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Fast Frequency Control of Low-Inertia Hybrid Grid Utilizing Extended Virtual Synchronous Machine

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***Abstract*—Massive integration of renewables e.g., wind, pv and energy storage in hybrid energy systems introduce new challenges in terms of frequent control due to the inherent low inertia characteristic of non-synchronous generators (NSG). In this paper, an extended virtual synchronous machine (VSM) control strategy is proposed to provide better frequency support in the hybrid low-inertia grids. This approach is realized by adding a fast frequency response (FFR) droop block to the VSM control of power converter. By applying the proposed control model, the power converters interfaced energy storage systems (ESS) are enabled to emulate the dynamic behavior of a synchronous machine and provide inertia for the grid. Furthermore, compared to the conventional VSM, which, just behaves like a synchronous machine, the proposed control approach provides better frequency support. Simulation results for an RMS study in DIgSILENT PowerFactory show the performance of the proposed control in a hybrid low-inertia grid.**

***Index Terms*—Frequency control, low-inertia grids, RMS studies, Voltage source converter, Virtual synchronous machine (VSM).**

I. INTRODUCTION

Hybrid power system integrates many distributed generation units (DGUs), mainly based on renewable energy sources (RES), and energy storage systems (EES) and provide increased grid flexibility and efficiency. Power electronics components, advanced control structures, and communication infrastructures play prominent roles in achieving this.

The power converter based DGUs, which are integral components of the modern grid, have a higher degree of operability and controllability compared to conventional power generators. This feature permits the DGUs to play a decisive role in the frequency and voltage stability.

Power converters, which serve as interfaces between DGUs and the ac bus, can be categorized into three main types. Grid feeding, grid supporting, and grid forming are three control architectures, which are used to inject the electrical power of RESs into the grid [1]. Grid feeding control, which operates in current control mode, is merely controlled to inject the maximum active power and required reactive power to the grid [2]. A grid supporting architecture regulates the output active and reactive power based on the voltage and frequency oscillations of its point of common coupling (PCC), or based on the power dispatch strategies of the demand side. Finally, the grid forming control architecture makes the converter behave as an ideal ac voltage source behind an impedance in the grid, and damps the grid voltage and frequency oscillations by contributing to the grid power-sharing by using proper controllers [1]. The grid forming voltage source converters (VSCs) are controlled to work with a defined frequency and voltage amplitude. This architecture plays a prominent role when several DGUs are connected in parallel so that their frequency and voltage amplitudes need to be adjusted based on the loading conditions.

Massive integration of DGUs and in general non-synchronous generators (NSGs) equipped with standard d-q current control introduce new challenges in terms of frequency control in the grid. Due to the inherent low inertia characteristic of NSGs, the voltage and frequency control become a major challenge in the power system operation and control [3]. Therefore, a proper control strategy, suitable for such low inertia grids, is required.

Compared to the traditional power grids, the penetration level of NSGs, with no inherent inertia, is higher in the modern grids. Lower inertia in the grid yields a more significant impact of disturbances on the grid frequency. The rotating parts of the synchronous generators and turbines interchange inertial energy with the grid so that the primary control loops have an acceptable time to react to the system load/generation imbalance or disturbances. However, the power converters interfaced DGUs do not normally provide an inertial response toward the grid. Consequently, a perturbation on the system or a large generation/load imbalance may lead to severe frequency deviations in the system, which in turn

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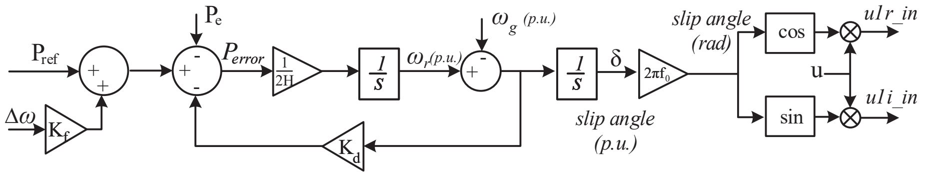

Fig. 1. Fast frequency response VSM control structure, implemented in DIgSILENT PowerFactory.

may lead to load shedding or system instabilities. This low-inertia challenge is a main bottleneck to integrate a high penetration of NSG in the power grid. For instance, due to the increasing penetration of NSG, frequency violations have increased in the Nordic grid [4]. In Ireland and Northern Ireland, the inadequate grid inertia significantly affected the frequency and voltage dynamic [5]. Moreover, in Great Britain (GB) the maximum time delay before start of power response is two seconds after the event. This delayed dynamic response means that with inertia reduction, they will be challenges to limit the frequency deviations [6].

Motivated by the mentioned problem, a fast and accurate control structure is a demanding approach for the reliable operation of the low-inertia grids. In [7], [8], instability problems of low-inertia grids are investigated. Virtual synchronous machine (VSM) and power synchronization control (PSC) approaches are presented in the literature to provide inertia by emulating the dynamic behavior of a synchronous machine [9]–[13]. However, PSC normally provides very little inertia. In [14]–[16], a model predictive control approach is presented to operate a high bandwidth control structure in a microgrid. However, the proposed control structure has only fast dynamic response and cannot provide inertia for the system. Furthermore, from the power system point of view, the lack of VSM control implementations for RMS studies is observed.

In this paper, an extended VSM control approach is implemented in DIgSILENT PowerFactory to not only provide the inertia for the grid but also to restore the system frequency very fast compared to conventional approaches. Thus, By implementing a VSM control of power converters in DIgSILENT PowerFactory, an RMS study for a low inertia grid is provided. Moreover, Compared to the conventional control methods, the proposed approach provides inertia for the grid as well as fast frequency support.

The RMS simulation results verify the control structure performance.

II. VSM Control Approach

The aim of VSM control is the emulation of a synchronous machine by a VSC, so that, from the power system point of view, the VSC should be able to have very similar dynamics as a synchronous machine. The major objectives of VSM control of power converters are as follows:

- Providing virtual inertia to contribute to the system frequency control.
- Enhancing the stability properties for connection to low-inertia grids and weak grids.
- Enabling stable operation with higher penetration of NSGs.
- Improving the frequency nadir (maximum frequency deviation) and the rate of change of frequency (RoCoF) in the system [3].

All the various approaches for VSM control are based on emulating the swing equation of a synchronous machine. The kinetic energy of the rotating mass in a synchronous machine with moment of inertia J $[kg{\times}m^2]$ and angular rotor speed ω_r [rad/s] is as follows:

$$E_r = \frac{J\omega_r^2}{2}. \tag{1}$$

The power, which accelerates the rotating mass, can be obtained by differentiating (1) as follows:

$$\frac{dE_r}{dt} = J\omega_r\frac{d\omega_r}{dt}. \tag{2}$$

If the variables are expressed in the per-unit system, and the angular speed varies slightly around the nominal angular synchronous frequency ω_{r_0} [rad/s], the first order swing equation can be expressed as follows [3]:

$$P_m - P_e - P_D = 2H\frac{d\omega_r}{dt}, \tag{3}$$

$$H = \frac{J\omega_{r_0}^2}{2\mathrm{S}_{\mathrm{base}}} \tag{4}$$

$$\frac{d\delta}{dt} = \omega_r - \omega_g, \tag{5}$$

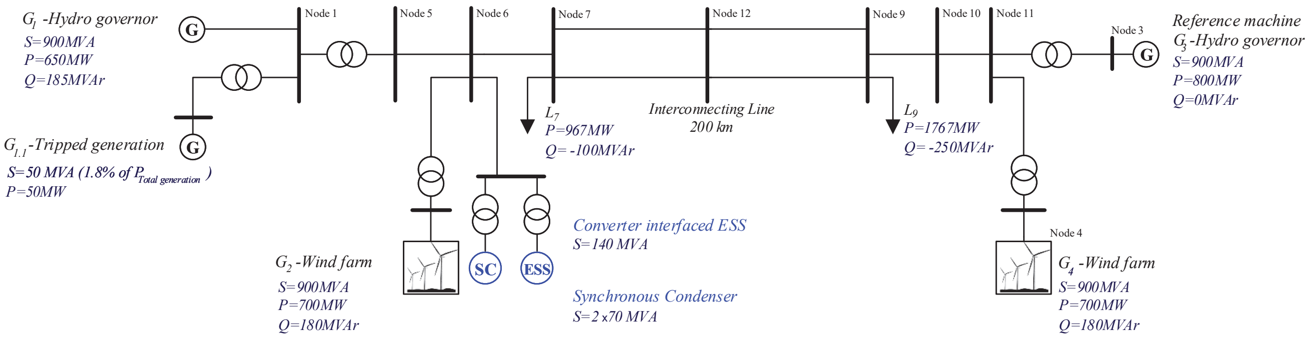

Fig. 2. Four-machine test system.

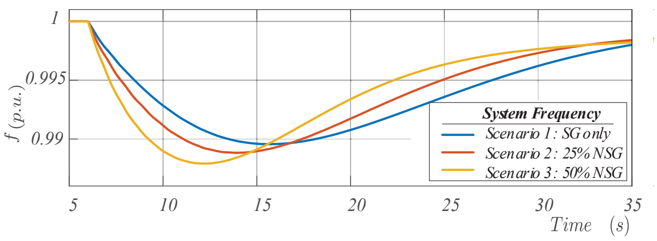

Fig. 3. Effect of increasing the penetration of Non-synchronous generation on the system frequency.

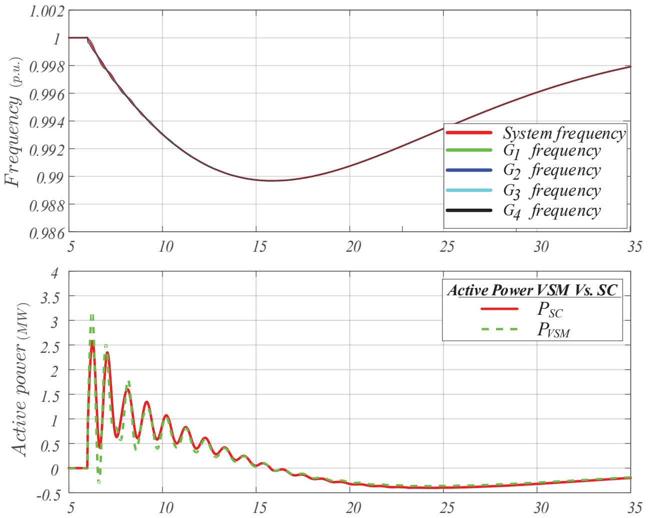

Fig. 4. System frequency and the active output power of a synchronous condenser (P_{SC}) and a power converter (P_{SC}) controlled as the VSM without the FFR control loop.

$$P_D = K_d(\omega_r - \omega_g). \tag{6}$$

Here, P_m [p.u.] is the prime mover mechanical power, P_e [p.u.] is the electrical power, and P_D stands for the damping term. Noting that in a practical case, ω_g (the speed of the reference machine G_3) is not available. Thus, the damping term loop presented here is hard to realize without remote measurements, and a wide area control system (WACS). ω_r [p.u.], ω_g [p.u.] and δ [p.u.] are the rotor angular speed, grid reference machine rotor angular speed, and the rotor angle respectively. Finally, H [s] is the inertia constant and S_{base} [VA] is the base rating of the machine.

By employing the control law (3), the VSM control should enable the VSC to appear as a virtual synchronous machine, with similar inertial response, in the grid. However, compared to the synchronous machine, the power electronic converters can react faster if a proper control structure has been applied.

III. Proposed Fast Frequency Response VSM

The proposed control structure is demonstrated in Fig. 1, where the real (*u1r_in*) and imaginary (*u1i_in*) part of the voltage phasor control the converter output. The control law (3) is applied to control the active output power of the converter interfaced ESS by a virtual angular speed like a synchronous machine. Therefore, the ESS controlled by the VSM supports the system frequency like a synchronous machine. Furthermore, another complementary term of fast frequency response (FFR) is added to the nominal active power to have better support for frequency deviations. Thus, the ESS controlled by the proposed extended VSM have a fast frequency response while providing inertia for the system.

$$\Delta P_{FFR} = K_f \Delta\omega, \qquad \Delta\omega = \omega_{nom} - \omega_r, \tag{7}$$

where, ω_{nom} [p.u.] is the nominal angular speed. In order to implement the VSM control in DIgSILENT PowerFactory a static generator (*ElmGenstat*) in voltage source mode connected to an ESS is employed to serve as a power converter interfaced ESS. In steady-state, the VSM works like a synchronous machine. However,

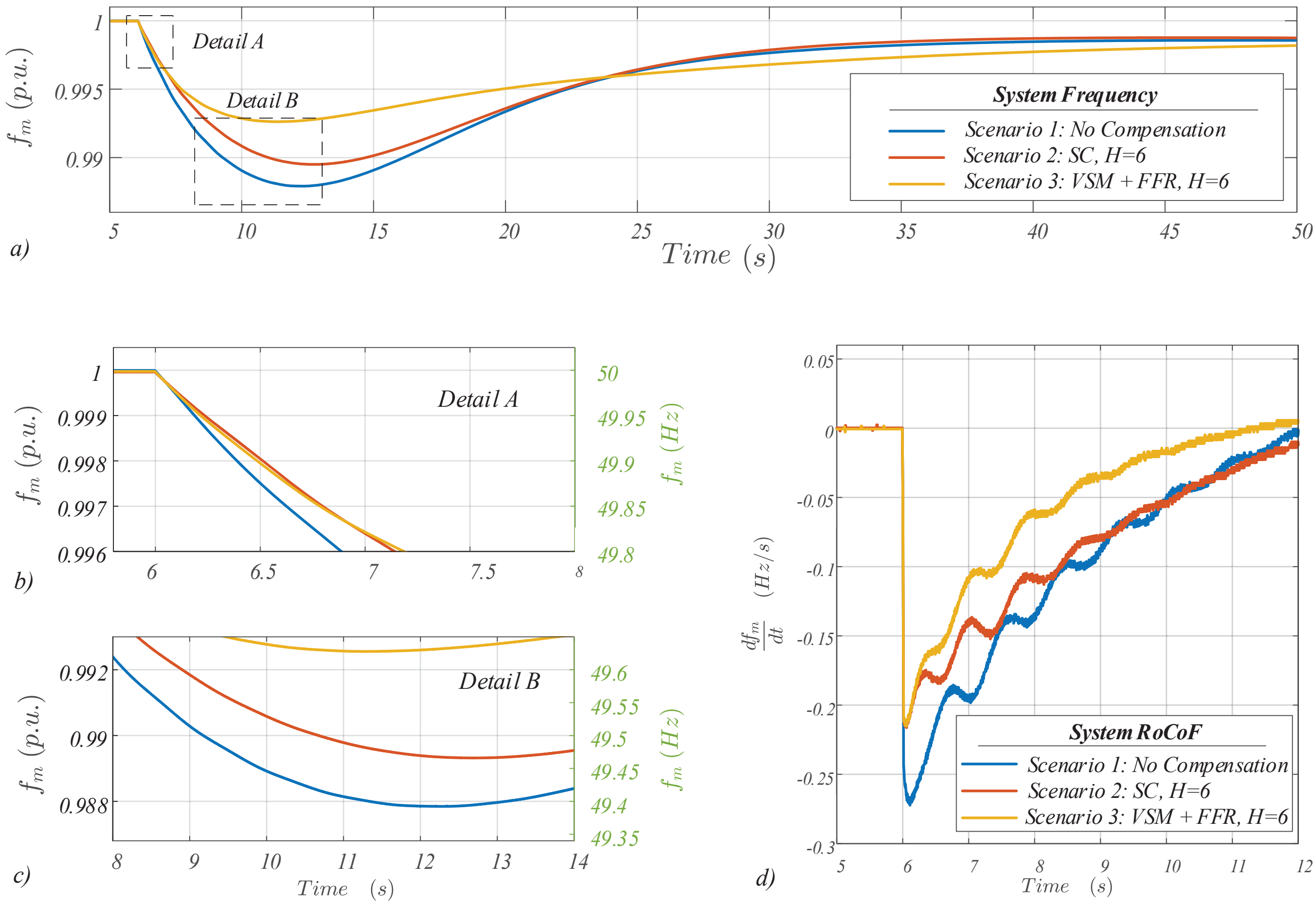

Fig. 5. The proposed control approach performance in three scenarios (a) system frequency, (b) inertia response, (c) frequency nadir, (4) system rate of change of frequency (RoCoF).

when the frequency deviates from the nominal value, the proposed control structure, firstly provide inertia like a synchronous machine, then it also supports the frequency control in the grid in case of disturbance.

IV. Simulation Results

To evaluate the proposed control structure performance, a four-machine test system inspired from [17] is employed to serve as a low-inertia grid. Generator 2 and generator 4 of the original model are replaced with wind turbine generators with the same power rating in three scenarios: 1) All the generators are synchronous generator. 2) Generator 2 is replaced by a wind turbine. 3) Both generator 2 and generator 4 are replaced by the wind turbines. As it is expected and shown in Fig. 3, when a generation trip ($G_{1.1}$) is applied, by increasing the penetration of NSGs, the RoCof is increased, and also the maximum frequency deviation is increased. To validate the VSM control performance, a synchronous condenser, which serve as a benchmark, and a converter interfaced ESS controlled as the VSM is connected to node 6, alternatively. Initially, the FFR term is not activated. Therefore, the converter and synchronous condenser, with the same inertia constant H, and rating, should have very similar dynamic behavior. A generation trip at node 1 is applied for two cases, i.e., synchronous condenser is connected, and converter controlled by the VSM is connected. As it can be seen in Fig. 4, the converter controlled by the VSM has a very similar dynamic behavior as a synchronous machine. Therefore, from the power system point of view, the proposed VSM control performance is validated.

Subsequently, the FFR is activated to have a better support of frequency deviations. For the scenario of 50% NSG penetration, Fig. 5 shows the dynamic behaviour of the system frequency (mass-weighted average) in three scenarios: 1) With no compensation (grid support); 2) With synchronous condenser; 3) With the proposed VSM equipped with the FFR. As it can be seen from Fig. 5 (b) and (d) the RoCoF for scenarios 2 and scenarios

3 are close to the same for the first seconds, when a generation trip event is applied. It means that the VSM provides an inertial behaviour like a synchronous machine. Then, after t=7s the VSM injects additional power until the frequency is restored close to the nominal value. The RMS simulation results shown in Fig. 5 verified that by applying the proposed control model, the frequency nadir is also improved significantly compared to the conventional VSM control structure, emulating the behaviour of a synchronous machine.

V. CONCLUSION

Increasing the penetration of non-synchronous generators e.g., wind turbine, PV and energy storage system (ESS) in hybrid power grids leads to frequency stability challenges due to the lack of rotating mass and kinetic inertia in the system. The virtual synchronous machine concept is a promising solution for improvement of the frequency nadir and the rate of change of frequency in low-inertia power electronic-based power systems. This paper has presented results for an extended virtual synchronous machine controller for power converters studied simulation of a low inertia grid. In this paper, VSM control is extended to have a fast frequency response while providing inertia for the system. Simulation results in DIgSILENT PowerFactory show that the proposed control structure emulates the dynamic behavior of a synchronous machine accurately. Furthermore, compared to a synchronous condenser, it provides better support of frequency deviations.

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