IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)
An International Open Access, Peer-reviewed, Refereed Journal

TRANSIENT ANALYSIS OF GRID WITH PARALLEL SYNCHRONOUS GENERATOR AND VIRTUAL SYNCHRONOUS GENERATOR

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Abstract: Implementation of distributed generating (DG) units in power systems is increasing rapidly, the need for the grid challenges the control and coordination of these energy resources. Especially in a grid with virtual synchronous generator (VSG)-controlled converters and conventional synchronous generators (SG). The inertia difference between the VSG and SG results in a poor transient performance when the transient occurring in the system. This paper analyzed the transient performance of the grid with parallel VSG and SG-connected systems. More importantly, a novel pre-synchronization control method is proposed to eliminate the phase jump when the transient occurring in the system. The VSG inertia and its damping can be designed considering the capacity ratio of VSG and SG units. In addition, with the power angle stability analysis, an active power provision strategy is introduced to suppress the transient power oscillation due to the inertia difference. Finally, the feasibility of the proposed methods is verified by simulations on a grid consisting of parallel VSG and SG units in MATLAB / SIMULINK.

***Index Terms* - Distributed generator (DG), virtual synchronous generator (VSG), synchronous generator (SG), power oscillation, transient performance, pre-synchronization.**

I. INTRODUCTION

Nowadays, the distribution of generating units such as PV, wind, etc. is increasing rapidly. The inverter is used to connect DG with the grid. 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 in the system [1]. A power system with a significant proportion of inverter-based DGs is prone to instability due to a lack of adequate balancing energy injection at the appropriate time interval. The solution can be found in the inverter-based DGs' control scheme. By controlling the switching pattern of an inverter, then it can emulate the behavior of a real synchronous machine. This control scheme is called Virtual Synchronous Generator (VSG). 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 changes and disturbances in the system [2]. VSG provides virtual inertia for the system, which improves the stability of the entire power system. Small schedulable SG units are usually used as the main power supply in a remote microgrid where the main grid is not available, and renewable-based DG units are used as the secondary supply.

The entire system dynamics vary significantly due to the inherent difference in inertia and capacity between the SG and DG. Changes in power supply or load, as well as faults, are common in such a grid. The dynamics of the entire system vary significantly. As a result, it focuses on the control and coordination of multiple generators [3]. To avoid frequency and power oscillations, a virtual impedance concept and a VSG model with optimized inertia and damping were implemented to address the parallel operation and stability issues of DGs during transient operation [4]-[6]. However, focus on the literature operation of parallel VSG and SG. When SGs are cut in, the system stability may be challenged due to the difference in the moment of inertia and prime mover shaft inertia for the VSG and SG units. In this case, the VSG-controlled units respond with fast dynamics to system disturbances, e.g., energy sources cutting in/out and load changes, fault. Which may induce severe transient power oscillations. Consequently, the oscillations affect the conventional SG rotor speed and lower the capacity of power allocations among units. The system may eventually go into instability. If the parallel operation pre-synchronization algorithm is not properly designed, poor transients may occur during the closure of circuit breakers [7]. In the prior-art research, the pre-synchronization has been relatively mature, while phase errors should be further alleviated. For instance, a self-synchronization method of the grid connected inverter based on the virtual impedance was proposed in [8]. The paper provided ideas for the VSG pre-synchronization but the LC filter impact was not considered. In turn, voltage phase deviations appear. In [9], a VSG pre-synchronization unit based on virtual power and secondary control was proposed, where the frequency and voltage amplitude were realized by a secondary controller. However, in this case, phase synchronization must be performed. After the second control and the regulation, the signal is irregular. In [10], [11], the phase difference was added to the frequency control loop through a proportional-integral (PI) regulator to improve the phase synchronization. However, the periodic phase jump may lead to slow dynamics or even synchronization failures. For better performance, this paper proposed a novel synchronization method to eliminate phase error that occurred during transients.

The rest of this paper is organized as follows. Section II gives details about the basic controls in the system. Section III deals with the pre-synchronization method for parallel SG and VSG-connected systems. Section IV gives the design of the parameters of the system. Section V deals with simulations and discussions. Section VI gives the conclusion of the paper.

II. BASIC CONTROL

2.1 Control of VSG technology

The general control block diagram of the VSG is shown in Fig.1, where the active and reactive power loops emulate the rotor motion with the prime mover and the excitation controller of a conventional SG, respectively. Thus, the VSG can provide the entire modulation signal for the system [12]. Additionally, the output current of the inverter is added to the virtual impedance module and the three-phase synthetic voltage of the VSG minus the virtual voltage drop e_{vabc}[13], as shown in Fig.2. Then, the output voltage e_{mabc} is modulated by the voltage and current double-loop control, and finally, the driving signals to the power converter can be obtained through the pulse width modulation (PWM).

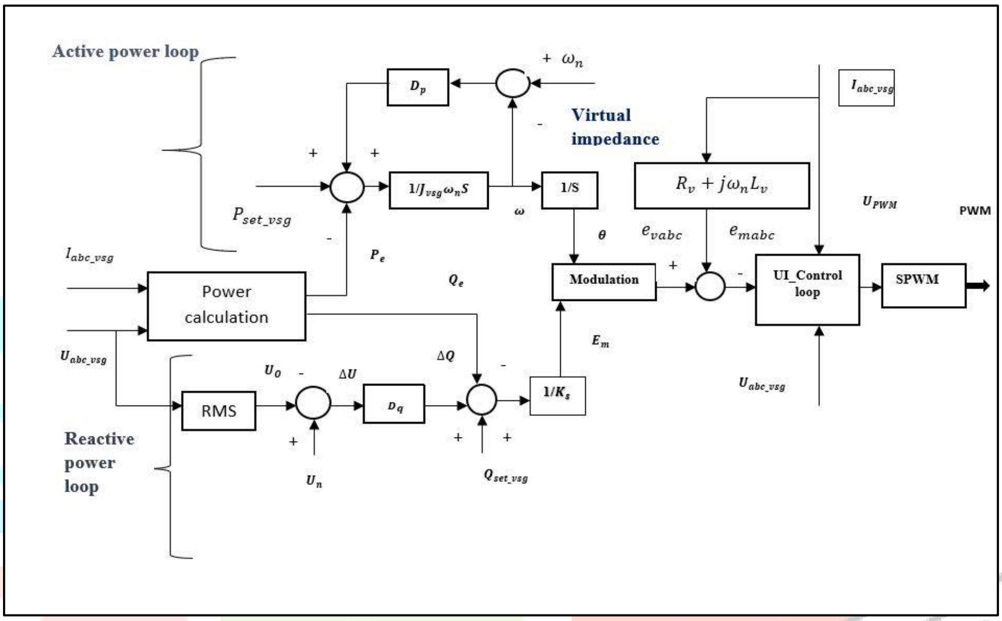


Fig.1.Controller diagram of VSG.

According to the system shown in Fig.2, the VSG system can be described as [15].

$$\begin{cases} Pset\_vsg + DP\,(\omega n - \omega)\text{-}Pe = J vsg\omega n\ d\omega\,/dt \\ Qset\_vsg + Dq\,(Un - Uo\,)\text{-}Qe = K\ dEm/\ dt \\ \delta = \int(\omega - \omega n\,)dt \end{cases} \quad (1)$$

where $Pset\_vsg$ and $Qset\_vsg$ are the given active and reactive power, DP and Dq are the coefficients of the active power frequency (P-ω) and reactive power-voltage (Q-V) droop relationships, Pe and Qe are the electromagnetic power, $Jvsg$ and K are the virtual moments of inertia and voltage coefficient, respectively, ωn and ω are the rated and actual rotor angular frequency, Un and Uo are the effective values of the rated and actual voltage amplitude, Em is the internal potential amplitude of the VSG, and δ is the power angle.

2.2 Control of SG

An SG control system, which consists of a governor (GOV) and an automatic voltage regulator (AVR). The GOV adjusts the prime mover shaft power Pm_sg according to the SG output angular frequency ωsg and the rated angular frequency ωn.AVR is used to control the voltage.

2.3 Grid With Parallel VSG and SG Units

PV systems play an important role as a sustainable energy system of the future. They are one of the key technologies to generate decentralized electricity for private households around the world, The PV based distributing generator acts as the virtual synchronous generator. This paper proposes parallel operation of both VSG and SG connected systems. The Block diagram is shown in fig.1. To study the coordination of different generation resources in the grid, an SG driven by a prime motor is selected as the main power supply. And VSG is acting as a secondary supply. When the breaker is open, the SG is operating, and solely supplying the loads. In this case, the VSG system is discussed and disabled. In contrast, when the breaker is closed, the SG and the VSG should share the loading power properly to maintain the entire system stability. However, the grid may go into instabilities in the case of transient eventualities (e.g., sudden load/power source changes that may happen in renewable energy-based systems, fault).

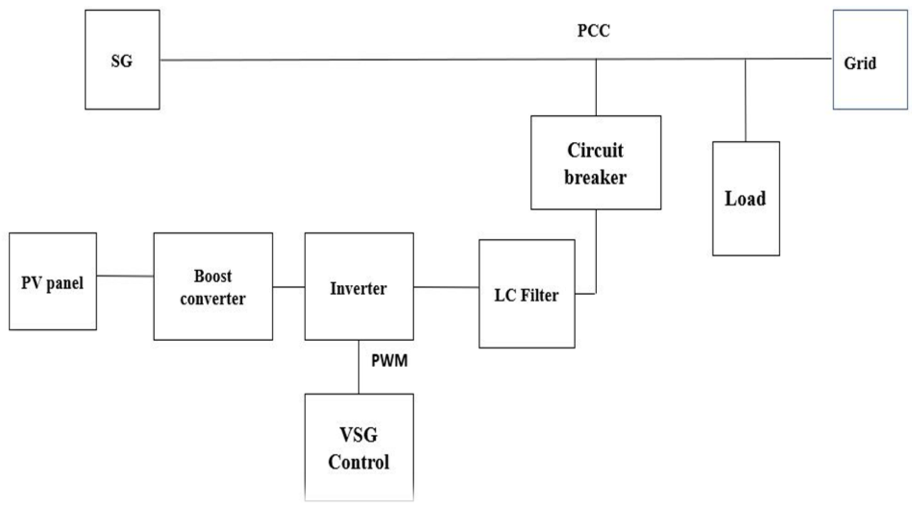


Fig. 2 Block diagram for parallel SG and VSG system.

III. PRE-SYNCHRONIZATION

To reduce the electromagnetic and mechanical impact and ensure the smooth cutting-in of the VSG system in a grid governed by an SG, the instantaneous output voltage of the VSG and SG should be consistent and have the same tendency, including amplitude, frequency, and phase before transient. Thus, the pre-synchronization is of high concern to ensure stable operation, especially in the system with weak overloading capacity. The VSG pre-synchronization is like the synchronization in grid connected applications (typically, a phase-locked loop is adopted for synchronization).

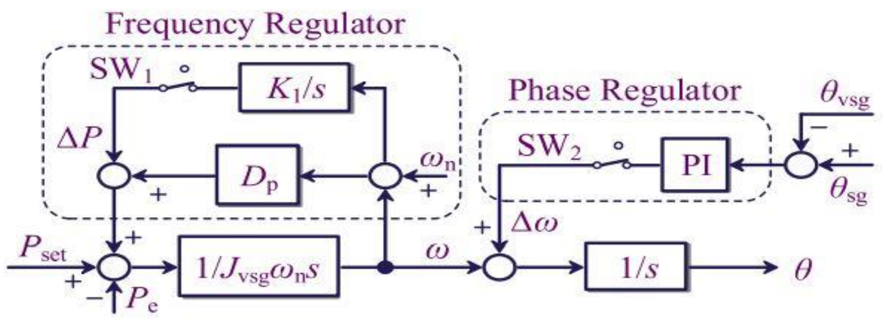


Fig. 3. Traditional VSG pre-synchronization algorithm

Fig.3.shows the Traditional VSG pre-synchronization algorithm, An integral regulator (i.e., KI/s) is applied to adjust the frequency difference, so does the voltage amplitude difference, which is relatively easy to implement. On the other hand, for the phase difference, a PI regulator is typically adopted to control the VSG output frequency, until both frequency and phase differences meet the closing standards.

However, in the case of transients, significant phase jumps may appear, which inevitably affects the pre-synchronization performance, and, in turn, the entire system stability. A novel pre-synchronization method is proposed to eliminate the impact of the phase angle jump. Considering the characteristics of sine and cosine functions, their values remain the same when the phase jumps between $\Delta\theta$ and $\Delta\theta - 2\pi$. Instead of the PI regulator using a constructed function, the frequency modulation signal can be obtained as:

$$\Delta\omega = \begin{cases} kc\,[1 - cos(\theta sg - \theta vsg)]\,, 0< \theta sg - \theta vsg \leq \pi \\ kc\,[E(\theta sg - \theta vsg) - 1]\,, -\pi < \theta sg - \theta vsg < \pi \\ kc\,[1 - cos(\theta sg - \theta vsg - 2\pi)]\,, 2\pi<\theta_{sg} - \theta_{vsg} \leq \\ k_c\left[cos\left(\theta_{sg} - \theta_{vsg} + 2\pi\right) - 1\right], \pi <\theta_{sg} - \theta_{vsg} \leq 2\pi \end{cases} \tag{2}$$

Where k_c is modulation index, and the ranges of [–2π, –π] and [π, 2π] rad denote the phase difference in the of phase jumps, $\theta_{sg} - \theta_{vsg}$ is the phase difference between SG and VSG and E is rated voltage. With the proposed parallel pre-synchronization method in (2), the output voltage amplitude, frequency, and phase of the SG and VSG units can be synchronized to avoid closing impact caused by the difference in the output voltage vector.

IV. MATHEMATICAL MODELING

This section deals with design the parameters for the grid with parallel SG and VSG connected systems. VSG design includes the design of PV panel, boost converter, inverter, and LC filter. For designing parallel SG and VSG connected systems a term called capacity ratio. The capacity ratio is defined as the ratio of the capacity of VSG to the capacity of SG.

$$\text{Capacity ratio (n)} = \frac{S_{vsg}}{S_{sg}} \tag{3}$$

For analyzing the transient performance considering the capacity ratio=1.
The moment of inertia can be given as:

$$J_{sg} = \frac{2HS}{\omega_n^2} \tag{4}$$

where H is the inertia time constant, representing the transient period (i.e., the time for the system returning to a steady-state), and S is the system capacity. With the flexibility of the VSG virtual inertia, the same H should be satisfied to ensure the rotor inertia matching, which is given as,s

$$\frac{J_{sg}}{S_{sg}} = \frac{J_{vsg}}{S_{vsg}} \tag{5}$$

Table I shows the parameters of parallel SG and VSG-connected systems.

TABLE 4.1

LIST OF COMPONENTS

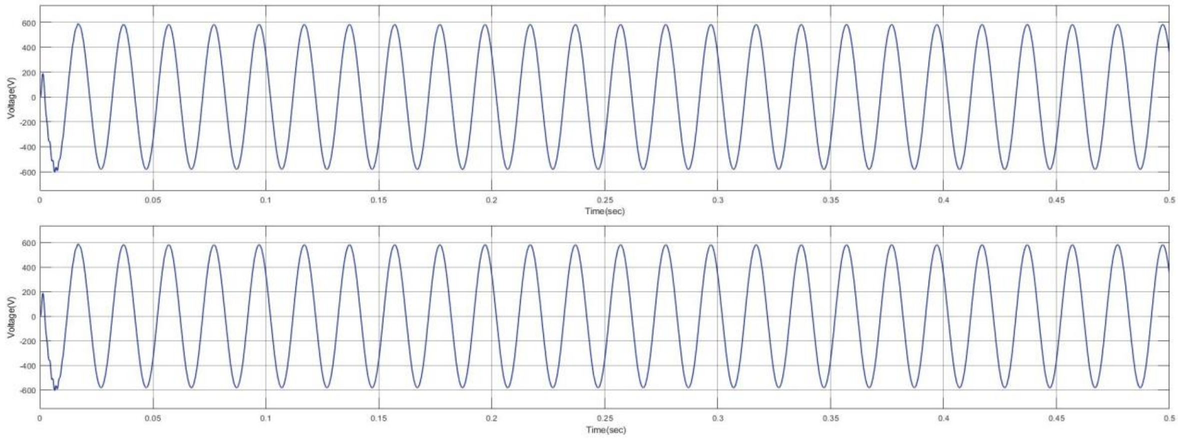
Sl. No	Name of the Component	Specification
1	Moment of inertia, Virtual inertia J_{sg}, J_{vsg}	0.0923kg/m2
2	System capacity of SG and VSG	8000VA
3	Stator impedance	1.62,4.5mH
4	Rated electromotive force E_n	415V
5	Rated rotor speed	1500rpm
6	Rated voltage amplitude	415V
7	Rated angular frequency	314.1rad/sec
8	P-f, Q-V droop coefficient D_P, D_q	900,320
9	VSG voltage coefficient K	6.5
10	Virtual impedance (R_v, L_v)	0.08ohm,8mH
11	Coefficient of frequency regulator K_I	3000
12	Pre-synchronization modulation index k_c	30
13	PV input voltage	320V
14	DC link voltage	700V
15	VSG switching frequency	10kHz
16	LC filter	9.68mH, 20.9μF

V. SIMULATION RESULTS AND DISCUSSIONS

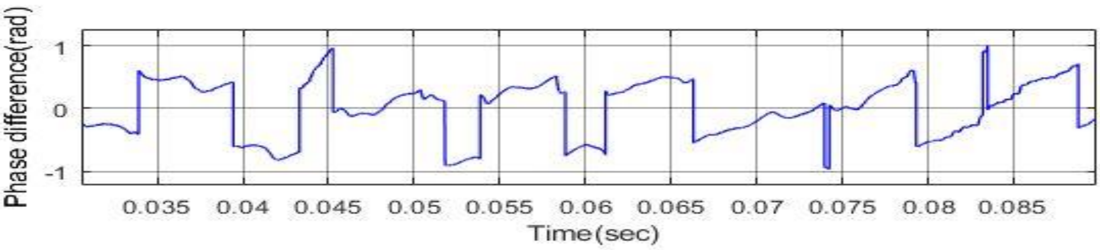
To verify the proposed pre-synchronization method and the active power setting mode, simulations are carried out on a grid with SG and 4 VSG units in MATLAB/Simulink. Various cases are considered and the parameters of the system are shown in Table 4.1.

5.1 Parallel Pre-Synchronization

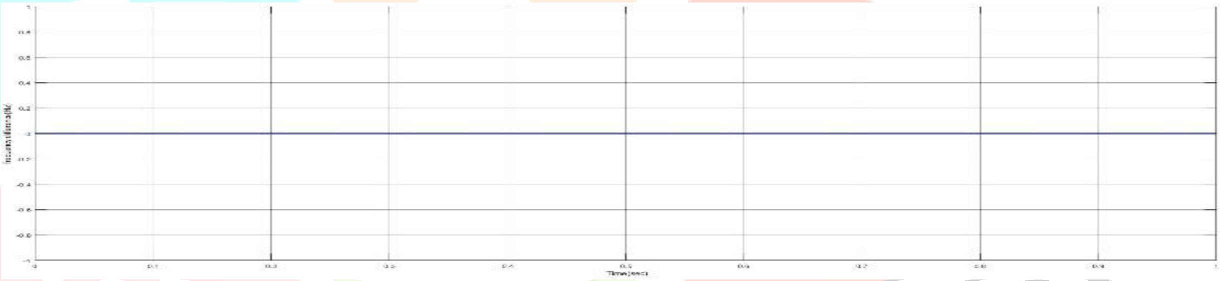
Here it consists of a frequency regulator and a phase regulator. The integral regulator is used as a frequency regulator, whereas a phase regulator depending upon the phase difference between the SG and VSG frequency modulation signal is formed by using if-else conditions. The signal theta from the synchronization is given the external signal for the circuit breaker.



(a)



(b)



(c)

Fig.5 Simulation results (a) Synchronization process of single-phase voltage waveform, (b) Phase difference, (c) Frequency difference

Fig.5. (a) shows the voltage waveform after synchronization. From this figure it is the clear voltage of both SG and VSG are the same (ie,415V). Fig.5. (b) shows the phase difference waveform. The maximum phase difference is about 0.6rad. Fig.5 (c) shows the frequency difference waveform. From the simulation, a zero-frequency difference is obtained.

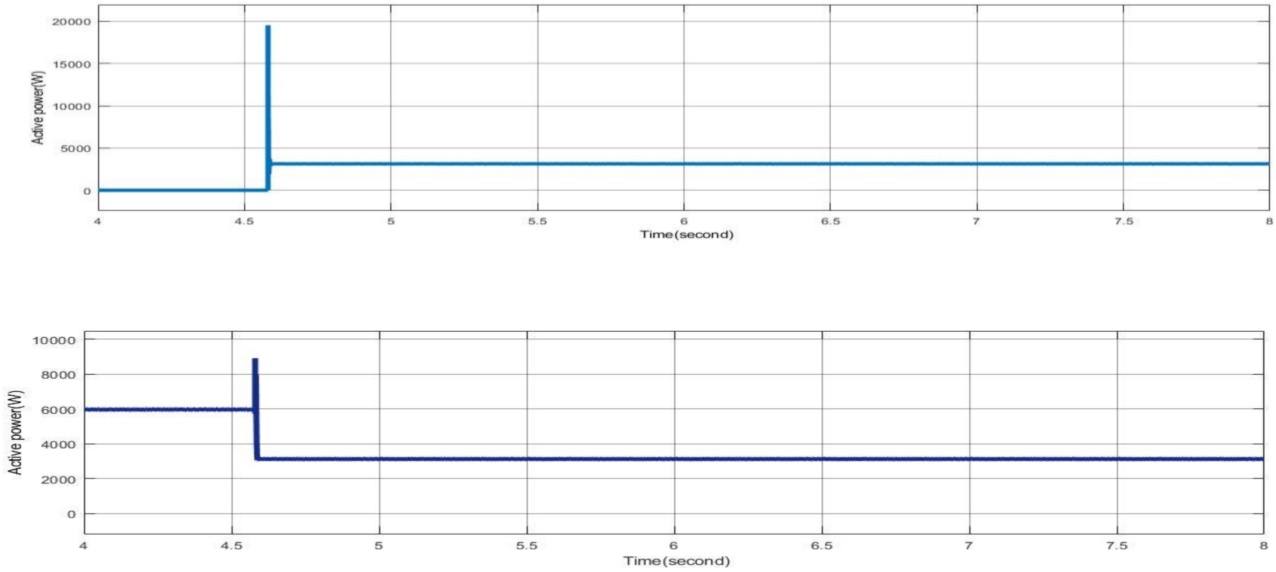
5.2 Performance Under Closing Transition

In this simulation, the capacity ratio of the VSG and SG is set as 1:1 and taking n = 1. In this case, the VSG is cut in at t = 4.58sec from Fig.6. The transient closing impact caused by the poor parallel pre-synchronization is eliminated. Fig.7 shows the simulation results of a parallel SG and VSG connected system under closing transition. Before t=4.58s active power of VSG zero,.6kW resistive load is supplied by SG. At t=4.58s, VSG is cut in suddenly. After t=4.58s, half of the power (ie.3kW) is shared by VSG and another half is shared by SG is shown in Fig.7 (a). Fig 7 (b) shows the load angle curve of SG. Before t=4.58s, the load angle was 20 deg. During t=4.58s, the load angle is increasing. During that instant load, the system is unstable. After the closing transition, the load angle is 20 deg. That system is stable. Fig 7 (b) shows the rotor speed of SG. Before t=4.58s, rotor speed was 1500rpm. During t=4.58s speed is decreased from 1500rpm after the closing transition speed is 1500rpm.

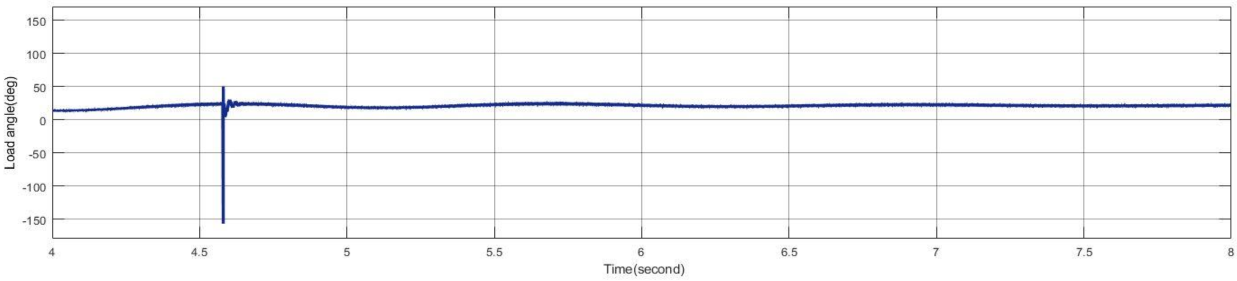
5.3 Performance Under Loading Transition

From this case, an extra 6kW resistive load is added at t =6s from Fig.6.The transient loading impact caused by the poor parallel pre-synchronization is eliminated. Fig.8 shows the simulation results of a parallel SG and VSG connected system under loading transition. Before t=6s active power of VSG was 3kW and active power was supplied by SG=3kW. At t=6s, an extra 6kW resistive load is added to the system. So, the total power of the system is now 12kW.After t=6s, half of the power (ie.6kW) is shared by VSG and another half is shared by SG is shown in Fig.8 (a). Fig 8 (b) shows the load angle curve of SG. Before t=6s, the load angle is

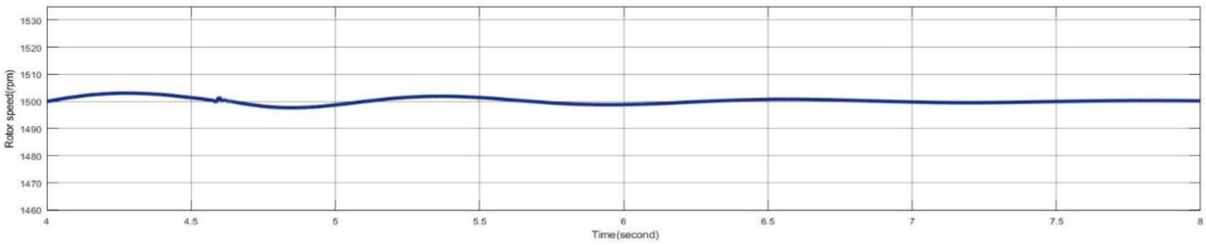
20 deg. During t=6s, the load angle is increasing. After the closing transition, the load angle is 20 deg. Fig 8 (b) shows the rotor speed of SG. Before t=6s, rotor speed was 1500 rpm. During t=6s speed is decreasing from1500rpm after that speed is settling to 1500rpm.



(a)

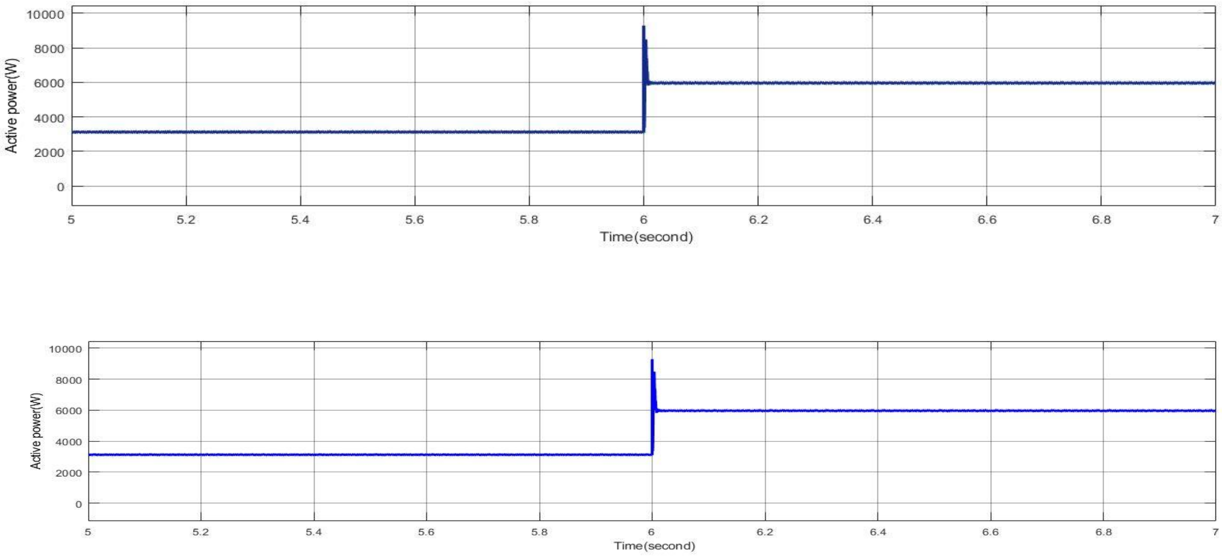


(b)

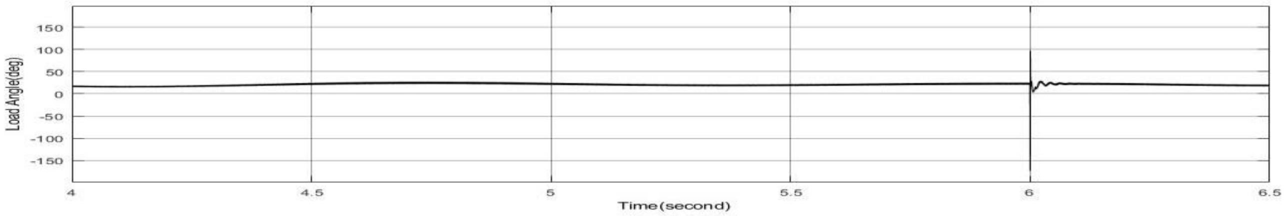


(c)

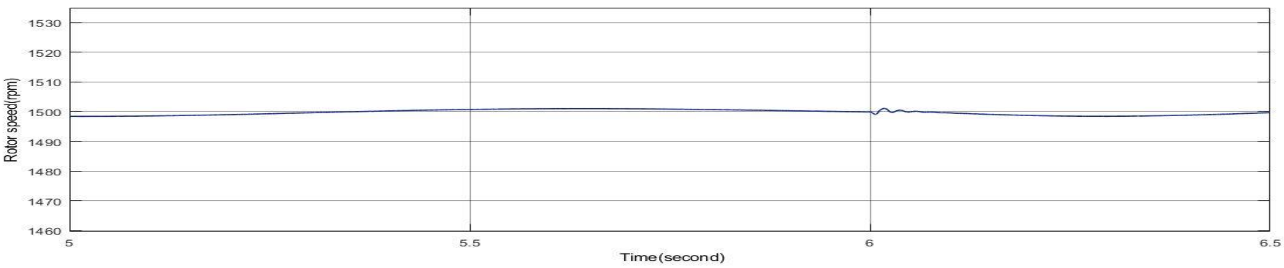
Fig.7 Simulation results of the grid with parallel SG and VSG system under closing transition. (a)Active power of VSG and SG, (b)Load angle of SG, (c)Rotor speed of SG.



(a)



(**b**)



(c)

Fig.8 Simulation results of the grid with parallel SG and VSG system under loading transition. (a) Active power of VSG and SG, (b) Load angle of SG, (c) Rotor speed of SG.

Power sharing between SG and VSG depends on the capacity ratio. In this paper, we use capacity ratio=1, so 50% power sharing occurs when both generating units are operating.

VI. CONCLUSION

In this paper, a grid consisting of SG and VSG units in parallel was simulated, and the control and coordination of generation resources under different inertia were discussed. It has been concluded that the system stability is challenged depending on the inertia differences between the SG and VSG, especially in the case of transients. Accordingly, a new pre-synchronization control method and a novel active power setting mode for the VSG were proposed to improve the transient performance of the grid. Synchronized the parallel SG and VSG connected system. Analyzed the loading condition of the grid with parallel VSG and SG, with capacity ratio=1. These methods are also beneficial to other grid-connected systems to eliminate the phase errors and the control studies of compatibly interconnecting different power supplies.

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