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Virtual Synchronous Generators dynamic performances

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Abstract--In this paper, dynamic performances of virtual synchronous generator are investigated. The virtual synchronous generator is based on the synchronverter (VSG) concept which is an inverter that mimics a synchronous generator (SG). The real and reactive power delivered by VSGs connected in parallel and operated as generators can be automatically shared using the well-known frequency and voltage drooping mechanisms. The VSG method is tested in comparison with the standard SG of the same parameters and capacity on a two bus test network. A comparative assessment is presented in terms of local performances and the fault critical clearing time (CCT). The results indicate good local performances and the contribution of the synchronverter to enhance the stability margin of the neighbouring AC zone.

Keywords— synchronverter, synchronous generator, frequency/voltage drooping.

I. INTRODUCTION

FOR economic, technical and environmental reasons, more renewable energy sources are being connected to power systems, generally via power electronic converters. The International Energy Agency (IEA) predicts that gross renewable electricity output will continue to pick up speed in the medium term to 2018, rising by approximately 40% and forecasts installed renewable capacity increasing from 1 580 GW in 2012 to 2 350 GW in 2018 [1]. Consequently, the AC/DC/AC converted power injected into AC networks has been increased. This means that more and more inverters will be connected to the grid and will eventually dominate power generation. When focusing eyes on system stability analysis, compared with traditional transmission network; one of the most features for renewable energy sources is the randomness output active and reactive power supplied to AC grids. Thus, as inverters are used to interface with grid, inverters dynamic behavior has important influences on system performance. Since inverter's corresponding part in transmission networks, synchronous generator SG is also an energy transforming devices. Thus it's natural to mimic SG character when designing inverter controller.

Generally, inverter controller can be divided into three types. The first one is called constant-PQ controller which controls inverter output active and reactive power as given values.

The controller is based on a current-controlled voltage source converter (CC-VSC), to inject the required real and reactive powers via current control [2]. The second is to mimic SG external characteristic and called droop controller. When system frequency or node voltage amplitude is out of its normal range, this type of inverter will automatically adjust its output active or reactive power, and try to control these electrical qualities back into normal ranges [3]. The last type is to mimic SG characteristics directly and called *synchronverter* [4], or virtual synchronous generator [5, 6]. Since the operation of AC systems via SGs voltage/frequency regulation is rather well known [7], the synchronverter concept led to new applications. For example, in [8], a STATCOM controller is synthesized from the mathematical model of synchronous generators operated in a compensator mode.

In this paper, we investigate the transient stability of a two-bus power system, considering two configurations of coupling system: coupling of AC-AC system and hybrid DC-AC system. For each configuration, local performances are studied and transient stability of the systems is assessed in terms of the CCT. The VSG parameters are adapted to the conventional SG parameters. Static and dynamic responses of the VSG and the SG are compared under different operating conditions. The VSG benefits its operation frequency and voltage drooping mechanisms for load sharing. It is shown that local performances obtained by VSG are better than the ones of SG. The transient stability margin is improved with the VSG, compared to the SG. Moreover, it is not necessary to have a large inertia as for a physical SG, where a larger inertia means that more energy is stored mechanically. A small inertia is good for overall grid stability.

The rest of the paper is organized as follows: in Section II, the synchronverter concept is briefly overviewed. Test power systems are presented in Section III, where different tests validations are presented in Section IV.

II. OVERVIEW OF THE SYNCHRONVERTER CONCEPT

A synchronverter VSG is an inverter of which regulations are chosen such that the resulting closed-loop mimics the behavior of a conventional SG. The VSG concept consists of a power part, as shown in Fig. 1, and an electronic part, i.e., the controller, as shown in Fig. 2. It is assumed that the DC bus of the synchronverter is constant.

An inverter plus an LC filter is the power part of the VSG as shown in Fig. 1. VSC inverter technologies shown in Fig. 1 are used. The overall structure is shown to be equivalent to a SG with capacitor bank connected in parallel with the stator terminal [4]. The phase terminal voltage $V_{abc} = [V_a \ V_b \ V_c]^T$ is

$$V_{abc} = -R_s i_{abc} - L_s \frac{di_{abc}}{dt} + e_{abc}, \quad (1)$$

where $i_{abc} = [i_a \ i_b \ i_c]^T$ is the vector of the stator phase currents, L_s , R_s are, respectively, the inductance and the resistance of the stator windings and $e_{abc} = [e_a \ e_b \ e_c]^T$ is the back emf. The controller includes the mathematical model of a three-phase round-rotor synchronous machine described by

$$2H \ddot{\theta} = T_m - T_e - D_p \dot{\theta}, \quad (2)$$

$$T_e = M \langle i_{abc}, \tilde{\sin} \theta \rangle, \quad (3)$$

$$e_{abc} = M s \theta \tilde{\sin} \theta, \quad (4)$$

$$P_s = M s \theta \langle i_{abc}, \tilde{\sin} \theta \rangle, \quad (5)$$

$$Q_s = -M s \theta \langle i_{abc}, \tilde{\cos} \theta \rangle. \quad (6)$$

where

T_m is the mechanical torque applied to the rotor,

T_e is the electromagnetic torque,

e are the three-phase generated voltage,

θ is the rotor angle,

$s = d/dt$ is the derivation operator,

P and Q are the active and the reactive power, respectively,

H is the inertia constant of all the parts rotating with the rotor,

M is the field excitation,

$\dot{\theta}$ is the angular speed of the machine and also the frequency of the control signal e_{abc} sent to the pulse width modulation (PWM) generator,

i_{abc} is the stator current vector flowing out of the machine,

The equations of $\tilde{\sin} \theta$ and $\tilde{\cos} \theta$ are defined as

$$\tilde{\sin} \theta = \begin{bmatrix} \sin \theta & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \end{bmatrix}^T,$$

$$\tilde{\cos} \theta = \begin{bmatrix} \cos \theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \end{bmatrix}^T.$$

The operator $\langle \cdot, \cdot \rangle$ denotes the conventional inner product in $\mathbb{R}^3$.

The electronic part controls the switches in the power part.

These two parts interact via the signals e_{abc} and i_{abc} .

The VSG given in Fig. 1 is connected to the grid via the impedance (L_g , R_g) such that

$$V_{abc} = \frac{1}{C_f s} (i_{abc} - i_{123}), \quad (7)$$

$$i_{123} = \frac{1}{(R_g + L_g s)} (V_{abc} - V_{123}). \quad (8)$$

To mimic the droop of the SG and to operate the VSG in a useful way, a controller that generates T_m and M is needed such that system stability is maintained and the desired values of real and reactive power are followed. Thus, the VSG operations are discussed.

Fig. 1. Power part of a VSG

Fig. 2. Electronic part of a VSG [4]

A. Frequency drooping and regulation of real power

The static frequency droop control loop is proposed where

$$T_m = T_{m_ref} + D_p (\omega_n - s\theta). \quad (9)$$

Thus, VSG shares load with the other generators of the AC grid to which it is connected in proportion, with the static droop coefficient D_p . Typical values for the frequency droop are a 100% increase in power for a frequency decrease between 3% and 5% (from nominal values). In (10), T_{m_ref} is the mechanical torque applied to the rotor and obtained from the set point (or reference value) of the real power P_{ref} by dividing it with the nominal mechanical speed ω_n , as shown in Fig. 2.

$$T_{m_ref} = \frac{P_{ref}}{\omega_n}. \quad (10)$$

The transfer function of the frequency regulation is:

$$\frac{\Delta \omega}{T_m - T_e} = \frac{1}{2Hs + D_p} = \frac{1/D_p}{\tau_f s + 1}. \quad (11)$$

The frequency loop time constant is:

$$\tau_f = \frac{2H}{D_p}. \quad (12)$$

The choice of τ_f determines the dynamic response of the loop. It is proportional to the moment of inertia H . A large τ_f is equivalent to having a large H , which makes the control less sensitive to the variations in the grid frequency and the system more stable. However, the response is slow. A small τ_f is equivalent to having a small H , which leads to fast frequency tracking.

B. Voltage drooping and regulation of reactive power

The reactive power Q_s is controlled by a voltage droop control loop using a voltage droop coefficient D_q , in order to regulate the field as

$$M = \frac{1}{k_s} (Q_m - Q_s), \quad (13)$$

$$Q_m = Q_{ref} + D_q (V_{ref} - V_m), \quad (14)$$

where V_m is the output voltage amplitude computed by using a phase locked loop. Another elementary method is as follows: Assume that $V_a = V_m \sin \theta_a$, $V_b = V_m \sin \theta_b$ and $V_c = V_m \sin \theta_c$, then

$$\begin{aligned} V_a V_b + V_b V_c + V_c V_a &= V_m (\sin \theta_a \sin \theta_b + \sin \theta_b \sin \theta_c + \sin \theta_c \sin \theta_a) \\ &= \frac{V_m^2}{2} (\cos(\theta_a - \theta_b) + \cos(\theta_b - \theta_c) + \cos(\theta_c - \theta_a)) \\ &\quad - \frac{V_m^2}{2} (\cos(\theta_a + \theta_b) + \cos(\theta_b + \theta_c) + \cos(\theta_c + \theta_a)). \end{aligned} \quad (15)$$

When the terminal voltages are balanced, i.e., when $\theta_c = \theta_a - \frac{2\pi}{3} = \theta_b + \frac{2\pi}{3}$, then the last term above is zero and we obtain

$$V_m = \frac{2}{\sqrt{3(V_a V_b + V_a V_c + V_b V_c)}}. \quad (16)$$

The time constant of the voltage loop is proportional to

$$\tau_v = \frac{k}{\omega_n * D_q}. \quad (17)$$

Hence the choice of τ_v affects the dynamic response of the amplitude tracking.

III. THE TEST POWER SYSTEM

The proposed test systems consist of two finite control areas are designed as Area 1, Area 2 feeding a common area load via AC lines, as illustrated in Fig. 3. Two cases are considered:

- Case 1: Area 1 is a SG equipped with a standard power frequency and voltage reactive power controls.
- Case 2: Area 1 is a VSG emulating a SG, modeled by (1)-(16).

The AC systems are chosen to have identical AC generator, with nominal voltage, short-circuit powers and frequency and given by $V = 100$ kV, $S_{cc} = 200$ MVA, $f = 50$ Hz.

For the VSG parameters, they are firstly adapted to match standard SG parameters [7], [9]: a 5% governor droop, an inertia constant $H=3.2$ s and a voltage regulation gain of 3%.

IV. SIMULATION RESULTS

The main advantage of the VSGs is to put into evidence the structure of classic SGs for which the controls are well known. The VSG operations are verified in a test power shown in Fig.3.b. Dynamic and transient performances of VSG are compared with SG of same capacity for different faults.

A. Response of VSG vs SG

A.1 Load share of the VSG

An important mechanism for VSGs and SGs for evenly sharing load (in proportion to their nominal load) is to vary the

Fig. 3.a. Coupling of AC-AC system

Fig. 3.b. Coupling of DC-AC system
Area 1: VSG

real power delivered to the grid according to the grid frequency. The VSG and the SG coupled via an AC lines as shown in Fig. 3.b are set in a parallel arrangement and are initially at nominal frequency $f_0 = 1.007$ p.u with power outputs, respectively, $P_s = 0.36$ p.u and $P_m = 0.12$ p.u given in Table I. When an active load increase $\Delta P_L = 0.13$ p.u, at $t=10$ s, causes the units to slow down, the governors increase output until they reach a new common operating frequency f' . The system responses are shown in Fig. 4 and 5. The frequency of the SG followed the VSG frequency, and the real and reactive power tracked their set points. The amount of load picked up by each unit depends on the droop characteristic such that

$$\Delta f = f' - f_0 = \frac{\Delta P_L}{D_s + D_m}. \quad (18)$$

The VSG and the SG increased their real power output by 0.064 p.u that is 6.5% of the power rating

$$\Delta P_s = P_s' - P_s = \Delta f * D_s, \quad (19)$$

$$\Delta P_m = P_m' - P_m = \Delta f * D_m. \quad (20)$$

The amount of load increase, correspond to a 0.32 % drop of the frequency. The load share of the VSG and the SG are summarized in Table. I. Hence, $\frac{\Delta P_s}{\Delta P_m} = \frac{D_s}{D_m}$, where D_s and D_m

are, respectively, the static droop of VSG and SG, which are equal to 1/5%. When a sudden change in load occurred, at $t=10$ s, as shown in Fig. 5, the reactive power dropped by about 0.042 p.u because the local terminal voltage V_{abc} was about 0.1 % higher than the nominal value, which depends on the droop characteristic

$$\Delta Q = -\frac{\Delta V}{D_q} = \frac{1-1.0012}{0.03} = 0.04 \text{ p.u}. \quad (21)$$

Table I: Load sharing

f_0 (p.u)	P_s (p.u)	P_m (p.u)	Δf Eq. (17) (p.u)	ΔP_s Eq. (18) (p.u)	ΔP_m Eq. (19) (p.u)	P'_s (p.u)	P'_m (p.u)
1.007	0.36	0.12	0.0032	0.064	0.064	0.43	0.18

Fig. 4. Responses of the SG in case 2

Fig. 5. Responses of the VSG in case 2

A.2 Local performances of VSG and equivalent SG

To test local performances, a +0.15 p.u step is applied to the reference of the active power and a +0.1 p.u step is applied to the reference of the voltage of the VSG at t=10 s. Fig. 6 shows the responses of active powers and speeds responses of the VSG and the SG. It can be noted that the VSG speed attains the steady state faster than the SG speed. Fig. 7 shows the responses of reactive powers and voltages responses of the VSG and the SG. It can be observed that better dynamic responses with the VSG concept are obtained, e.g. more damped dynamics oscillations and fast responses are attained with VSG. We note that the overshoot in the voltage response is of limited magnitude.

A.3 Transient stability

The robustness of the VSG is evaluated by assessing the transient stability of the whole test power system, following severe fault. The latter is quantified by the Critical Clearing Time (CCT), which is the maximum time duration that a short-circuit may act without losing the system capacity to recover to a steady-state stable operation. To evaluate the CCT, a three phase short-circuit fault was simulated near the load. According to this study, the fault critical clearing time for case 1 (AC-AC) estimated at $CCT_{AC-AC} = 230$ ms is less than for a mixed system case 2 (DC-AC) with a $CCT_{DC-AC} = 350$ ms.

Fig. 6. Comparison of case 1 & 2 for a +0.15 p.u step in P_{ref}

Fig. 7. Comparison of case 1 & 2 for a +0.1 p.u step in V_{ref}

As a result, the VSG concept improved also the transient stability of the neighboring AC system. Furthermore, a severe short-circuit of 200 ms duration is applied. Fig. 8 shows the responses of active power and speed in case 1 and 2. It can be observed that the transient oscillations obtained with the VSG are more damped than the ones obtained with the SG. The active power response of SG is more oscillatory than the VSG; oscillations are attributed to electromechanical dynamics of the rotor to reach steady state, for the case of VSG, power control is electronic.

Fig. 8. Comparison of case 1 & 2 for a 200 ms short-circuit

Fig. 9. Responses of the VSG with different inertia constant

B. Response of VSG to system faults

The VSG shown in Fig. 3.b is tested with different inertia values H in order to improve transient stability of the system.

B.1 Effect of inertia values

Fig. 9 shows the responses of the VSG to a +0.13 p.u load change and with different inertia constant. We note that local performances with a small inertia are better.

In addition to the previous simulations and in order to better investigate the transient stability, the critical clearing times are obtained with different inertia constant. The results are resumed in Table II and confirm the improvement of transient stability with a small inertia. As a result, it is not necessary to have a large inertia as for a physical SG, where a larger inertia means that more energy is stored mechanically. We can observe that a small inertia is good for overall grid stability.

Table II: CCTs with different constant inertia

	3.2	2	1.5	0.032
CCT (ms)	175	250	300	unstable system

B.2 Frequency regulation by PID governor

Standard parameters of SG presented above are applied to the VSG. For performances improvement, the static droop control loop is replaced by the PID governor. Results presented in Fig. 10 shows that local performances of VSG with the same parameters of SG are improved with PID governor.

V. CONCLUSION

This paper presented a dynamic performances study of the virtual synchronous generator. The latter is based on the synchronverter control strategy. The study is based on a comparative analysis of a SG/VSG two-area system, feeding a common load. For each configuration, dynamic performances to different system fault are studied and the transient stability of the system is assessed in terms of the fault critical clearing time. Due to the controllable features, the virtual synchronous generator of the same capacity and parameters with a standard SG can be used to improve the dynamic system oscillations, the response time and the transient stability of interconnected AC systems in terms of increasing the fault critical clearing time.

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Fig. 10. Responses of the VSG with PID governor

VII. APPENDIX

Network data (Fig. 3)

Area 1&2: Generator: Rated 200 MVA, 20 kV, line voltage=100 kV, frequency=50 Hz, $R_s=0.75 \Omega$, $L_s=0.2$ H, X_l (p.u): leakage Reactance = 0.18 X_d (p.u): d-axis synchronous reactance = 1.305, T'_{d0} (s): d-axis open circuit sub-transient time constant = 0.296, T'_{d0} (s): d-axis open circuit transient time constant = 1.01, X_q (p.u): q-axis synchronous reactance = 0.053, X_q (p.u): q-axis synchronous reactance = 0.474, X''_q (p.u): q-axis sub transient reactance = 0.243, T''_{q0} (s): q-axis open circuit sub transient time constant=0.1, Coupling Delta/ Y_g
Primary resistance (p.u)=0.002, Primary inductance (p.u)=0.12
Secondary resistance (p.u)=0.002, Secondary inductance (p.u)=0.12
M=2H (kWs/kVA): Mechanical starting time = 6.4.
Governor control system
 D_m (%): permanent droop =5, servo-motor: $k_a = 10/3$, t_a (s) = 0.07, regulation
PID: $k_p = 1.163$, $k_i = 0.105$, $k_d = 0$
Excitation control system
Amplifier gain: $k_a = 200$, amplifier time constant: T_a (s) = 0.001, damping
filter gain $k_f = 0.001$, time constant t_e (s) = 0.1
Generator transformers Rated 400 MVA, 20/ 100 kV
Load: $P_L=200$ MW
AC transmission lines: Resistance per phase (Ω /km) =0.03, Inductance per phase (mH/km) =0.32 , Capacitance per phase (nF/km) =11.5
Pi line length= 100 km
AC filter: reactive power=40 MVAR
DC system: voltage= ± 100 kV, rated DC power=200 MW