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POWER-FREQUENCY CONTROL OF ENERGY STORAGE INVERTER ANALYZED USING HIL

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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 aim of the study is to improve inverter voltage control by inclusion of frequency change signal. In this way inverter could contribute to improvement of system stability within frequency range of interest, i.e., 0.2Hz-2.5Hz. The proposed inverter control is verified using developed real-time model in Matlab/Simulink, tested using hardware in the loop (HIL) concept.*

Key Words: ***Energy storage/Grid inertia/Inverter Control/ Power frequency control/HIL/real time***

1. INTRODUCTION

Disturbances in an interconnected power system lead to frequency deviations in the grid. 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 since the frequency response of the system could significantly change.

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].

2. PROPOSED 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):

$$2\Delta P = \frac{\partial(\mathrm{J}_{sys}\cdot\omega_{el}^{2})}{\partial t} \quad (1)$$

A dedicated MATLAB/Simulink models are developed to examine this change [11], [12].

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.

The energy flow between the inverter and power system can be determined with (2):

$$P_{inv} = \frac{E_{F1}\cdot E_{F2}}{X_L}\cdot\sin(\delta_2-\delta_1) \quad (2)$$

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

$$\Delta T_{av100} = T - T_{av100} \quad (3)$$

If we define the actual waveform of a grid voltage as (4):

$$v_{grd}(\mathrm{t}) = E_{F1}\sin(\omega T) \quad (4)$$

and the inverter voltage waveform as (5):

$$v_{inv}(\mathrm{t}) = E_{F2}\sin(\omega T_{av100}) \quad (5)$$

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

$$P_{inv} = \frac{E_{F1} \cdot E_{F2}}{X_L} \cdot \sin(\omega \cdot \Delta T_{av100}) \approx \frac{E_{F1} \cdot E_{F2}}{L_L} \cdot \Delta T_{av100} \quad (6)$$

3. TEST SYSTEM MODEL

Block diagram of a system is shown in Fig. 1. Parameters of generators G are given in Tabele 1. Input parameters of synchronous generator are mechanical power on generators' shafts and excitation voltages. Both inputs are implemented with regulation, where generators output voltage is regulated with excitation voltages, while speed of generator is controlled with mechanical input powers.

Table 1. *Parameters of generator G*

Parameters of generator G		
Rated Power	kVA	16
Voltage	V	400
Frequency	Hz	50
Number of poles		2
Friction	N·m·s	0.013
Moment of inertia	kg·m^2	0.1278

Generator G is constantly connected to $Load_1$. Disturbance in the system is produced when $Load_2$ is connected in parallel to the $Load_1$.

Inverter with energy storage is connected in parallel to the synchronous generator G trough *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 speed of rotor of synchronous generator is closely followed and compared in order to determine the difference in response of generator's speed under different working conditions.

4. SIMULATION RESULTS

Input parameters for generator G are constant during simulation, rotors' speed is 1500 rpm while nominal output voltage is 220 V rms. $Load_1$ has only active component of 14kW, which represents 87,5% of nominal output power of generator. When the system is in steady state, switch between $Load_1$ and $Load_2$ is closed at the same time. Total load power connected to the generator now is 15kW of only active power, which represents increase of 7%. Switch is kept closed for 50 seconds. After that it is again opened again for another 50 seconds. Pattern of opening and closing of switch is repeated every 50 seconds.

In Fig. 2 the reaction of speed of generator G to a described disturbance is shown when the generator has two different moments of inertia and when the inverter is disconnected from the grid. The red line represents the change of speed of generator when the moment of inertia J_1 of generator is as given in Table 1. The black line represents the change of speed of generator with moment of inertia $J_2 = 4 \cdot J_1$.

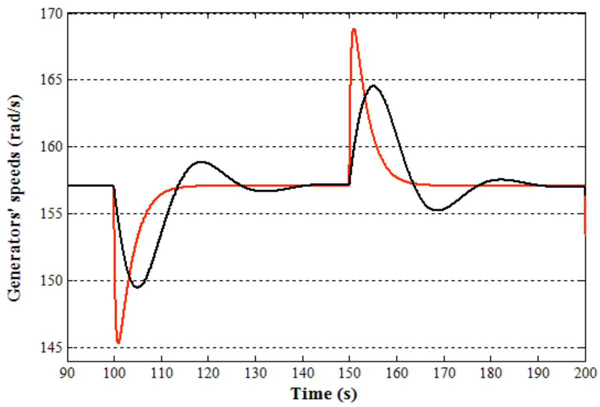

Fig. 1. *Speed of generator G with J_1 (red line) and with J_2 (black line) when inverter is not connected*

It can be seen from Fig. 2 that the speed of generator G with moment of inertia J_1 has fallen from 157 rad/s to 145 rad/s which represents the fall of 7,6%, while the speed of generator G, when it moment of inertia is J_2, 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 G with moment of inertia J_2 is a bit oscillatory. That is because of parameters of PI regulator of speed which is adjusted of generator G with smaller moment of inertia. Also the rate of change of speed of generator G, when it has smaller moment of inertia, is much faster compared to when it has bigger moment of inertia.

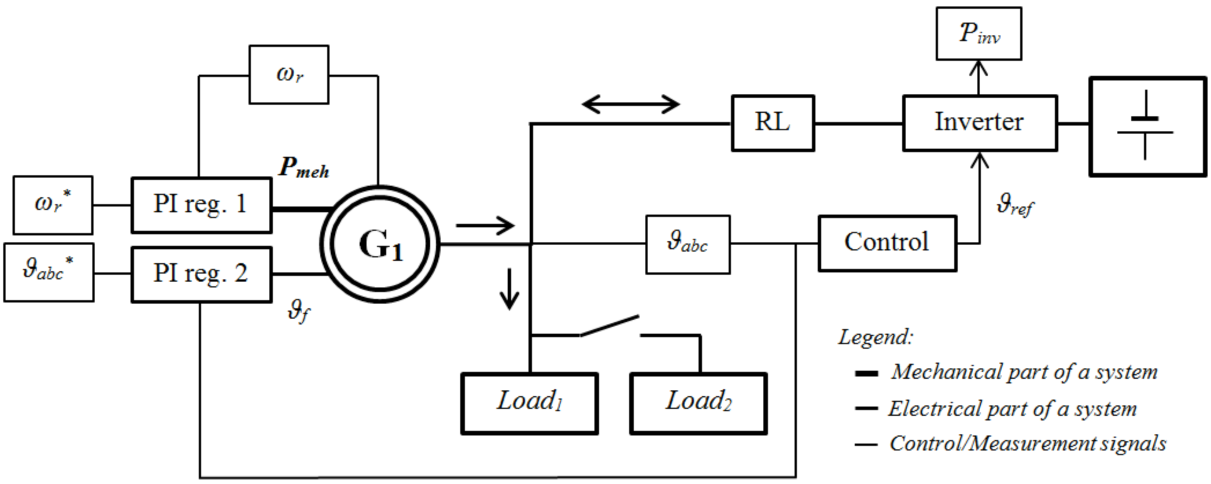

Fig. 2. *Block diagram of inverter control*

In Fig. 3 the reaction of speed of generator to a described disturbance is shown when the generator with moment of inertia J_1 is working in parallel with inverter controlled with proposed inverter control (red line) and when generator has moment of inertia J_2 (black line). It can be seen that now the change of speed of generator G that is working in parallel with the inverter is as if the generator has greater moment of inertia. When the load is increased, the speed of generator G 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 G when it has bigger moment of inertia.

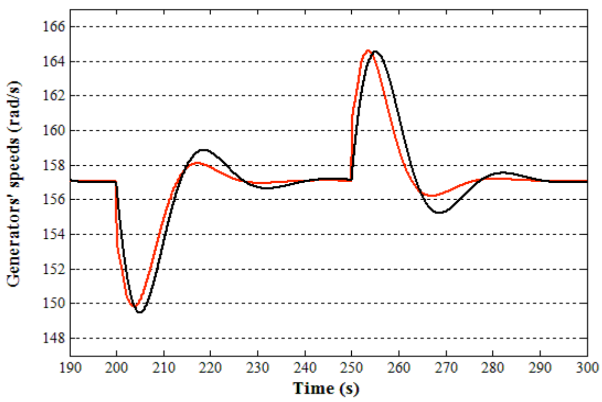

Fig. 3. *Speed of generator G (red line) and generator G (black line) when inverter is connected*

5. CONTROL VERIFICATION USING HIL

The proposed control solution, previously verified by Matlab Simulink simulation results, is tested using hardware in the loop where control algorithm is embedded in real time controller, while inverter and power system and grid are modeled in Matlab.

In hardware-in-the-loop simulation systems, part of the simulation loop is composed of computer software, while the rest is the actual hardware systems [13].

One advantage of HIL simulation is that the validation of control results is very straightforward. In industrial control, HIL simulation techniques can significantly reduce the time required to design controllers and can increase the reliability of the systems.

Fast prototype design is a new approach in controller design and implementation. The controllers can be constructed with Simulink and Stateflow, and the executable code for the controllers can be generated easily, and the parameters of the controllers can be tuned on-line, according to the actual control behavior. The designed controller can be regarded as a prototype, and once the control results are satisfactory, the code can be downloaded to the real controllers and the control actions can be carried out without the use of MATLAB or Simulink [13].

For this solution, the basic idea is to use DSP card (TI's F28335) for embedded control algorithm, since it is supported by MATLAB and Simulink Embedded Coder. Since manual coding is slow, introduces defects, and is difficult to compare to design, the first step is to generate C code for DSP card right from the simulation diagram to save time by automatically generating embedded code.

Simulating plant and controller in one environment allows optimizing system-level performance, while automate tuning process using optimization algorithms and accelerate process using parallel computing.

Proposed control algorithm uses as input information about synchronous generator three phase voltages (see block diagram in Fig. 1). Using technique in detail explained in [11], [12], reference voltages for gating inverter switches are determined by shifting the generator voltage waveform in time. Such a generated algorithm could be used in two ways: one is to accelerate further simulations, replacing control algorithm with C compiled S-function [13] and the other is to deploy C algorithm on DPS card for further testing.

Simulation block diagram used for testing is given in Fig. 4.

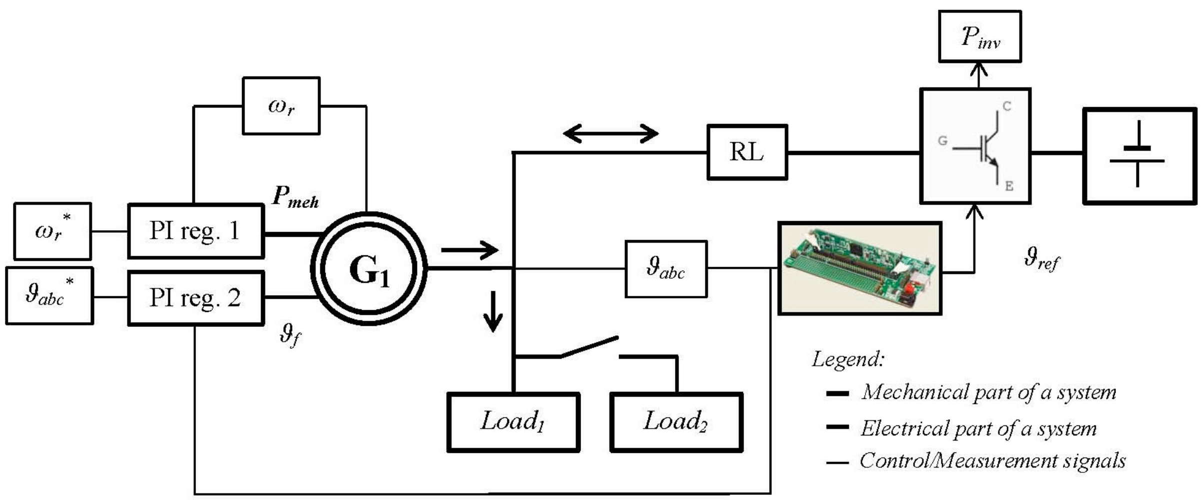

Fig. 4. *Block diagram of inverter control*

In the following figures results of HIL simulation are shown. Fig.5 shows inverter voltage. In Fig. 6 load voltage after load changes are presented, while Fig. 7 shows spectrum of load voltage.

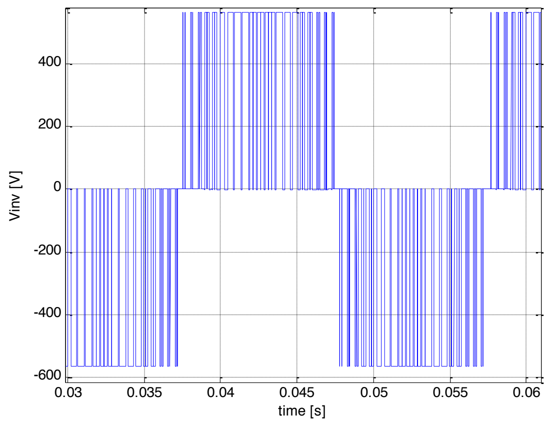

Fig. 5. *Inverter voltage during load changes*

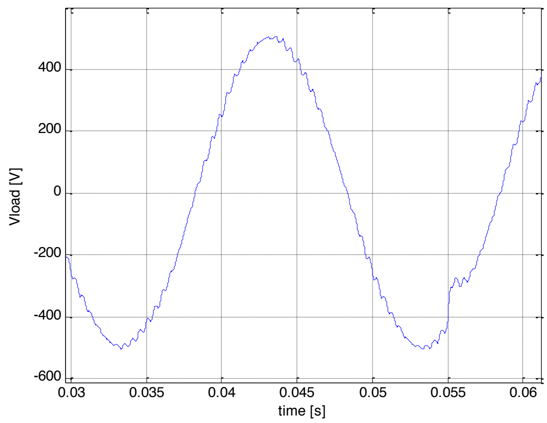

Fig. 6. *Load voltage during load changes*

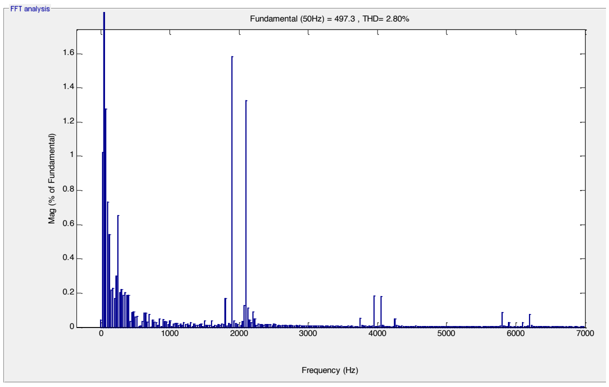

Fig. 7. *Load voltage spectrum*

From Fig. 7 it could be observed that even after sudden load change that could be seen in a load voltage waveform in Fig. 6, voltage total harmonic distortion is still low (2.8%) and much below permissible values as per international standard [14].

6. CONCLUSIONS

It has been demonstrated that, with appropriate power frequency control of energy storage inverter, 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.

In order to accelerate prototype development and embedding algorithm in DSP control card, a hardware-in-the-loop concept is used. At first the control algorithm is automaticaly generated to C code from simulation block diagram. Obtained results are compared with mathematical model simulation. The next step is to use generated C code in DSP card and to control the real inverter, when complete system prototype is developed.

Applied methodology proves that with the proposed 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.

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