POWER SYSTEM STABILIZATION USING SYNCHRONOUS GENERATOR WITH BANG–BANG CONTROL STRATEGY

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Abstract*: *Virtual synchronous generators (VSGs) present attractive technical advantages and contribute to enhanced system operation and reduced oscillation damping in dynamic systems. Traditional VSGs often lack an interworking during power oscillation.. The VSG design of our research incorporates the swing equation of a synchronous machine to express a virtual inertia property. Unlike a real synchronous machine, the parameters of the swing equation of the VSG can be controlled in real time to enhance the fast response of the virtual machine in tracking the steady-state frequency. Based on this concept, the VSG with alternating moment of inertia is elaborated in this project. The damping effect of the alternating inertia scheme is investigated by transient energy analysis. In addition, the performance of the proposed inertia control in stability of nearby machines in power system is addressed. The idea is supported by simulation, which indicates remarkable performance in the fast damping of oscillations.

Keywords: Grid connected inverter, smart grid, transient stability, virtual synchronous generator (VSG), voltage source inverter

INTRODUCTION

Conventional enormous synchronous generators (SGs) comprise rotating inertia due to their rotating parts. These generators are capable of injecting the kinetic potential energy preserved in their rotating parts to the power grid in the case of 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. The most challenging issue with the inverter-based units is to synchronize the inverter with the grid and then to keep it in step with the grid even when disturbances or changes happen [1]-[3]. A power system with a big portion of inverter based DGs is prone to instability due to the 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 the VSG concept, the power electronics interface of the DG unit is controlled in a way to exhibit a reaction similar to that of a synchronous machine to a change or disturbance. VSG control generates amplitude, frequency, and phase angle for its terminal voltage based on its power command. Therefore, as a corollary, it can contribute to the regulation of grid voltage and frequency. In addition, synchronizing units, such as phase-locked loops, can be removed [4]. The VSG concept and application were investigated in [5], [6]. The same concept under the title of Synchronverter is described in [7]. The VSG systems addressed in [8]-[10] are designed to connect an energy storage unit to the main grid. Reference [11] implements a linear and ideal model of a synchronous machine to produce current reference signals for the hysteresis controller of an inverter. In this Virtual Synchronous Machine (VISMA), the authors also added an algorithm to compensate small disturbances and improve the quality of the grid voltage. Reference [12] introduces a mechanism for voltage, frequency and active and reactive power flow control of the VSG. The effect of the VSG on the transient response of a microgrid is addressed in a more recent publication [13]. Our research group has introduced a new VSG design, enhanced the voltage sag ride-through capability of the VSG [14], evaluated it in various voltage sag conditions [15], and finally added reactive power control to have a constant voltage at VSG terminals [16]. The quantities of the VSG, such as its output frequency and power, oscillate after a change or disturbance similar to those of a synchronous machine. However, the transient condition tolerance of an inverter-based generating unit is much less than a real synchronous machine. Therefore, a VSG system may stop working redundantly due to oscillations with high amplitude after a change or disturbance. VSG control has an advantage in that its swing equation parameters can be adopted in real time to obtain a faster and more stable operation. This property of the VSG system is used to introduce the VSG with adoptive virtual inertia [17]. This scheme removes the oscillations and thereby, increases the reliability of the VSG unit against changes or disturbances. In this concept, the value of the virtual moment of inertia is changed based on the relative virtual angular velocity (the difference between virtual mechanical velocity generated by the VSG and grid angular frequency) and its rate of change. Therefore, we call it Alternating Inertia scheme. This paper goes into detail on the Alternating Inertia control with the objective of clarifying its damping and stabilizing effect. The damping effect is investigated by the transient energy analysis and its stabilizing performance on the nearby machines in the power system is investigated by simulations.

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 with the VSG concept. The model of synchronous generator that 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 generators is used as the heart of the VSG model:

$$P_{\text{in}} - P_{\text{out}} = J\omega_m \left(\frac{d\omega_m}{dt}\right) + D\Delta\omega \qquad (1)$$

where *Pin*, *Pout*, *J*, *ωm*, and *D* are the input power (as same as the prime mover power in a synchronous generator), the output power of the VSG, the moment of inertia of the virtual rotor, the virtual angular velocity of the virtual rotor, and the damping factor, respectively. $\Delta\omega$ is given by $\Delta\omega = \omega m - \omega grid$, *ωgrid* being the grid frequency or the reference frequency when the grid is not available. 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. Having the essential parameters, (1) can be solved by numerical integration. By solving this equation in each control cycle, the momentary *ωm* is calculated and by passing through an integrator, the virtual mechanical phase angle *θm* is produced. *Vref.* in Fig. 1 is the voltage reference that determines the voltage magnitude at the inverter terminal. Implementing a controller for *Vref.* results in a regulated voltage and reactive power at the VSG terminal.

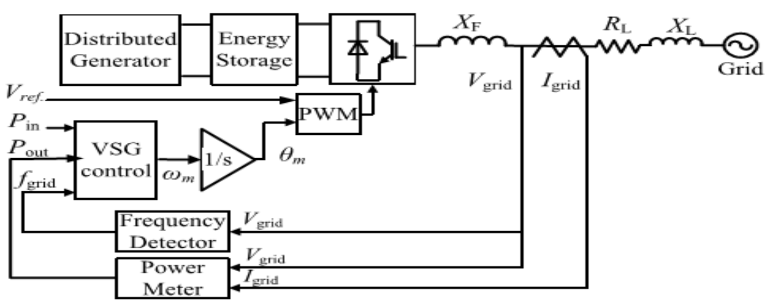

Fig. 1. Block diagram of VSG unit.

However, *Vref.* is set constant in the simulations and experiments because voltage control does not affect the idea of this paper. The phase angle and the voltage magnitude reference are used as the VSG output voltage angle and magnitude commands for generating PWM pulses for the inverter.

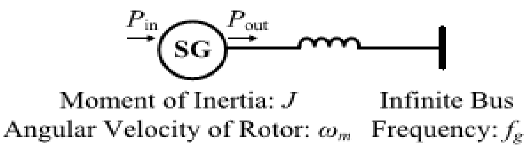

Fig. 2. Model of SG

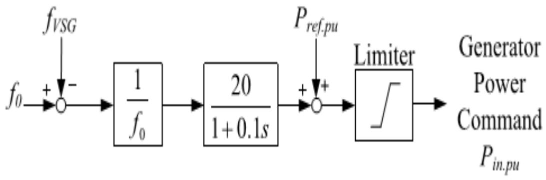

Fig. 3. Governor diagram

. The value of J together with D determines the time constant of the VSG unit. Selecting the proper value of them is a challenging issue without a routine. Mimicking a synchronous machine, J is given by J =2HSbase/ω 2 0 where H is the machine inertia constant, Sbase is the base power of the machine, and ω is the system frequency. The parameter H tells that for which period of time the machine is able to supply the nominal load based solely on the energy stored in the rotating mass. The higher H, the bigger the time constant, is resulting in a slower response but smaller frequency deviation after a change or disturbance. Although it depends on the machine size and power, for typical synchronous machines H varies between 2 and 10 s.

THE BANG-BANG CONTROL STRATEGY

In control theory, a bang-bang controller (on-off controller), also known as a Hysteresis controller, is a feedback controller that switches abruptly between two states. These controllers may be realized in terms of any element that provides hysteresis. They are often used to control a plant that accepts a binary input, for example a furnace that is either completely on or completely off. Most common residential thermostats are bang- bang controllers. The Heaviside step function in its discrete form is an example of bang-bang controller signal..

Segment	$\Delta\omega$	$d\omega_m/dt$	Mode	Alternating J
a→b	$\Delta\omega > 0$	$d\omega_m/dt > 0$	Accelerating	Big value of J
b→c	$\Delta\omega > 0$	$d\omega_m/dt < 0$	Decelerating	Small value of J
c→b	$\Delta\omega < 0$	$d\omega_m/dt < 0$	Accelerating	Big value of J
b→a	$\Delta\omega < 0$	$d\omega_m/dt > 0$	Decelerating	Small value of J

TABLE I: MACHINE MODES DURING OSCILLATION

The bang–bang control strategy is summarized in Table 1. During each cycle of oscillations, the value of J is switched four times. Each switching happens at the points that the sign of either ω or dωm/dt varies. Before the disturbance, the VSG is operating with the normal value of J. When the disturbance happens, the transition from a to b starts with ω >0 and dωm/dt >0. In this condition, the Jbig is adopted. At the end of the first quarter-cycle, that is point b, the sign of dωm/dt changes. It means that the small value for J is added at this point. At point c, the sign of ω changes and J retrieves it big value. It will be the end of the first half-cycle. During the second half- cycle, the value of J is switched to the Jsmall at point b, and again at the end of one cycle at point a, Jbig is adopted. This procedure is repeated for each cycle of oscillation until the transients are suppressed and ω equals zero at the new equilibrium point, that is, point b. A threshold for ω can be applied to avoid the chattering of J during normal operation. However, this threshold is set to zero in this paper.

POWER ANGLE CURVE

Power angle is the angle between voltage and current, so theoretically it can be defined wherever voltage and current exists. Power angle in transmission lines usually depends on variety of factors such as loads, network parameters, line impedance, etc. also called power factor

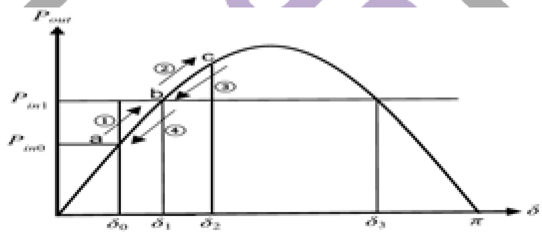

Fig. 4. Power-angle curve of a typical synchronous machine

After a change in system, for example, a change in prime mover power from *Pin*0 to *Pin*1, the operating point moves along the power curve, from point "a" to "c" and then from "c" to "a." The machine condition during each phase of an oscillation cycle is summarized in Table I. One cycle of the oscillation consists of four segments. During each segment, the sign of the *dωm/dt.* together with the sign of the relative angular velocity $\Delta\omega$ defines the acceleration or deceleration. For example, in segment 3 of Fig. 4, during transition from points "c" to "b," both *dωm/dt* and $\Delta\omega$ are negative and act in the same direction; therefore, it is an acceleration period. Whereas, when they have opposite signs like segment, it is a deceleration period. The objective is to damp frequency and power oscillation quickly by controlling the acceleration and deceleration term. The derivative of angular velocity, dωm/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, one can select a large value of J during acceleration phases (a to b and c to b) to reduce the acceleration and a small value of J during deceleration phases (b to c and b to a) to boost the deceleration. The big moment of inertia Jbig and the small one Jsmall can be chosen within a wide range depending on the rated power so that the difference between Jbig and Jsmall determines the damped power in each half-cycle of oscillation by alternating inertia. The value of Jbig can be equal to the normal value ofJ. However, applying a very larger value than the normal J will result in a smaller frequency excursion at the first quarter-cycle but a sluggish response. The value of Jsmall determines the transient of the second quarter-cycle of oscillation. A very small value of Jsmall (<0.1 kgm 2)will result in a satisfactory response. Damping factor is an important term that defines the VSG response. An inappropriate value of damping factor may result in a high magnitude of oscillation or a sluggish response. Besides, a proper value of the damping factor in a specific working point may not end up with an acceptable response in other conditions. The Alternating Inertia concept allows the VSG system to exert a suitable time constant in each phase of oscillation; therefore, the importance of the damping factor in the behavior of the VSG system is reduced considerably. To assess this matter, the damping factor was changed to zero, and the same scenario was applied. Fig. 7 shows the output power and angular velocity of the VSG in this condition. It is observed that the system operates stably, and the oscillations are eliminated by the Alternating Inertia idea even with a zero value for the damping factor.

GRID STABILITY ENHANCEMENT BY ALTERNATING INERTIA VSG IN PRALLEL WITH OTHER MACHINES In micro grid applications, an inverter-based DG works in parallel with other DGs that may include synchronous machines. Consider the island micro grid of Fig 5. the VSG block has the control scheme shown with the output filter inductance of 9.7%.the objective of this part is to access the effect of alternating inertia scheme of the VSG on the stability of the parallel SG. To clarify the effectiveness of the idea, the capacity of the VSG unit was assumed o be 20% of the SG that is insignificant. A symmetrical fault happened at the load point at t=0.2 s and lasted for 0.3 s. In this condition, the system comprising the VSG with the fixed value of moment of inertia J=8.445kgm2 was not able to recover from the fault as shown in fig.. The same scenario was applied to the system with alternating inertia of Jbig=8.445 and Jsmall=0.084kgm2.the waveforms of power, SG rotor angle, and angular frequency are shown in fig.. As it is observed, the alternating inertia scheme improved the stability of the adjacent machine by the extra damping effect imposed on the transient energy directly.

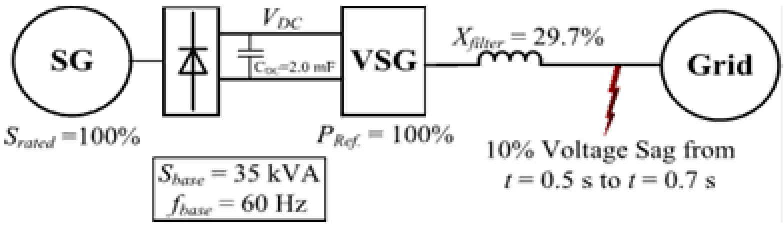

Fig-5 VSG unit in parallel with the SG in micro grid.

Therefore, the critical transient energy and thereby transient stability area will always have its maximum value, that is, 2b – πPm. Other corollaries regarding the transient stability area and the critical clearance time that can be inferred from the alternating inertia concept are forgone because of prolixity.

VSG AS AN INTERFACE BETWEEN THE SG AND GRID:

Another configuration is shown in fig.6. an SG is connected to the grid/micro grid through a VSG unit. The prime mover of the SG can be a gas or diesel engine, and an inverter interface is required to correct the generated power to be
will effect the stable operation of the SG. To assess the effect of the alternating inertia control on the stability of such systems, a symmetrical three-phase voltage sag with 10% remained voltage magnitude and the duration of 0.2 s was applied from grid side, and the performance of the system was monitored. The reference power and damping factor of the VSG were 1 and 17 pu, respectively and a fixed inertia factor to 5kgm2 was applied.

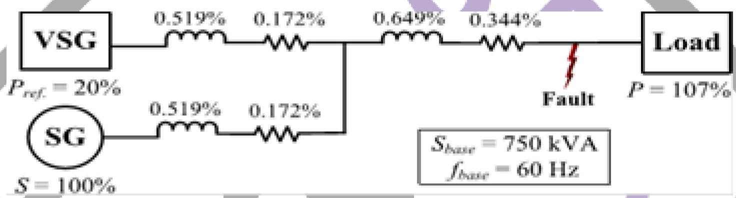

Fig.6 SG connected to the grid via VSG unit

Rotor angle and DC-link voltage were affected by the grid voltage sag considerably. The high-peak transient of DC-link voltage is mainly because of the oscillation of the VSG output power. The same scenario was applied to the system with the alternating inertia control with Jbig = 5 and Jsmall = 0.05kgm2. To discriminate the stabilizing effect in the system, the damping factor D was not zero. It should be mentioned that the system with fixed inertia and a zero damping factor was unable to recover from much milder faults.

SIMULATION CIRCUITS AND RESULTS

VGS WITH FIXED MOMENT OF INERTIA AND DAMPING FACTOR:

In these case simulation results were performed on the system model of Fig.1 with the parameters of Pbase = 50 KW, f base = 60 Hz, RL = 12.5%, XL = 33.0%,XF = 42.4% and D = 17 pu. The system was subjected to increase in the VSG power reference in two steps of 70% and 30% at t = 2 s and t = 8 s, respectively. Fig 8 shows the output power and frequency of the VSG with the fixed value of J = 6 kgm2.

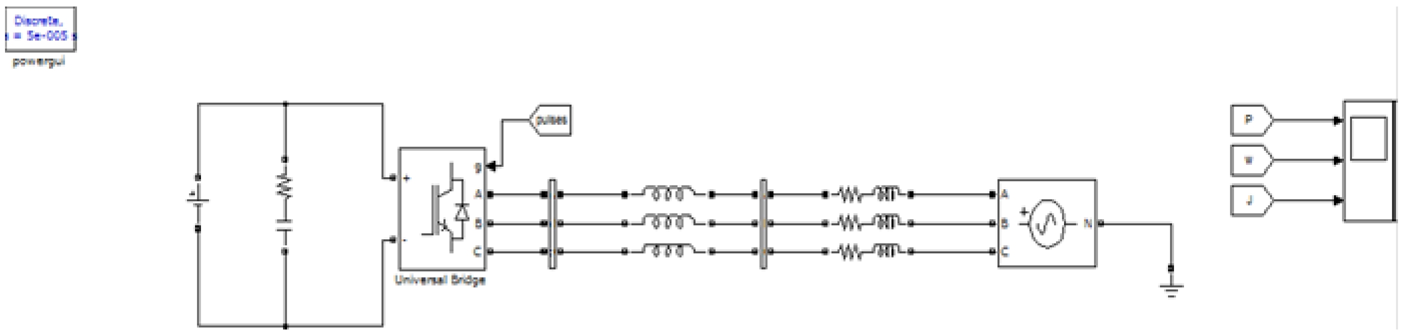

Fig 7 Matlab simulation circuit

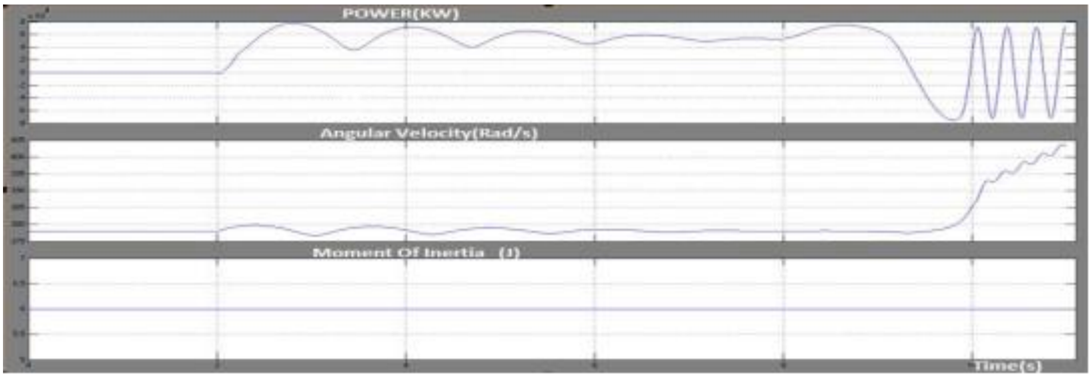

Fig 8 Output power, Virtual angular velocity and virtual moment of inertia of VSG with fixed J = 6 kgm2 and D = 17 pu.

The above fig 8 shows the change in output power, virtual angular velocity with respect to time when VSG power is increased in two steps by fixing the constant value of moment of inertia and damping factor as 17 pu.

At first step of power increase at t = 2 s oscillations take place and continues and at t = 8 s we further increase VSG power then amplitude of oscillations increase rapidly.

VSG WITH ALTERNATING MOMENT OF INERTIA AND DAMPING FACTOR:

The VSG with fixed value of J cannot stabilize the frequency at the second step of power increase. Then, the control scheme of the VSG was changed to alternating inertia control, and the same previous scenario was applied. As it is observed in fig 10, alternating inertia settles the values of J out of Jbig = 6 kgm2 and Jsmall = 1 kgm2. This process does not only stabilize the system, but also suppresses the frequency and power oscillations effectively.

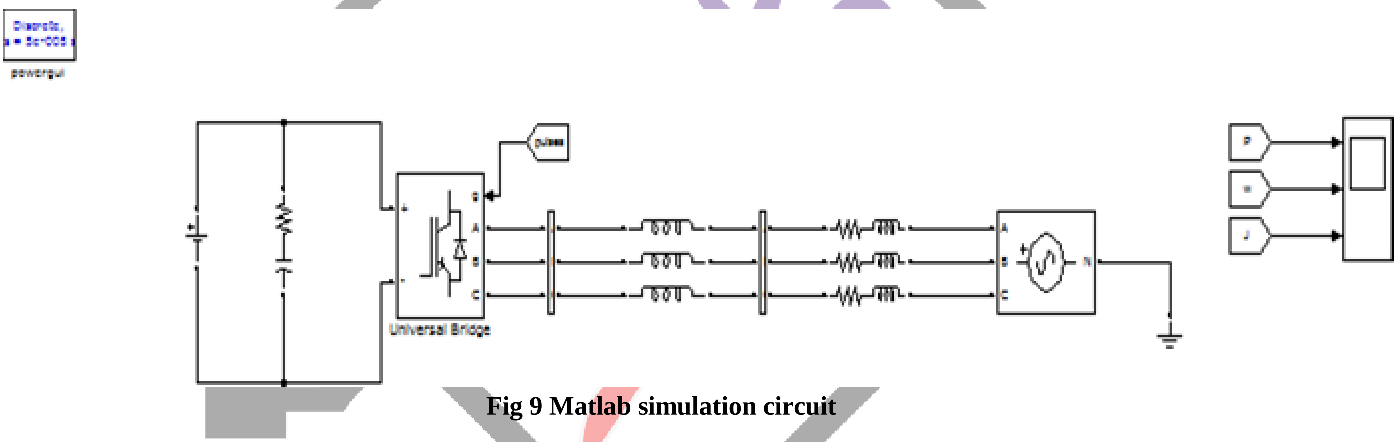

Fig 9 Matlab simulation circuit

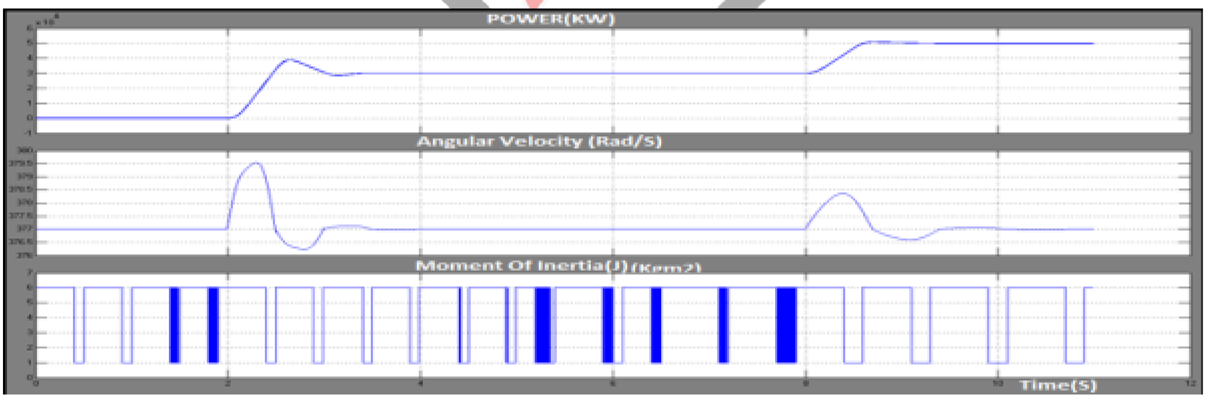

Fig10 Output power, Virtual angular velocity and virtual moment of inertia of VSG with alternating J : 1 and 6 kgm2 and D = 17 pu.

The above fig shows the change in output power, virtual angular velocity with respect to time when VSG power is increased in two steps by alternating the value of virtual moment of inertia and damping factor as 17 pu. At first step of power increase at t = 2 s slight oscillation take place and gets stable until at t = 8 s we further increase VSG power then oscillation take place with lesser amplitude after that stable state is attained.

VSG IN PARALLEL TO SG WITH FIXED MOMENT OF INERTIA AND DAMPING FACTOR

The VSG block has the control scheme shown in Fig with the output filter inductance of 9.7%. The objective of this part is to assess the effect of the alternating inertia scheme of the VSG on the stability of the parallel SG. To clarify the effectiveness of the idea, the capacity of the VSG unit was assumed to be 20% of the SG that is insignificant. A symmetrical fault happened at the load point at t = 0.2 s and lasted for 0.3 s

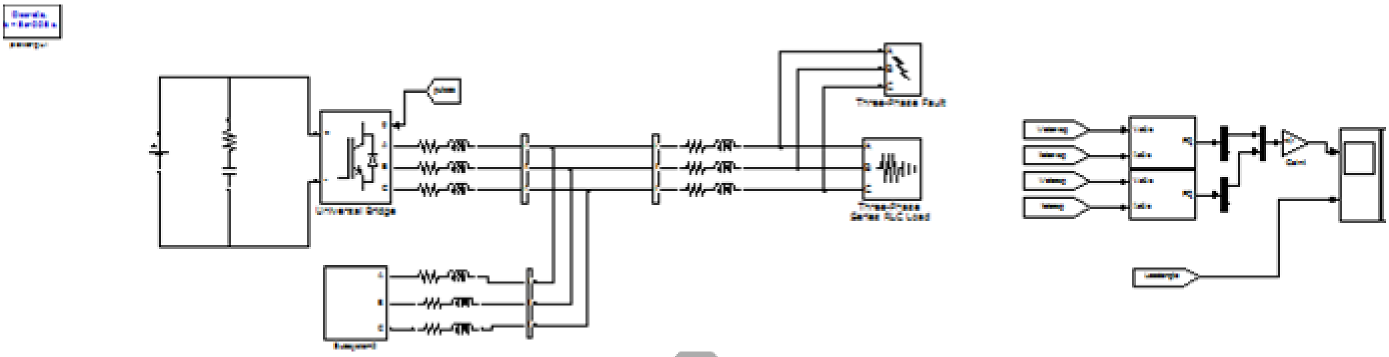

Fig11 Matlab simulation circuit

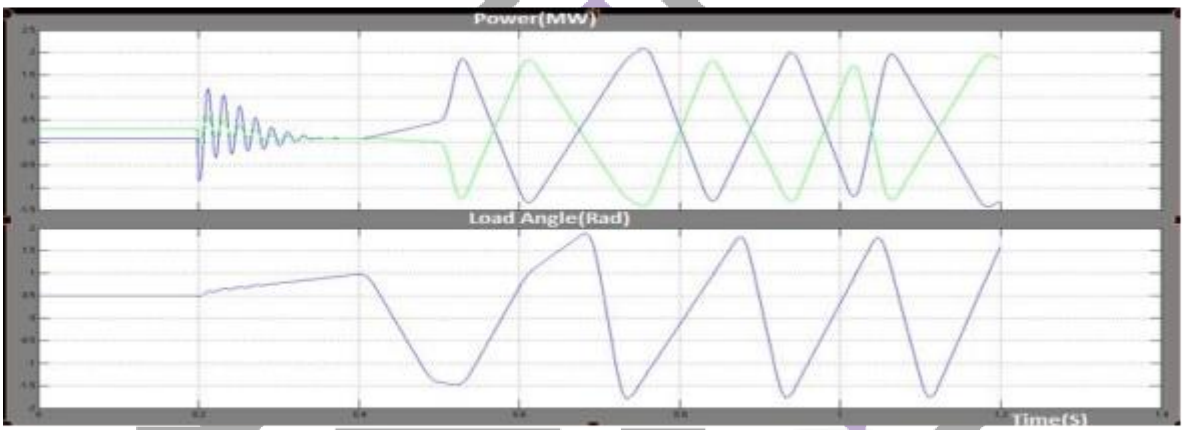

Fig 12 VSG and SG powers and SG rotor angle waveforms of the system with fixed moment of inertia and D = 17 pu.

The above fig shows a symmetrical fault happened at the load point at t = 0.2 s and lasted for t = 0.3 s and with fixed value of virtual moment of inertia J = 8.445 kgm2 , the power in the VSG and SG units oscillate according to load angle with large amplitudes and was not able to recover from the fault.

VSG IN SERIES TO SG WITH FIXED MOMENT OF INERTIA AND DAMPING FACTOR

If the VSG unit is not robust enough, the disturbances from grid/microgrid will affect the stable operation of the SG. To assess the effect of the alternating inertia control on the stability of such systems, a symmetrical three-phase voltage sag with 10% remained voltage magnitude and the duration of 0.2 s was applied from grid side, and the performance of the system was monitored. The reference power and damping factor of the VSG were 1 and 17 pu, respectively, and a fixed inertia factor equal to 5 kgm2 was applied.

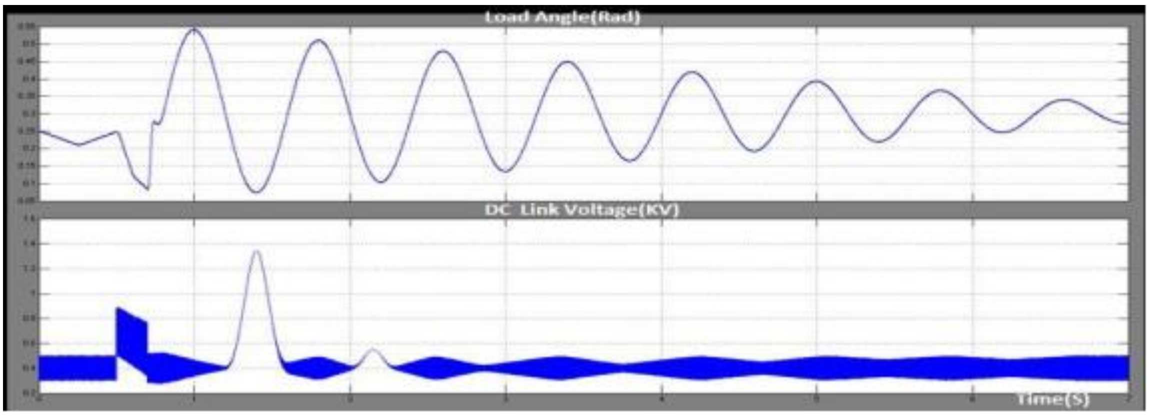

Fig 13 SG load angle and dc-link voltage of the system

VSG IN SERIES TO SG WITH ALTERNATING MOMENT OF INERTIA AND ZERO DAMPING FACTOR

The high-peak transient of dc-link voltage is mainly because of the oscillation of the VSG output power. The same previous scenario was applied to the system with alternating inertia as the only stabilizing effect in the system, the damping factor D was set zero. It should be mentioned that the system with fixed inertia and a zero damping factor was unable to recover from much milder faults. As it is observed in fig 4.14, the oscillation was suppressed by the alternating inertia scheme, and the severe transient of dc-link voltage was also eliminated. The above fig shows the SG rotor angle and dc-link voltage were affected by the symmetrical three-phase voltage sag with 10% voltage magnitude and the duration of 0.2 s was applied from grid side.

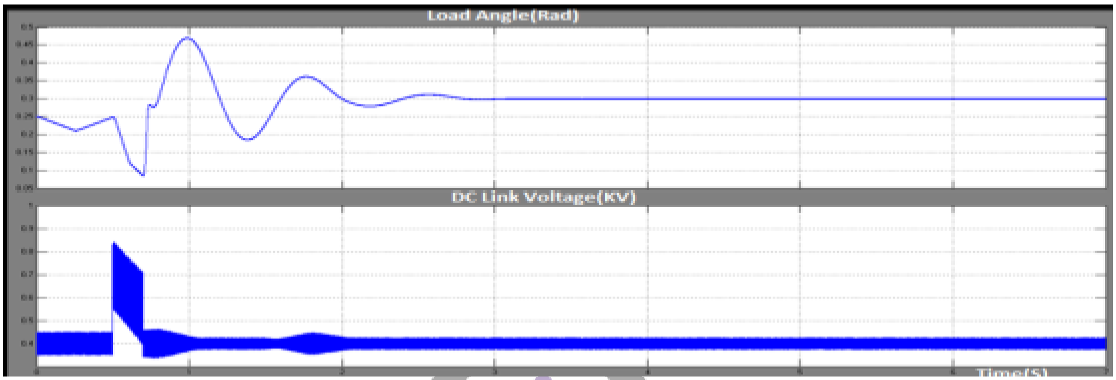

Fig 14 SG load angle and dc-link voltage of the system of fig 4.9 containing VSG with alternating inertia

The above fig 14 shows that after the application of a symmetrical threephase voltage of duration 0.2 s due to the alternating inertia with Jbig = 5 kgm2 and Jsmall = 0.05 kgm2 and 0 damping factor the oscillations was suppressed transient dclink voltage was also eliminated and system get stabilized.

CONCLUSION

In this paper, the alternating inertia structure was elaborated. The alternating inertia scheme adopts the suitable value of the moment of inertia of the 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 mitigated, and on the other hand, during deceleration, a small value for inertia factor was adopted to increase the deceleration effect. The system transient energy analysis was used to assess the stabilizing effect of alternating inertia control. It was clarified by the energy analysis that the system transient energy is reduced promptly by the reduction in the value of the moment of inertia. Actually, in the case of a real synchronous machine, this transient energy is dissipated by damping terms during oscillations, whereas the alternating inertia control eliminates the transient energy directly and prevents its flow from dc storage and dissipation. Compared to normal damping factor D, the damping exerted by alternating inertia is considerably more effective and has identical results in any conditions. In addition, the transient energy can be reduced to zero at the end of the first quarter-cycle by alternating inertia control. Therefore, any transients can be eliminated before appearing. The idea does not only stabilize the VSG unit, but also enhances the stability of other machines in the system. Two configurations were assessed by simulation and the stabilizing effect of alternating inertia on the adjacent machines was illustrated. The proposed scheme was realized on the simulation and the results affirmed that outstanding stabilizing effect of alternating inertia.

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