform as (5):

\[ v_{inv}(t) = E_{f2} \sin(\omega T_{100}) \]  

than the power flow between the inverter and the grid is given with (6):

\[ P_{inv} = \frac{E_{f1} \cdot E_{f2}}{X_L} \cdot \sin(\omega \cdot \Delta T_{100}) \approx \frac{E_{f1} \cdot E_{f2}}{L_L} \cdot \Delta T_{100} \]  

### 3 Test System Model

Block diagram of a system is shown in Fig. 3. Two synchronous generators G1 and G2 with all the same parameters except moment of inertia, where \( J_{G1} \) is 15 times smaller than \( J_{G2} \), are used in simulation. Synchronous generator G2 is used in order to facilitate comparison. Parameters of generators G1 and G2 are given in Fig. 4.

Input parameters of synchronous generators are mechanical power on generators’ shafts and excitation voltages. Both inputs are implemented with regulation, where generators output voltages are regulated with excitation voltages, while speeds of generators are controlled with mechanical input powers. PI regulators used for control of speeds and output voltages of both generators have the same proportional and integral coefficients, so:

\[ P_{reg1} = P_{reg3} \]  

and

\[ P_{reg2} = P_{reg4} \]  

References for both generators’ speeds and output voltages are the same.

<table>
<thead>
<tr>
<th>Parameters of Generators</th>
<th>G1</th>
<th>G2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power kVA</td>
<td>16</td>
<td>400</td>
</tr>
<tr>
<td>Voltage V</td>
<td>50</td>
<td>400</td>
</tr>
<tr>
<td>frequency Hz</td>
<td>2</td>
<td>400</td>
</tr>
<tr>
<td>Number of poles</td>
<td>0.013</td>
<td>0.013</td>
</tr>
<tr>
<td>Friction N·m·s</td>
<td>0.1278</td>
<td>1.917</td>
</tr>
<tr>
<td>Moment of inertia kg·m²</td>
<td>1.917</td>
<td>1.917</td>
</tr>
</tbody>
</table>

Generator G1 is constantly connected to \( Load_1 \) while generator G2 is constantly connected to \( Load_3 \), where:

\[ Load_1 = Load_3 \]  

Disturbance in the system is produced when, in parallel to the \( Load_1 \) and \( Load_2 \), \( Load_2 \) and \( Load_4 \) are connected, where:

\[ Load_2 = Load_4 \]  

Fig. 3 Block diagram of testing system

Fig. 4 Parameters of generators G1 and G2
Inverter with energy storage is connected in parallel to the synchronous generator G1 through \( RL \) branch. Electric power \( P_{inv} \) delivered by the inverter is calculated, as is amount of energy provided by the inverter and energy storage to the grid. Rotating speeds of rotors of synchronous generators are closely followed and compared in order to determine the difference in response between two generators under the same load conditions.

4 Results of simulation

Input parameters for both generators G1 and G2 are the same and constant during simulation, rotors’ speeds are 1500 rpm while nominal output voltages are 220 V rms. \( Load_1 \) and \( Load_2 \) have only active component of 14kW, which represents 87.5% of nominal output power of generators. When the system is in steady state, switches between \( Load_1 \) and \( Load_3 \), and \( Load_2 \) and \( Load_4 \) are closed at the same time. Total load power connected to both generators now is 15kW of only active power, which represents increase of 7%. Switches are kept closed for 50 seconds. After then they are opened again for another 50 seconds. Pattern of opening and closing of switches is repeated every 50 seconds.

Total amount of kinetic energy stored in rotating masses of a generator during its work is relatively small to the power of overall system. In the case of a generator G1, kinetic energy of rotor during its rotation is easily calculated with (11):

\[
E_{KG1} = \frac{1}{2} J \omega^2 = \frac{1}{2} \cdot 0.1278 \cdot 157^2 = 1575 Ws = 0.44 Wh
\]

Even when we increase inertia 15 times, as is the case with generator G2 compared to generator G1, total kinetic energy is still relatively small and is given with (12):

\[
E_{KG2} = 15 \cdot E_{KG1} = 23625 Ws = 6.56 Wh
\]

This still represents the overall kinetic energy of generators. The energy released during the change of speed is even smaller and for generator G2, when the speed falls 5% from 157 rad/s to 149 rad/s, total kinetic energy lost can be calculated with (13):

\[
\Delta E_{KG2} = \frac{1}{2} J (\omega_1^2 - \omega_2^2) = \frac{1}{2} \cdot 1.917 \cdot (157^2 - 149^2) = 2346 Ws = 0.65 Wh
\]

When the inverter connected in parallel with generator G1 is turned off, the difference between speed changes of generators, during the load changing, will be consequence of different moments of inertia of generators. It can be seen from Fig. 5 that the speed of generator G1 has fallen from 157 rad/s to 145 rad/s which represents the fall of 7.6%, while the speed of generator G2 has fallen from 157 rad/s to 149 rad/s which represents the fall of 5%. It can also be seen that the response of speed of generator G2 is a bit oscillatory. That is because of parameters of PI regulator of speed which is adjusted of generator G1 with smaller moment of inertia. Also the rate of change of speed of generator G1 is much faster than the rate of change of speed of generator G2.

When the inverter connected in parallel with generator G1 is turned on and the same change of load is applied to the system, the change of speed of generator G1 differs significantly and is shown in Fig. 6. It can be seen that now the change of speed of generator G1 is as if the generator has greater moment of inertia. When the load is increased, the speed of generator G1 falls from 157 rad/s to 150 rad/s before it returns back to 157 rad/s which is very similar to the behavior of generator G2.
In Fig. 7 power flow between the inverter and the grid is shown. It can be seen that, immediately after the disturbance, the power starts to flow from the inverter to the grid and it has a pick of around 600W. After the pick, the energy flow starts to fall and even turns negative before it goes back to zero when the system returns to steady state. The negative power flow is the consequence of “fight” between PI regulator of speed and connected inverter. The change of power produced by generator G2 is shown on Fig. 8 with black line, while the change of power produced by generator G1 when inverter is connected to the grid is shown with red line. Gray areas represent the difference between the two power flows and it perfectly collides with the power flow of inverter. That means that total power produced with generator G1 combined with power provided by the inverter is equal to the power produced by generator G2. That means that both systems will have similar response to the same disturbances.

That also means that the total energy flow between inverter and the grid during one disturbance period equals zero. All the power provided by the inverter at the beginning of the disturbance to slow down the rate of change of speed is then recouped when the speed starts rising again. Cumulative energy flow between inverter and the grid is shown in Fig. 9 and it has a peak of 1300 Ws before it falls back to zero.

5 Conclusion
It has been demonstrated that, with appropriate inverter control, it is possible to emulate power system inertia. The net energy flow during system transients is shown to be close to zero, thus enabling usage of energy storage with limited capacity. Distributed application of such inverters with energy storage, or connected to renewable energy source, can preserve power system inertia, thus contributing to system stability.

Considering the elaborated model case of power and energy flow between the inverter and the grid, it can be noticed that the pick power supplied by the inverter to the grid is around 600W which is roughly 5% of total power provided by the generator. Also the total amount of energy that traveled form the energy storage to the grid was 1300Ws, or 0.2 Wh, before it started falling back to zero. This proves that with the right inverter control and with relatively small energy storage, compared to the size of overall system, with capability of injecting high density power to the grid, inertia of the system could be easily emulated when needed.

References:


