A CONVERTER CONTROLLER OF VIRTUAL SYNCHRONOUS MACHINE FOR STABLE OPERATION OF MICROGRID

Masahide HOJO, Ryo IKESHITA, Takeaki TERAUCHI
The University of Tokushima –Japan
(hojo, ikeshita, terauchi) @ee.tokushima-u.ac.jp

Yoshinobu UEDA, Toshihisa FUNABASHI
Meidensha Corporation - Japan
(ueda-yo, funabashi-t) @mb.meidensha.co.jp

ABSTRACT

The synchronizing torque is an important factor for stable operation of the traditional grid supplied by a lot of synchronous generators. However, high penetration of static power converters which are accompanied by batteries or renewable energies may results in weakening the synchronizing torque, especially in a microgrid. In this case, a Virtual Synchronous Machine (VSM) can be one of the effective methods to enhance the synchronizing torque by making the power converter behave like a synchronous machine. It can achieve better stability of the microgrid but it requires high power rating to the converters. This paper verifies the benefit and cost of the VSM based on simulation study from the viewpoint of steady-state stability of the microgrid.

INTRODUCTION

The conventional power system has been supplied by a lot of synchronous generators. They have kept a good power balance among them by their synchronizing torques. On the other hand, a distributed generator injects its maximum output power by observing the phase angle of the voltages at its coupling point. The power balance can be kept successfully while the total amount of power generated by the distributed generators is negligible compared to the synchronous generators.

Today, with a growing demand of high penetration of renewable energies, a microgrid [1] can be one of the effective strategies to achieve it. They are often installed with batteries to compensate their fluctuating output power. As a result, a lot of static power converters will be normally installed in the microgrid with traditional synchronous generators. In case that the total rated power of the converters exceeds the one of synchronous generators, it is afraid that the synchronizing torque of the microgrid may be spoiled. In the circumstances, there is a proposal of a Virtual Synchronous Machine (VSM) [2], [3], which make the converter behave like a traditional synchronous machine. Assumed that the converter is supported by an ideal dc voltage source and consists of ideal semiconductor devices, the VSM can be considered how to control the converter as well as how to prepare the energy source at the dc side.

However, the VSM operation may require some excessive power trades to the converter. For example, the converter is forced to supply some excessive power during a system disturbance to enhance the system stability. The traditional synchronous generators used to supply the synchronizing power by both energy from their inertia and somewhat high ride-through capability under over ratings. From this viewpoint, the converter rating required to realize the VSM should be carefully considered.

This paper verifies the benefit and cost of the VSM in a microgrid. A converter control method emulating the power trade between the synchronous machines is developed in order to enhance the steady-state stability. The effectiveness and requirements of the controller are verified by some examples of simulation study.

A MICROGRID MODEL AND CONVERTER CONTROLLES

In order to consider an active power interaction between a synchronous generator and a static power converter, a simple system model is used in this paper, as shown in Fig. 1. For the simplicity, the synchronous generators and the converters are represented by single ones, respectively. V_g and V_c represent the fundamental components of terminal voltages at the synchronous generator and the converter and their phase angles are represented by θ_g and θ_c, respectively. The terminal voltage of the synchronous generator is assumed to be regulated by a traditional Automatic Voltage Regulator.

This paper discusses a VSM control for enhancement of steady-state stability in the microgrid. In the steady-state,

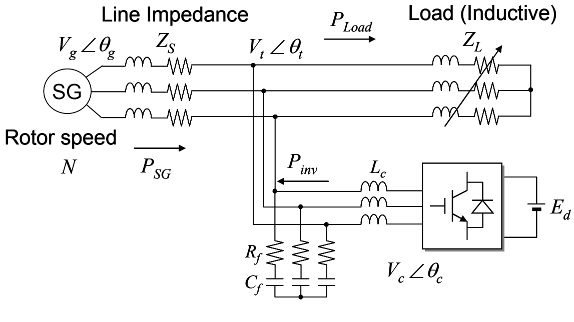


Figure 1. A simplified microgrid model with a synchronous generator and a VSM.

the voltage amplitude of the converter V_c is assumed to be quickly regulated to its nominal value. Therefore, the phase angle θ_c is considered as following three modes.

Regular mode

This mode means that the converter is operated like a traditional static power converter. It detects the phase angle of the terminal voltage at the coupling point θ_t and decides its output voltage. Therefore, the converter follows the frequency regulated by the synchronous generator and trades its favorable output power. Assume that the initial value of the converter phase angle is θ_{c0}, the converter phase angle θ_c can be determined as

$$\theta_c = \theta_{c0} + \int \omega_g dt \, , \qquad (1)$$

where ω_g is the angular velocity of the synchronous generator. The converter operated by this mode can be considered as a synchronous machine whose inertia is zero.

Infinite bus mode

The infinite bus has an infinite inertia and a constant voltage. This mode may require extremely high energy to the converter but it is quite stable all through the operation of the microgrid. In this case, the converter phase angle can be represented by the nominal value of the angular velocity ω_0, as

$$\theta_c = \theta_{c0} + \int \omega_0 dt \, . \qquad (2)$$

Interaction mode

The synchronous generators trade their power after a disturbance and keep a stable cooperation in a power system. The power trade is realized by the difference of the phase angle between them. From this viewpoint, the power trade can be realized by modulating the phase angle of the converter as shown in Fig. 2. If a small disturbance makes the phase angle of the synchronous generator θ_g lag behind the reference angle θ_0 by $\Delta\theta$, the phase angle of the converter θ_c will be increased to lead θ_0 by $\Delta\theta$. In this case, the angular velocities can be formulated by

$$\int (\omega_c - \omega_0) dt = \int (\omega_0 - \omega_g) dt \, . \qquad (3)$$

Therefore, the phase angle θ_c can be derived as

$$\theta_c = \theta_{c0} + \int (2\omega_0 - \omega_g) dt \, . \qquad (4)$$

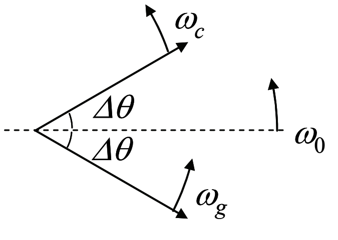


Figure 2. A phase angle control of the VSM.

VERIFICATION OF THE VSM CONTROL

The proposed VSM control is verified by simulation study. A system model shown in Fig. 1 is used with the parameters summarized in Table. 1. The dc side voltage of the converter is assumed to be supported by ideal dc voltage source. On the other hand, the traditional rotating synchronous machine is represented by a Motor-and-Generator combination which employs a speed governor and an automatic voltage regulator.

Table 1. Parameters for simulation study.

Microgrid	
Operating frequency f_0	60Hz
Frequency range	± 0.2Hz
Rated RMS voltage (3ϕ, line-to-line)	200V
Line impedance Z_s	0.10Ω, 6.0mH
Load (inductive) Z_L (t <0.2s)	2.5Ω, 10mH
(0.2s < t < 1.2s)	1.1Ω, 0.9mH
Converter	
Dc voltage source E_d	300V
Interconnecting Inductance L_c	1.0mH
Ac filter capacitor C_f	23.0μF
Switching frequency	10kHz

The proposed control is equipped with a sinusoidal wave generator and the well-known triangular-wave Pulse Width Modulation of a three-phase voltage sourced converter, as shown in Fig. 3. The converter controller has three control modes as discussed in the previous section. The controller normally selects the regular mode which means the traditional converter operating mode, but, if the angle goes out of a certain range, the controller employs the phase angle for the VSM interaction mode. It is defined by the integral of the nominal frequency along an internal clock of the controller, with its initial value as the phase angle used at the time of mode change. In this section, the interaction mode is tested in comparison with the regular mode.

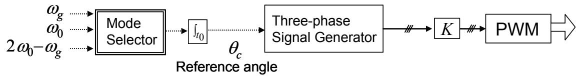
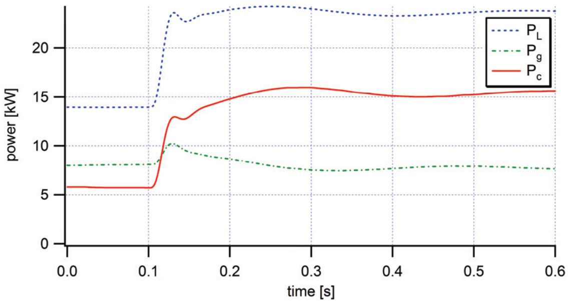


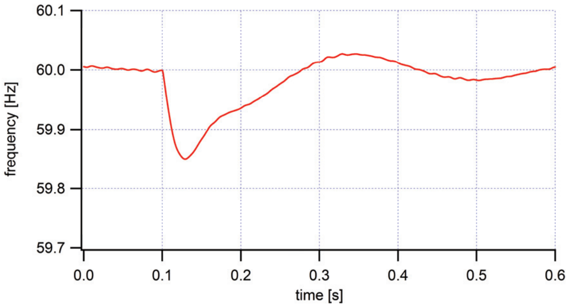
Figure 3. A controller of the converter.

Fig. 4 displays simulation results by the VSM operation with the interaction mode. A load variation is applied at t=0.1s as a disturbance. Just after the load variation, the converter does not follow the voltage at the coupling point but supplied power to the rotating generator as well as the load. By this function, the rotating generator can quickly bring its operating frequency back to its nominal value, as can be seen in Fig. 4 (b). Fig. 4 (c) displays the output current of the converter whose amplitude is varying to enhance the system stability. Fig. 4 (d) shows the instantaneous terminal voltage at the coupling point just around the load variation. Any voltage disturbances cannot be seen in the waveform.

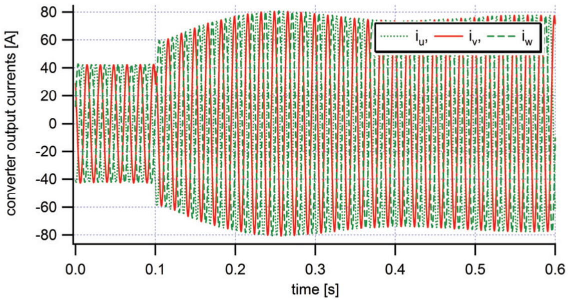
Fig. 5 shows the results when the regular mode is continuously applied to the converter. In this case, the output power of the converter does not vary along the variation of the output power of the synchronous generator. Therefore, the system frequency stays below its nominal value for a long time. Although the frequency can recover by the speed governor of the synchronous generator, it takes long time compared to the interaction mode.



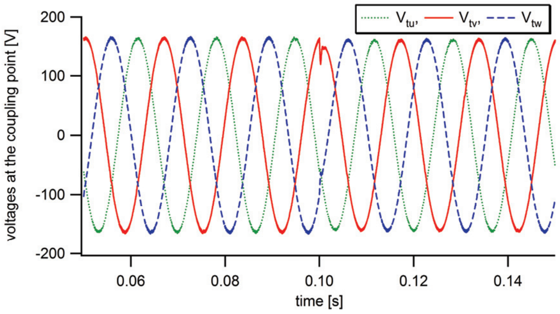
(a) Output power of the synchronous generator P_g, and the converter P_c, and the load power P_L.



(b) Frequency variations.



(c) Output current of the converter.



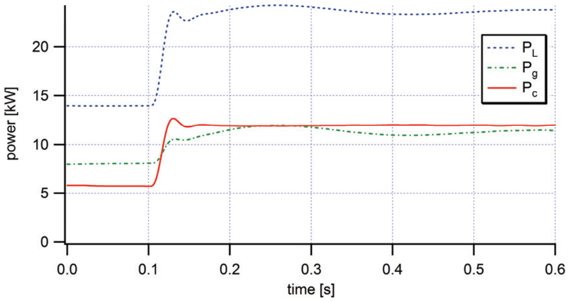
(d) Voltage waveforms at the coupling point.

Figure 4. Simulation results with the interaction mode of the VSM operation.

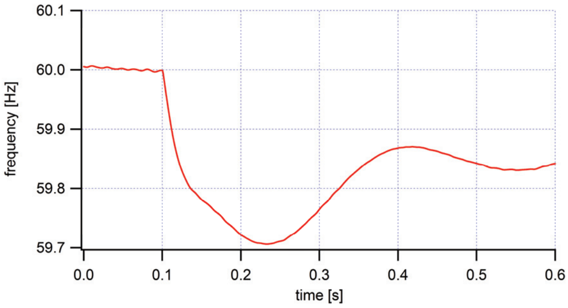
In comparison with Fig. 4 and Fig. 5, it can be confirmed that the system frequency is quickly regulated by the VSM converter but the required converter output current is larger than the conventional converter control.

CONCLUSIONS

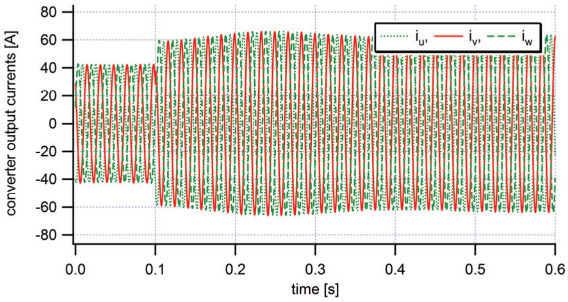
This paper discusses the benefit and cost of the VSM in a microgrid. A converter control method emulating the power trade between the synchronous machines is developed and equipped to the static power converter. The effectiveness of the controller is tested by simulation



(a) Output power of the synchronous generator P_g, and the converter P_c, and the load power P_L.



(b) Frequency variations.



(c) Output current of the converter.

Figure 5. Simulation results with the regular mode of the converter.

study in case of a small disturbance. Two control strategies, the VSM mode and the conventional one are tested. It is confirmed that the VSM achieves a better stability in the microgrid but it requires additional output current.

Quantitative evaluation of the required capacity of the converter and the effectiveness for enhancement of microgrid stability can be considered as a future work.

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