Distributed Generation Grid Integration Using Virtual Synchronous Generator with Adoptive Virtual Inertia

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***Abstract*— Virtual Synchronous Generator (VSG) is a control scheme applied to the inverter of a distributed generating unit in order to support power system stability by imitating the behavior of a synchronous machine. The VSG design of our research incorporates the swing equation of synchronous machine to express a virtual inertia property. Unlike a real synchronous machine, the parameters of the swing equation of VSG can be selected real-time to enhance the fast response of the virtual machine in tracking the steady-state frequency. Based on this concept, the VSG with adoptive moment of inertia and the negative moment of inertia idea is introduced newly. The idea is supported by simulation and experimental results which indicate remarkable performance in fast damping of frequency oscillations.**

I. INTRODUCTION

Conventional enormous synchronous generators comprise rotating inertia due to their rotating parts. These generators are capable of injecting the kinetic potential energy preserved in its rotating parts to power grid during disturbances or sudden changes. Therefore the system is robust against instability. On the other hand, penetration of Distributed Generating (DG) units in power systems is increasing rapidly. A power system with a big portion of inverter based DGs is prone to instability due to lack of adequate balancing energy injection within the proper time interval. The solution can be found in the control scheme of inverter-based DGs. By controlling the switching pattern of an inverter, it can emulate the behavior of a real synchronous machine. In Virtual Synchronous Generator (VSG) concept, the power electronics interface of DG unit is controlled in a way to exhibit a reaction similar to that of a synchronous machine to a change or disturbance [1].

VSG concept and application were investigated in [2, 3]. The same concept under the title of Synchronverters is described in [4]. The VSG systems addressed in [5-7] are designed to connect only an energy storage unit to the main grid. Reference [8] implements a linear and ideal model of synchronous machine to produce current reference signals for hysteresis controller of inverter. In this Virtual Synchronous Machine (VISMA), authors also added an algorithm for small disturbance compensation to improve voltage quality of grid. Reference [9] introduces a mechanism for voltage, frequency and active and reactive power flow control of VSG. Our research group has introduced a new VSG design [10], enhanced voltage sag ride-through capability to the VSG and evaluated it in various voltage sag conditions [10, 1], and finally added reactive power control to have a constant voltage at VSG terminals [11].

VSG is designed to behave like a synchronous generator. Therefore, its quantities like output frequency and power oscillates after a change or disturbance similar to those of a synchronous machine. On the other hand, the ratings of an inverter based generating unit are much less than a real synchronous machine. Therefore VSG system may stop working redundantly due to oscillations with high amplitude after a change or disturbance. Since a simplified model of synchronous generator is embedded in the VSG to produce desired switching pattern for inverter switches, it is more flexible than a common synchronous generator. In other words, we can change the parameters of a VSG during its normal operation to obtain a faster and more stable operation. We use this advantage of VSG system and introduce VSG with adoptive virtual inertia to remove the oscillations and thereby, increase the reliability of VSG unit against changes or disturbances. In this concept, the value of virtual moment of inertia is determined by considering relative virtual angular velocity (the difference between virtual mechanical velocity generated by VSG and grid angular frequency) and its rate of change. Thereby the acceleration and deceleration can be controlled in each segment of oscillation. Since this method makes a choice of appropriate value for moment of inertia, we call it Adoptive Inertia scheme. We even go forward and introduce a negative inertia concept that showed outstanding performance in frequency stabilization. All proposed ideas are verified by experiments on a laboratory scale DSP controlled inverter.

In section II of this paper, the structure of VSG system is discussed in detail. The logic and process of Adoptive Inertia idea is introduced in section III. Negative inertia concept is introduced in part IV. Simulation results are included in sections III and IV. In section V, an analytical approach is used to observe the behavior of the relative speed and its rate of change during oscillation after a disturbance. The performance of the new idea in fast frequency stabilization

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can be illustrated lucidly by this approach. Experimental results are represented in part VI. Finally, conclusion is given in Section VII.

II. Virtual Synchronous Generator Structure

Fig. 1 shows the control block diagram of the VSG system. In this scheme, a distributed resource (DR) is connected to the main power system via an inverter controlled via VSG concept. The model of synchronous generator which is used in this paper is a cylindrical-rotor type synchronous generator connected to an infinite bus as shown in Fig. 2. The well-known swing equation of synchronous generator is used as the heart of VSG model:

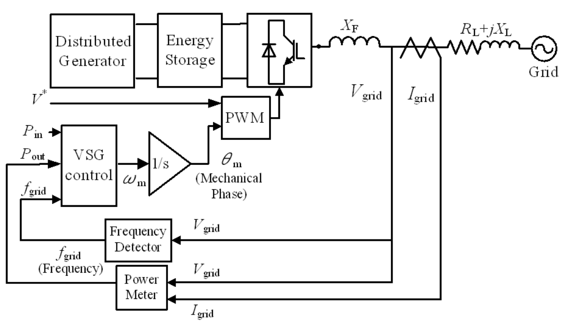


Figure 1. Block diagram of VSG unit.

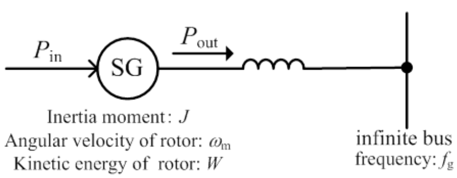


Figure 2. Model of synchronous generator.

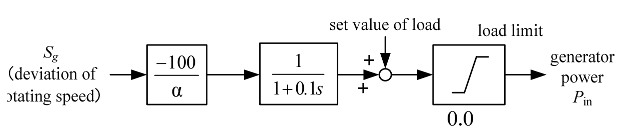


Figure 3. Governor diagram (δ is the speed regulation factor).

$$P_{in} - P_{out} = J\omega_m \, {d\omega_m}/{dt} - D\Delta\omega \, . \tag{1}$$

Where P_{in} is input power (as same as the prime mover power in a synchronous generator), P_{out} is output power, J is the moment of inertia of the rotor, ω_m is the virtual angular velocity of the virtual rotor and D is the damping factor. $\Delta\omega_m$ is the difference between ω_m and grid frequency. Using voltage and current signals measured at the VSG terminals, its output power and frequency are calculated. A governor model shown in Fig. 3 is implemented to tune the input power command based on the frequency deviation. In this model, S_g is the normalized discrepancy between ω_m and grid frequency and α is the speed regulation constant. Having the essential parameters, (1) can be solved by numerical integration. By solving this equation in each control cycle, the momentary ω_m is calculated and by passing through an integrator, the virtual mechanical phase angle, θ_m is produced. This phase angle and a voltage magnitude reference are used as the VSG output voltage angle and magnitude commands for generating PWM pulses.

III. Virtual Synchronous Generator with Variable Moment of Inertia

Consider the power-angle curve of fig. 4. After a change in system, e.g., a change in prime mover power from P_{in0} to P_{in1}, operating point moves along the power curve, from point "a" to "c" and then from "c" to "a". Machine condition during each phase of an oscillation cycle is summarized in Table 1. It should be noted that the sign of the $d\omega_m/dt$ does not determine acceleration or deceleration by itself; whereas, its sign respect to the sign of the relative angular velocity defines the acceleration or deceleration. For example, in segment ③ of Fig. 4, during transition from points "c" to "b", both of $d\omega_m/dt$ and $(\omega_m-\omega_{grid})$ are negative and act in the same direction, therefore it is an acceleration period. On the other hand, they have opposite signs like segment ④, it is a deceleration period.

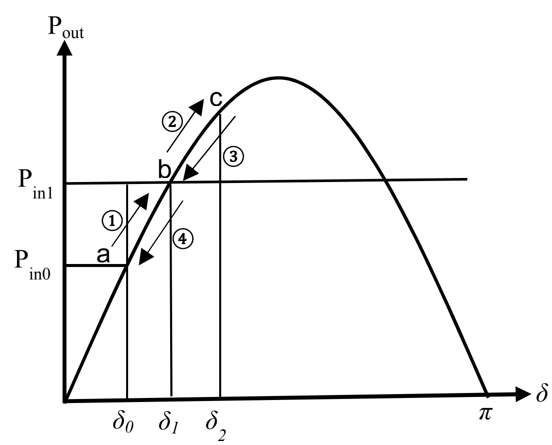


Figure 4. Power-angle curve of a typical synchronous machine.

Our purpose is to damp frequency and power oscillation quickly by controlling the acceleration and deceleration term. The derivative of angular velocity, $d\omega_m/dt$ indicates the rate of acceleration or deceleration. Considering (1), it is observed that this rate has a reverse relation to the moment of inertia, J. Based on this fact, we select a large value of J during acceleration phases ("a" to "b" and "c" to "b") and a small value of J during deceleration phases ("b" to "c" and "b" to "a"). This process is summarized in Table 1. Figs. 5 and 6 show simulation results of this concept. Simulations were performed on the system model of Fig. 1 with the parameters of P_{base}=50 kW, V_{base}=200 V, f_{base}=60 Hz,

TABLE I. MACHINE MODE IN EACH PHASE OF OSCILLATION

a→b	$\omega_m-\omega_{grid}>0$	$d\omega_m/dt>0$	**Accelerating**	Big value of J
b→c	$\omega_m-\omega_{grid}>0$	$d\omega_m/dt<0$	**Decelerating**	Small value of J
c→b	$\omega_m-\omega_{grid}<0$	$d\omega_m/dt<0$	**Accelerating**	Big value of J
b→a	$\omega_m-\omega_{grid}<0$	$d\omega_m/dt>0$	**Decelerating**	Small value of J

R_L=0.125 pu, X_L=0.330 pu and D=17 pu. The system was subjected to changes in power reference in two steps. Fig. 5 is related to a VSG with fixed value of $J=6$ kgm^2. To show the effectiveness of the proposed idea, the simulations were carried out on a weak system that VSG with fixed J cannot stabilize the frequency at second step of power increase. By using the Adoptive Inertia idea, frequency and power oscillations are suppressed effectively in Fig. 6.

Damping factor is an important term that defines the VSG response to small or big deviations in its input variables (control signals or disturbances). An inappropriate value of damping factor may result in a high magnitude oscillating or a sluggish response. Besides, a proper value of damping factor in a specific working point may not end up with an acceptable response in other conditions. The Adoptive Inertia concept allows VSG system to exert suitable time constant in each phase of oscillation, therefore the weight of damping factor in the behavior of VSG system is reduced considerably. Fig. 7 shows the output power and angular velocity of VSG with fixed moment of inertia and zero value for damping factor. In this condition, oscillations last for long time. Whereas oscillations are eliminated by the Adoptive Inertia idea even with zero value of damping factor as shown in Fig. 8.

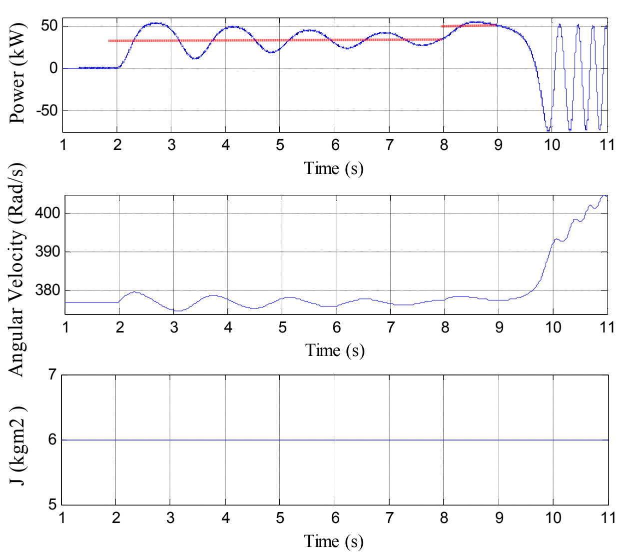


Figure 5. Output power, virtual angular velocity, and virtual moment of inertia of VSG with fixed J and D=17 pu.

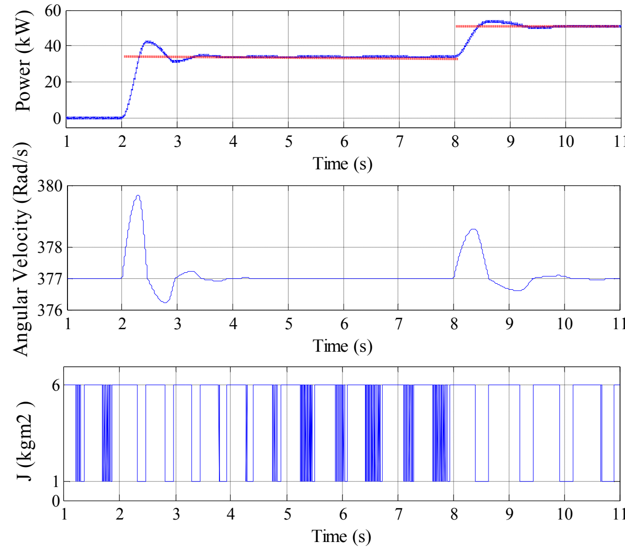


Figure 6. Output power, virtual angular velocity, and virtual moment of inertia of VSG with adoptive J and D=17 pu.

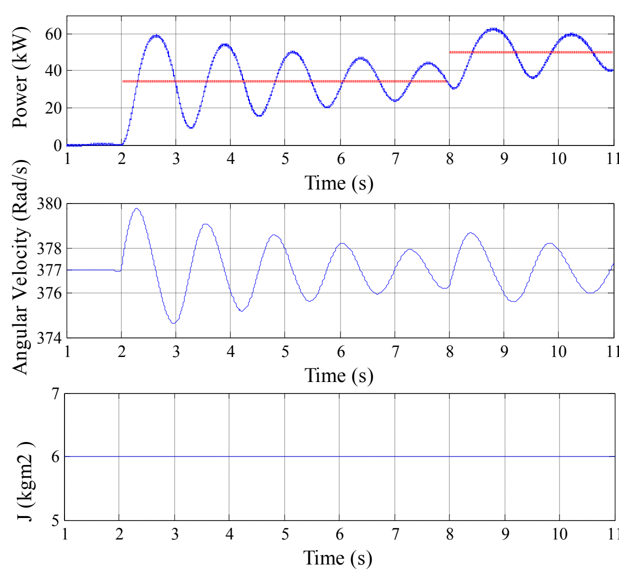


Figure 7. Output power, virtual angular velocity, and virtual moment of inertia of VSG with fixed J and zero damping factor.

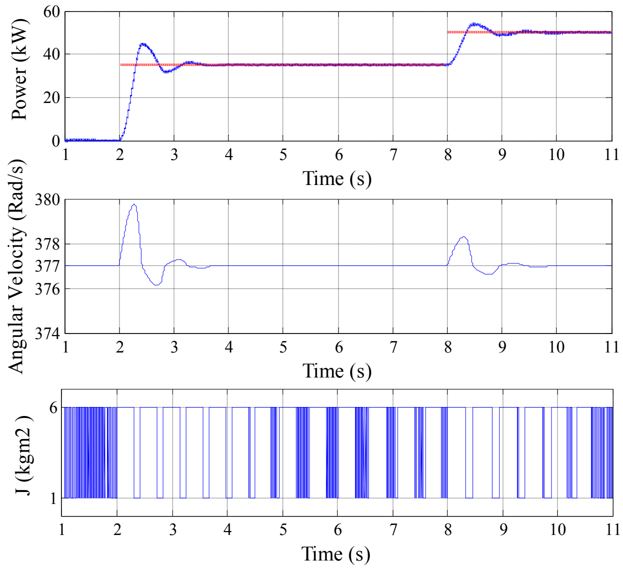


Figure 8. Output power, virtual angular velocity, and virtual moment of inertia of VSG with adoptive *J* and zero damping factor.

IV. Virtual Synchronous Generator with Negative Moment of Inertia

In Fig. 4, during transition from point "c" to "b", $\omega_m-\omega_{grid}<0$, $d\omega_m/dt<0$, and the prime mover power is less than the electrical power. During this transition, since both rotor relative velocity respect to grid frequency and its derivative are negative, the rotor is accelerating in reverse direction. This acceleration continues until the difference between the input power and output power becomes equal to damping term. Then, when the damping term is bigger than the power mismatch, $d\omega_m/dt$ turns into positive value and the rotor starts to slow down. If we impose a negative value (-0.5) for the inertia factor during acceleration period of this phase, the acceleration will not happen. Therefore, the rotor will be stabilized quickly. This idea resembles a sudden change in poles direction of the rotor of a real synchronous machine that is impossible in reality. Fig. 9 shows the output power and frequency curves of VSG with negative inertia concept applied. It is observed that the angular velocity oscillates only a half-cycle. At the beginning of the second half-cycle, when the angular velocity goes a little below the grid frequency, VSG adopts the negative value for the inertia factor. Therefore the sign of the derivative of angular frequency changes to positive. At this point, the oscillation status is changed from acceleration to deceleration. The negative inertia period lasts until the VSG angular velocity is locked to the grid frequency.

V. Stabilization Analysis by Frequency-Acceleration Plot

Reference [12] addresses an algorithm for synchronous machine out-of-step detection. The idea behind this algorithm is based on the behavior of angular frequency and its derivative on a phase plane during swings. We use this concept to see how Adoptive Inertia acts in swing suppression. Consider the power-angle curve of Fig. 4. If we draw the angular velocity of rotor and its derivative in each segment of one oscillation cycle, it will be a circular form as shown in Fig. 10. Angular frequency-acceleration trajectory of one cycle of undamped oscillation is shown in Fig. 10-(a). Each segment of the swing in this figure is deduced by the explanation given for Fig. 4. For example, during the transition of segment ①, $\omega_m-\omega_{grid}>0$ and $d\omega_m/dt>0$. In case of a stable swing, the circles of oscillations converge at the stable point eventually (Fig. 10-(b)) whereas, for unstable swings, the plot diverges (Fig. 10-(c)).

The angular frequency-acceleration trajectory of simulated VSG is shown in Fig. 11. In Fig. 11-(a) that refers to the VSG with fixed moment of inertia, the trajectory converges eventually after passing several circles. Whereas the trajectory of Fig. 11-(b) is forced to converge faster by varying the acceleration (deceleration) magnitude via adopting the inertia value in each section of an oscillation cycle. It can be seen that the circular form is deformed because of change in system parameters at each section. The plot of angular frequency-acceleration trajectory of VSG with negative inertia scheme is shown in Fig. 11-(c). It is observed that the graph converged even faster. In this figure, after the first half cycle, virtual angular velocity will not go below the grid frequency; therefore the second half cycle of oscillation is eliminated.

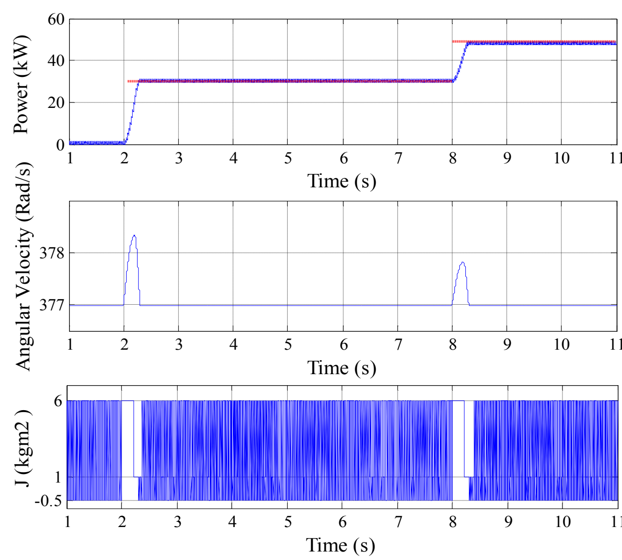


Figure 9. Output power, virtual angular velocity, and virtual moment of inertia of VSG with Negative Inertia scheme and *D*=17 pu.

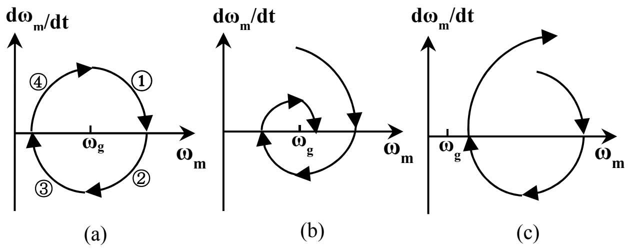


Figure 10. Angular frequency-Acceleration curves of: (a) one cycle of undamped swing, (b) stable swings, (c) unstable swings.

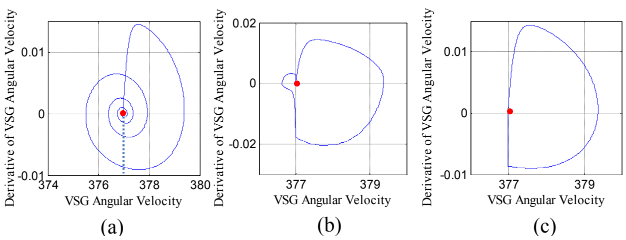


Figure 11. Angular frequency-Acceleration curves of VSG with: (a) fixed moment of inertia, (b) Adoptive Inertia scheme, (c) Negative Inertia scheme

VI. Experimental Results

The idea of variable inertia was verified by applying on a laboratory scale test system. The overall system configuration is depicted in Fig. 12 and main parameters of the system are presented in TABLE II. The transmission unit (TU) in Fig. 13 simulates the π model of a 40 Km transmission line shown in Fig. 8.

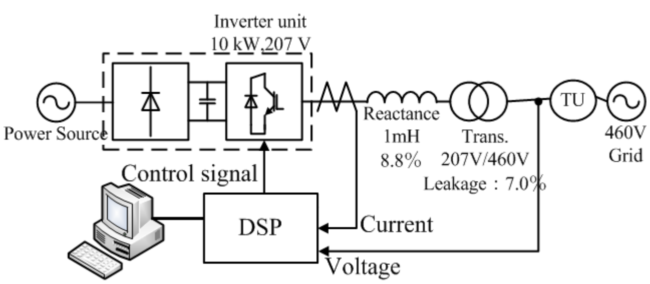


Figure 12. Experimental system.

TABLE II. Specifications of VSG.

Base power P_{base}	10 kW
Base voltage V	207 V
Base Frequency	60 Hz
Interconnecting reactance X_L	7.0%
Damping factor	17 pu

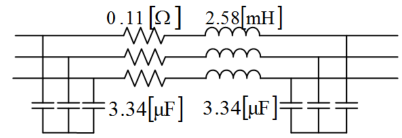


Figure 13. Transmission Unit.

Initially, the VSG model illustrated in fig. 1 with the constant moment of inertia, J=0.563 kgm^2 was subjected to a step change of 3 kW in the power reference. The output power and generated angular velocity of the VSG is shown in Fig. 14. When the power reference increased, VSG output power follows the power command after passing severe oscillations with the amplitude of 2 kW. It can be concluded that if higher power command applied, the VSG might stop working because of overcurrent restriction.

Then the VSG block of Fig. 1 was replaced with a VSG with Adoptive Inertia scheme. The same step change was applied and the result is shown in Fig. 15. It is observed that the virtual angular velocity and power oscillations disappear by the embedded concept. In this condition the VSG can be loaded at the power levels closed to its rating. To investigate this claim, we applied a bigger step increase in power reference that the VSG with fixed J stops working due to overcurrent relays actions. The results represented in Fig. 16 show that by the Adoptive Inertia idea, VSG can accept severer change or disturbance.

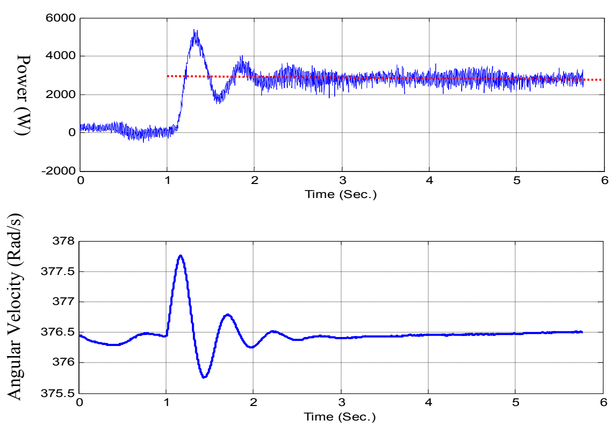


Figure 14. Output power and virtual angular velocity with fixed moment of inertia of 0.563 kgm^2 and D=17 pu.

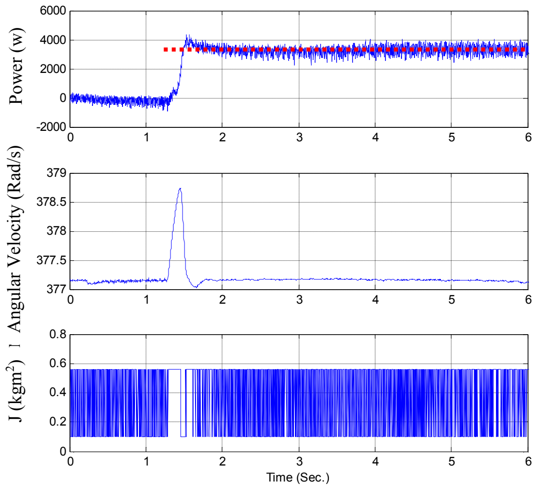


Figure 15. Output power, virtual angular velocity, and virtual moment of inertia of VSG with adoptive J and D=17 pu.

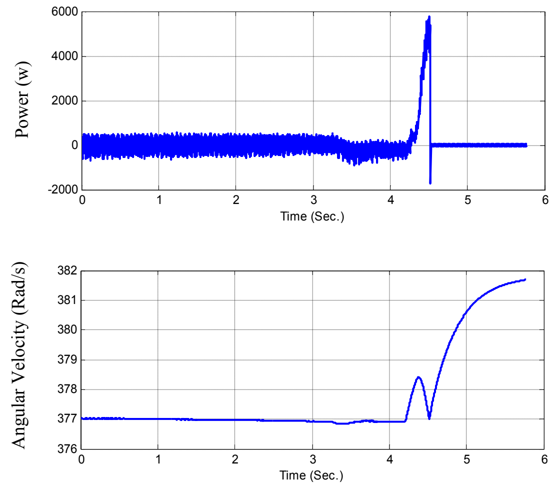


Figure 17. Output power and virtual angular velocity with fixed moment of inertia of 0.563 kgm^2 and zero damping factor.

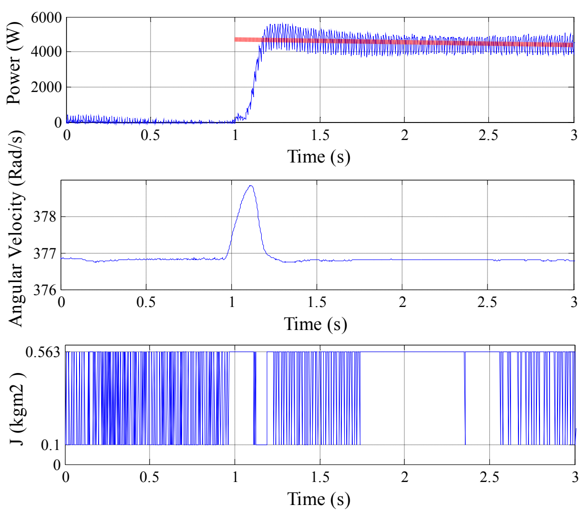


Figure 16. Output power, virtual angular velocity, and virtual moment of inertia of VSG with adoptive J and D=17 pu after a step change of 5 kW.

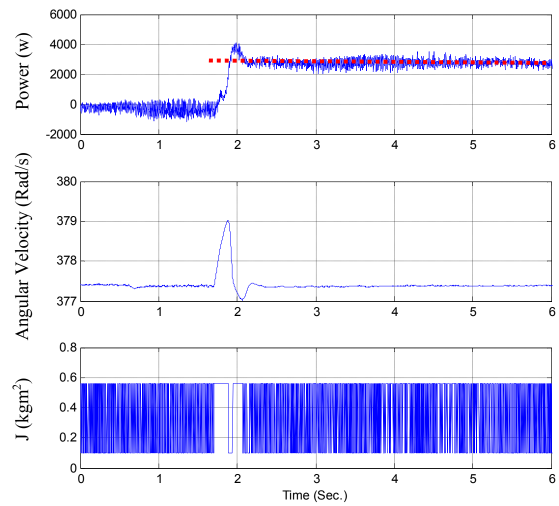


Figure 18. Output power and virtual angular velocity with Adoptive moment of inertia and zero damping factor.

To see the effect of Adoptive Inertia idea on the stabilization of frequency, we tested the VSG with zero damping factor, D. Fig. 17 contains the wave forms of VSG with fixed J of 0.563 and damping factor of zero after a step change in power reference. As we expect, VSG cannot get into step with grid frequency and fails to track power reference that is simply an unstable condition. With the same value for damping factor, implementing the Adoptive Inertia idea can help the VSG to work more robust after a sudden change or disturbance. Output power, virtual angular velocity and real-time adopted J are shown in Fig. 18.

The proposed negative inertia theorem was tested on the same experimental system. A step change of 5000 W (0.5 pu) was applied to the input power reference. Fig. 19 shows the VSG output power, virtual angular velocity, and the moment of inertia during this experiment. As it is observed, even with a big step change in power reference that normally VSG with fixed moment of inertia will fail to bear the oscillations, the negative inertia concept removes the oscillations and inverter follows the power command safely.

Fig. 20 includes the angular frequency-acceleration trajectory of the practical VSG. Part (a) of this figure is of the VSG with fixed moment of inertia. Since it is a stable oscillation, the trace converges near the grid frequency. The trajectories of VSG with Adoptive and negative inertia schemes are shown in Figs. 20-(b) and 20-(c) respectively. The proposed concepts force the graph effectively to converge quickly with less oscillation. This result confirms the discussion stated for the simulation results of Fig. 11.

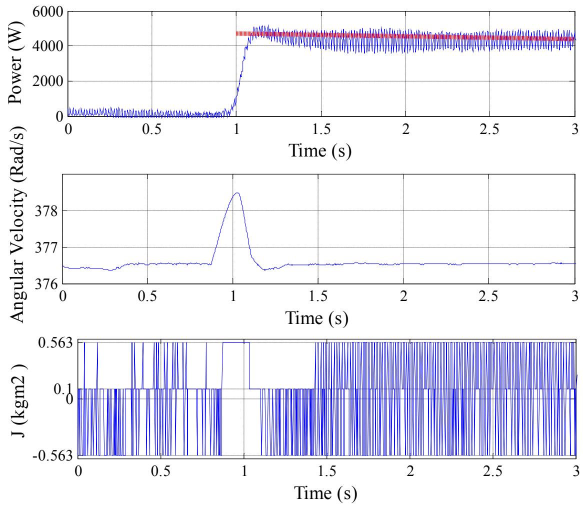
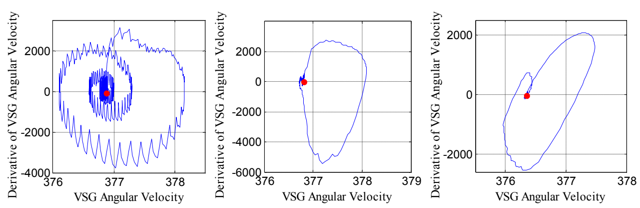


Figure 19. Output power, virtual angular velocity, and virtual moment of inertia of VSG with negative Adoptive Inertia scheme and D=17 pu.



(a) (b) (c)

Figure 20. Angular frequency-Acceleration curves of practical VSG with: (a) fixed moment of inertia, (b) Adoptive Inertia scheme, (c) Negative Inertia scheme.

VII. Conclusion

In this paper we proposed an adoptive structure for real-time selection of suitable value for the moment of inertia of a Virtual Synchronous Generator (VSG) considering its virtual angular velocity and acceleration/deceleration in each phase of oscillation. By selecting a big value for the moment of inertia during acceleration, the haste was reduced and on the other hand, during deceleration, a small value for inertia factor is adopted to increase the deceleration effect. We also introduced the negative moment of inertia that removed the oscillations effectively. Angular frequency-acceleration plot was used to observe the effect of new ideas in rapid oscillation rejection. Both methods dragged the system to the stable point by adopting the proper magnitude for acceleration/deceleration terms. Effectiveness of the methods in fast damping of frequency and power oscillations was verified by practical experiments.

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