Electromagnetic Modelling and Operation Analysis of Virtual Synchronous Machine for Frequency Response

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Abstract. Virtual synchronous generators (VSGs) utilizing renewable energy sources (RESs) have been proven to be an appealing solution for overcoming the challenges of renewable energy sources (RESs) consumption in power systems. In order to address these issues, researches have been developed to improve the dynamic characteristics of VSG power systems. However, most of the studies at home and abroad focus on the negative impact of VSGs on the grid voltage, and few on the frequency, safety and efficiency of VSGs. The first part of this paper focuses on the VSG’s electromagnetic detail model with the ability to support the system voltage and frequency deviations, the second part discusses the mathematical investigation on its response as a VSG. Finally, according to the technical requirements of the power grid, mechanical and electromagnetic loads are simulated, the influence of service life is analyzed, and design suggestions are put forward.

1. Introduction

As the penetration level of renewable energy into power systems keeps on increasing, the renewable energy has created significant challenges for current electric power systems, including difficulties in achieving frequency stability due to the reduction in system inertia caused by inverters. This low system inertia issue could affect the power systems stability and resiliency in the situation of uncertainties, thus threatening their dynamic security.

Synchronous generators (SGs) can autonomously suppress frequency/voltage deviations with their inertial forces and automatic voltage regulators. In view of the problems raised by the inverter based res, various control systems that enable the wind turbine to operate like SG are studied [1-3], and these systems are known as VSGs. Because the frequency/voltage controls can be tuned flexibly to enhance the dynamic response of the system, the VSG is considered to be a useful solution for improving the resilience of a wind energy involved power system. The VSG simulates the dynamic behaviour of an SG and represents its fundamental swing equation by virtual inertia In [3-7], it is proven that VSGs can supply uninterruptable power between grid-connected and islanded operation modes. In addition to the frequency control, VSGs are able to operate to regulate the system voltage like SGs. Although numerous studies have focused on various types of VSGs, most of them focus on the negative impacts of VSGs on the grid voltage and frequency, safety of VSGs are relatively less mentioned.

The first part of this paper focuses on the VSG’s electromagnetic detail model with the ability to support the system voltage and frequency deviations, while the second part discusses the mathematical investigation on its response as a VSG. Finally, according to the technical requirements of power grid,
the mechanical and electromagnetic loads are simulated, the influence of life is analyzed, and the design suggestions are put forward.

2. Frequency and voltage supporting requirements of VSG

The VSG has been presented to emulate the behaviour of a real conventional SG to compensate the inertia reduction in renewable power systems, actually, there are lots of instructions about the WTG’s responses to frequency and voltage deviations, but these instructions are mentioned not systematically but separately in grid codes of different countries. Great changes have been made in recent years that leads to the consequence that the concept of VSGs are proposed explicitly as enterprise standards including inertia response, primary frequency response, reactive power regulation and voltage ride through, etc., among which, frequency related technical requirement are:

2.1. Virtual Inertia response

If the frequency is out of the dead band from 49.97Hz to 50.03Hz, and the active power of VSG is greater than 20% of \( P_N \), VSG should perform a virtual inertia character according to equation 1 to provide a rapid frequency support to increase or decrease the active power output.

\[
\Delta P \approx -T_J f_N P_N \frac{df}{dt}
\]

where \( \Delta P \) is the deviation of active power of VSG, \( T_J \) is the inertia constant of VSG, \( f_N \) is system nominal frequency, \( f \) is the frequency of VSG’s terminal, and \( P_N \) is the nominal power capacity of VSG.

2.2. Primary frequency response

As illustrated in figure 1, the frequency points of 49.97Hz and 50.03Hz is the dead band and a control band for RPPs contracted for primary frequency response. The SO shall decide and advise the RPP generator on the droop settings required to perform control between the various frequency points. The RPP shall be equipped with the frequency control droop settings. Each droop setting shall be adjustable between 4% and 20%. The actual droop setting usually is 5%, following the same trend as the SO.

![Figure 1. Droop setting for primary frequency control.](image)

The frequency control shall be commenced within 5 seconds and completed no later than 10 seconds after receipt of an order to change the setpoint. The accuracy of the control performed and of the setpoint shall not deviate by more than \( \pm 2\% \) of the rated power. VSG should provide a \( P_{\Delta} \) of not less than 10% of \( P_{\text{available}} \). \( P_{\Delta} \) is the amount of active power by which the available active power has been reduced in order to provide reserves for stabilization of the frequency.

3. Model and Control algorithm for VSG

The system frequency control can be divided into three main processes: electrical and mechanical model, inertia response process, primary control process, and secondary control process. All of these
should be emulated for VSG implementation. Also, the RESs exchange power to renewable power systems through power inverter, which should be considered for VSG implementation. The main components of VSG are:

3.1. Electrical and mechanical model
VSG model is shown in figure 2, as we see, it consists of pitch control system, wind turbine, drive chain, generator and converter. Pitch control system and converter balance the wind energy and power generation based on the swing equation:

\[ \Delta P_M(s) - \Delta P_L(s) = (2H + D)\Delta f(s) \]  

(2)

The above equation describes the behaviour of the rotor dynamics. Where \( f \) is the frequency deviation, \( P_M \) is mechanical power change, \( P_L \) is load change, \( H \) is the system inertia, and \( D \) is load damping coefficient.

![Figure 2. Functions and structures of VSG model.](image1)

![Figure 3. Single diagram of VSG frequency response simulation.](image2)

3.2. Inertia and primary frequency response control
As mentioned before, the SG utilizes turbine governor, as the primary frequency control to compensate for the deviation of system frequency. During the inertia response process, the synchronous generator releases the kinetic energy stored in its rotating mass, when the power unbalance occurs. Then, if the frequency deviation exceeds the nominal value, the primary frequency controller is activated immediately.

Let \( P_{in} \) and \( P_{out} \) denote the input and output active powers expressed in pu. In this study, small variations are represented using the prefix D.

\[ \Delta P_{in} - \Delta P_{out} = M \left( d\Delta \omega / dt \right) \]  

(3)

If \( H_{gov}(s) \) represents the transfer function of its governor, \( \Delta P_{in} = -H_{gov}(s)\Delta \omega \) is satisfied in the Laplace field. Therefore, by rewriting \( \Delta P_{out} \) as \( \Delta P_{in} \) and setting \( G_{PF}(s) \) can be derived.

\[ G_{PF}(s) = \frac{\Delta \omega}{\Delta P} = -\frac{1}{M_s + H_{gov}(s)} \]  

(4)

Generally, \( H_{gov}(s) \) can be written most simply as \( H_{gov}(s) = K/(1+sT) \), where \( K \) with no units indicates the inverse of a droop constant, and \( T \) in seconds indicates the engine an electrical delays, which certainly exist in actual systems. The result of this expansion is

\[ G_{PF}(s) = -\left( T_s + 1\right) / \left( M Ts^2 + Ms + K \right) \]  

(5)
3.3. Delta Production control
A Delta Production Constraint is used to constrain the active power from the RPP to a required constant value in proportion to the possible active power. A Delta Production Constraint is typically used to establish a control reserve for control purposes in connection with frequency control.

4. Simulation of frequency response

4.1. Simulation scenarios and settings
The VSG frequency responses were verified by PSCAD/EMTDC software. The test system was simulated for a single WTG connected to a simple power system, as shown in figure 4. The frequency response of VSG was evaluated and analyzed for the following cases:
- Scenario A: Frequency response without primary frequency control;
- Scenario B: Frequency response with virtual inertia and droop profile;
- Scenario C: Frequency response with primary frequency control under power reservation;

The performance VSG for improving the frequency stabilization analyzed and examined in response to grid frequency deviation at terminal of WTG for the test system depicted in figure 1. Different wind speeds are considered in the paper as it is important to validate the control performance of power reservation under wind variations. The wind speed is assumed constant for the duration of interest, as the frequency response and recovery is an electromechanical process about tens of seconds, and wind speed does not fluctuate too rapidly in practical situations. The parameters of the system are listed in table 1.

| parameter               | value     | parameter               | value  |
|-------------------------|-----------|-------------------------|--------|
| Frequency               | 50 Hz     | Shaft spring constant   | 0.11   |
| Base active power       | 5 MW      | Shaft mutual damping    | 1.5    |
| Base wind speed         | 11 m/s    | Turbine inertia constant| 4.32   |
| Reactive power reference| 0 pu      | Number of poles         | 6      |
| Power reference         | 1 pu      | PLL filter              | 500 rad/s |
| Frequency droop gain    | 20        | PLL proportional gain   | 0.084  |
| rated voltage           | 690 V     | PLL integral gain       | 4.7    |

Figure 4. Single diagram of VSG frequency response simulation.

4.2. Simulation scenarios Setup
Scenario A: Grid frequency stability is a balance criterion between electric power generation and load demand. Therefore, with increasing the penetration level of RESs into renewable power systems, the overall system inertia in renewable power system might be significantly reduced, thus the frequency
deviation increases. Scenario A shows the VSG’s response without primary frequency control, thus the VSG acts as a totally free response. Wind speed is 15m/s.

Scenario B: Set a disturbances of generation unit outage to simulate the VSG with virtual inertia and droop control to respond the disturbances continuously. The grid frequency of the system ramps down from 60Hz to 59.5 Hz. This disturbance continues for 12 seconds, and simulate the VSG with virtual inertia and droop control to respond to the disturbances continuously.

Scenario C: Set virtual inertia and droop control parameters as same as Scenario B, but the VSG operates with a reservation of 10% PN. Set a same frequency event as Scenario B, and simulate the response of VSG with virtual inertia and droop control.

4.3. Safety analysis

The system frequency drooped with a depth from 50Hz to 49.95Hz at 55.5s in the power network. Figure 5 shows the free response of VSG against the frequency decreases, the virtual inertia control and primary frequency control loops emerge once the system frequency becomes out of the allowable frequency limits that set in figure 1. Pg and Qq are the active and reactive power separately. Pq increased due to the control delay of transfer functions, including PLL of converter and active power control loops. WWT_D and Wg_D are the nominal rotational speed of blade and generator. WindTRQ is the output torque of turbine and Tm is the input torque of the generator. The results of frequency response with virtual inertia and droop profile are shown in figure 6, where Pg increased more than that of figure 5 because of the inertia and primary active power control, but it didn’t last long enough as there was no active power reservation before system frequency decreased. WWT_D and Wg_D had the same operating trend but a slight alternate fluctuation with each other.

![Figure 5. VSG’s response against frequency decrease without active power reservation.](image1)

![Figure 6. VSG’s response against frequency decrease with active power reservation.](image2)

Figure 7 and figure 8 show the performance of the VSG under active power reservation. Before system frequency droops, 10% of nominal active power was reserved by pitch angle regulation. After system frequency droops, the VSG increases its power output in steady state and follows the speed variation of the grid frequency, releasing energy from its inertia corresponding to the change of speed, and settles at the new operating frequency of the grid with increased power output to contribute to the frequency control of the power system, which can also be seen from the active power PgpuD in Fig.
12. The frequency control is commenced within 1 seconds and completed within 5 seconds after the reception of an order to change the set-point. The accuracy of the control performed and of the set-point deviate by no more than ±2% of the rated power.

5. Conclusions
This paper has highlighted the inherent advantages of the VSM as a possible alternative for releasing the potential advantages of the distributed autonomous control actions of power electronics converters.

Figure 7. Active and reactive power of VSG’s frequency response with power reservation.

Figure 8. Torque and rotational speed of VSG’s frequency response with power reservation.

An implementation method of VSM concept is introduced in detail. It is based on an electromagnetic model which provides a reference for cascaded voltage and current controllers. These models have been simulated numerically with three scenarios in order to verify and illustrate the impact of the frequency disturbance of power system on VSM implementation and a few of its inherent features. The results of theoretical analysis show that VSG completes its response within 5 seconds after the reception of an order to change the set-point. The deviation of the proposed control accuracy does not exceed ±2% of the rated power. The operation risk of VSM that complied with the requirement of frequency response mainly lies in the sudden torque change and the mechanical fatigue caused by it. The maximum torque is about 1.3pu after the system frequency recover to normal, this should be solved by parameter optimization of pitch and control algorithms.

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