



# **Self Synchronized Controller for Grid Connected Voltage Source Converter**

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**ABSTRACT:** Grid-connected inverter is typically used to interface the renewable energy into the utility grid. When significant portion of grid power is inverter-based, it will be advantageous to imitate certain characteristics of the conventional generators. A synchronverter is inverter that mimics a synchronous generator. All grid-connected inverters need phase locked loop (PLL) to provide the phase, frequency and amplitude of the grid voltage as references to the controller. But, PLL has negative effects on the control performance. In this paper, a radical step is taken to remove the phase locked loop (PLL) by integrating the synchronization function into the synchronverter. This removes the slow element in the system that affects the speed of synchronization. This improves speed of synchronization, reduces the complexity, cost and computational difficulty of the controller. The inverter can perform frequency, voltage regulation, real power and reactive power control without using a dedicated phase locked loop.

**KEYWORDS:** Droop control, grid connection, PLL, renewable energy, synchronization, synchronverter.

## **I. INTRODUCTION**

The day by day increasing demand for energy can create problems for the power distributors, like grid instability. The major portion of the global energy demand can be supplied by the burning of fossil fuels. But due to increasing air pollution, global warming concerns, diminishing fossil fuels and increasing cost; it is necessary to have renewable energy sources as a future solution. But due to the low efficiency and controllability of the renewable energy system, its connection to the utility network can lead to grid instability, if it is not properly controlled. To solve this problem, such systems have to employ some sort of interface to inject the synchronized power into the grid. A grid-connected inverter is used typically to interface the renewable energy system to the utility grid [1]. When renewable power generation forms a significant portion of the grid power, it will be advantageous to operate the inverter in the same way as conventional power generators; or at least, to imitate certain characteristics of the conventional generators [2], [3]. A synchronverter is grid-connected inverter that mimics a synchronous generator [4]. It includes the mathematical model of a synchronous machine. A typical synchronverter will have all the good and bad properties of a synchronous generator (SG). Then, the dynamics seen from the grid side will be same as that of a synchronous generator. Since the real power and reactive power are functions of frequency and voltage respectively, its controller is, in principle, a power controller with integrated capability of voltage and frequency regulation. Hence, it is able to achieve real power control, reactive power control, frequency regulation and voltage regulation.

For proper synchronization of the power converters to the utility grid, grid-connected inverters need synchronization units like phase locked loops (PLL) [5] [6]. The PLL will provide the frequency, amplitude and phase of the grid voltage as references for the power controller [7]-[10]. But PLL has negative impact on the control performance [11], [12]. They are inherently nonlinear and hence it is extremely difficult and time consuming to tune various parameters in PLL. A slow synchronization operation will affect the performance of the system and degrade the stability. On the other hand, a highly complex PLL will be computationally intensive and causes significant burden to the controller. Hence, a compromise should be made in the design of PLL in terms of complexity, speed and accuracy of synchronization. The synchronization operation needs to be done quickly and accurately in order to maintain synchronism, which makes the design of the controller and the PLL very challenging. Lot of researches have been done to increase the accuracy and speed of synchronization, but the problem is still open [13]-[15]. The synchronization unit is often not fast enough with acceptable accuracy and it also takes time for the power and voltage controller to track the references provided by PLL.

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In this paper, a radical step is taken to remove the phase locked loop and synchronize the inverter with the grid itself without the need of a dedicated phase locked loop. Since the synchronous machine is inherently able to synchronize with the grid, it is possible to integrate the synchronization function into the power controller. It can automatically synchronize with the grid before connection and track the grid frequency after connection. This leads to a compact control structure. The self-synchronization capability of a synchronverter will remove the major nonlinear element in the controller that affects the speed of synchronization. This improves the speed of synchronization, reduces the complexity and computational difficulty of the PLL and reduces the cost of controller. Hence all the functions of a synchronverter such as frequency regulation, voltage regulation, real power control and reactive power control can be done without the need of a dedicated phase locked loop. The closest work in this direction is [16], where no PLL is needed during normal operation; but, a backup PLL is required before connection.

The grid-connected renewable energy systems are presented in Section II. The self-synchronization control is proposed in Section III and the simulation results in Section IV followed by conclusion made in Section VI.

## II. SELF SYNCHRONIZATION CONTROL FOR GRID CONNECTED INVERTER

When renewable power generators provide significant portion of the grid power, it will be advantageous to operate the inverter in the same way as the conventional generators or at least to imitate certain characteristics of conventional generators. A synchronverter is an inverter that mimics a synchronous generator. The model of a synchronous machine can be found in different sources [17]-[18].

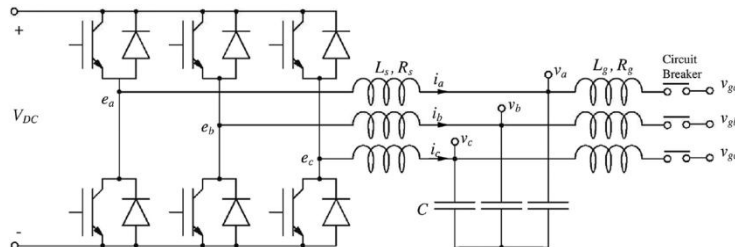


Figure 1: Power part of synchronverter

It consists of mainly a power part and an electronic part. The power part as shown in Figure 1 includes three inverter legs operated by pulse width modulation (PWM) and LC filters to reduce the voltage ripples during switching operations. The electronic controller as shown in Figure 2 includes the mathematical model of a three phase round rotor synchronous machine represented by,

$$\ddot{\theta} = \frac{1}{J}(T_m - T_e - D_p \dot{\theta}) \quad (1)$$

$$T_e = M_f i_f \langle i, \widetilde{\sin \theta} \rangle \quad (2)$$

$$e = \dot{\theta} M_f i_f \widetilde{\sin \theta} \quad (3)$$

$$Q = -\dot{\theta} M_f i_f \langle i, \widetilde{\cos \theta} \rangle \quad (4)$$

$$\text{where } \widetilde{\sin \theta} = \begin{bmatrix} \sin \theta \\ \sin(\theta - \frac{2\pi}{3}) \\ \sin(\theta + \frac{2\pi}{3}) \end{bmatrix} \text{ and } \widetilde{\cos \theta} = \begin{bmatrix} \cos \theta \\ \cos(\theta - \frac{2\pi}{3}) \\ \cos(\theta + \frac{2\pi}{3}) \end{bmatrix}$$

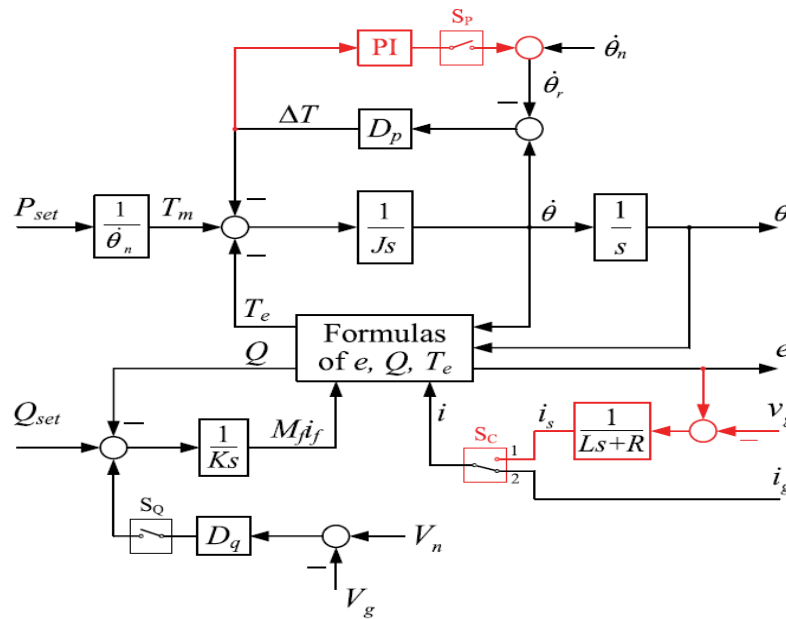


Figure 2: Electronic part of self-synchronized synchronverter

$T_m, T_e, e, \theta$  and  $Q$  are the mechanical torque, electromagnetic torque, three-phase generated voltage, rotor angle, and reactive power of synchronverter respectively.  $J$  is the virtual moment of inertia of the rotating parts,  $i_f$  is field excitation current and  $M_j$  is the maximum mutual inductance between the stator and the field windings.  $\dot{\theta}$  is the virtual angular speed of the machine and  $i$  is the stator current flowing out of the machine. It is assumed that number of pole pairs for each phase is 1. The self-synchronization function can be achieved by means of:

- a) Virtual current  $i_s$  is generated from the voltage error between generated voltage ( $e$ ) and grid voltage ( $v_g$ ) and the current that is fed to the controller can be either the virtual current  $i_s$  or the grid current  $i_g$ .
- b) A PI controller is added to regulate  $\Delta T$  of the frequency droop block to zero and to generate the reference frequency  $\dot{\theta}_r$  for the controller.

### 3.1 Initial synchronization operation

The per-phase model of a synchronverter, connected to an infinite bus is shown in Figure 4.

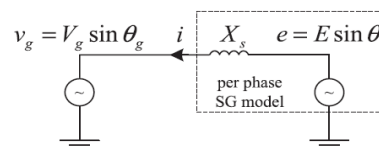


Figure 4: Per phase model of SG connected to infinite bus

The generated real power and reactive power of SG/synchronverter are given by



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$$P = \frac{3E}{2X_s} \sin(\theta - \theta_g) \quad (5)$$

$$Q = \frac{3V_g}{2X_s} [E \cos(\theta - \theta_g) - V_g] \quad (6)$$

Where  $E$  is the induced voltage amplitude of the SG,  $V_g$  is the amplitude of the infinite bus voltage,  $\theta_g$  is the phase of grid voltage,  $\theta$  is the phase of SG and  $X_s$  is the synchronous reactance of the SG.

From equations (5) and (6) suppose when  $\theta$  and  $E$  are controlled to be

$$E = V_g \quad (7)$$

$$\theta = \theta_g \quad (8)$$

then there is no real power or reactive power exchanged between the connected SG and grid. In reverse case, if  $P$  and  $Q$  are controlled to be zero, then the condition (7) and (8) are satisfied and the generated voltage  $e$  is same as that of grid voltage  $v_g$ . Thus, phase frequency and amplitude of generated voltage is same as that of grid. Under this condition the SG can be connected to or disconnected from the grid without causing large transients. This principle can be used for synchronizing asynchronverter with the grid before connection.

For initial synchronization operation, it is necessary to operate the synchronverter under set mode with  $P_{set}$  and  $Q_{set}$  equal to zero. As a result, the condition (7) and (8) can be satisfied when it is connected to the grid. When switch  $S_P$  is turned ON and  $S_Q$  is turned OFF the synchronverter is operated under the set mode. If  $P_{set}$  and  $Q_{set}$  are both 0, then the operation mode is the self-synchronization mode and the inverter is able to synchronize with the grid. But the grid current  $i_g$  is 0 until the circuit breaker is closed. A virtual per-phase inductor  $L_s + R$  is introduced to connect the synchronverter with the grid in order to mimic the process of connecting a physical machine to the grid. The virtual current is routed into the controller via the switch  $S_C$  thrown at position 1. The virtual current  $i_s$  is given by

$$i_s = \frac{1}{L_s + R} (e - v_g) \quad (9)$$

Using this virtual current,  $T_e$  and  $Q$  can be calculated according to (2) and (4). Virtual impedance can be chosen within a wide range. Small values can speed up the synchronization operation but with a large transient current. When the virtual current is driven to zero, then the synchronverter is synchronized with the grid. Then, the circuit breaker can be turned on to connect it to the grid. After circuit breaker is closed, the Switch  $S_C$  should be turned to position 2 so that the grid current  $i_g$  is fed into the controller. Hence no PLL is required for the initial synchronization operation.

## 3.2. OPERATION AFTER CONNECTING TO GRID

### 3.2.1 FREQUENCY CONTROL

The timeconstant  $\tau_f = \frac{J}{D_p}$  of the frequency loop is much smaller than the time constant  $\tau_v = \frac{K}{\theta_n D_q}$  of the voltage loop. Hence, while considering the dynamics of frequency loop,  $M_f i_c$  can be assumed as constant. Moreover, from equation (5), the real power generated by the synchronverter is proportional to  $\sin \delta$ . As a result, the electromagnetic torque  $T_e$  is also proportional to  $\sin \delta$ . Suppose if the grid frequency  $\hat{\theta}_g$  decreases, then the power angle  $\delta$  and the electromagnetic torque  $T_e$  increases. Hence the input to the integrator block  $\frac{1}{s}$  decreases and the synchronverter frequency  $\hat{\theta}$  decreases. This process continues until  $\hat{\theta} = \hat{\theta}_g$ . Similar process occurs if the grid frequency is increased. Hence, the synchronverter frequency  $\hat{\theta}$  automatically converges to the grid frequency without using the complex PLL.



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### 3.2.2 REAL POWER CONTROL (SET AND DROOP MODE)

When switch  $S_p$  is turned ON, PI controller will be inserted in the frequency droop control loop. Hence,  $\Delta T$  is controlled to 0 under the steady state condition. Thus  $T_e$  becomes equal to  $T_m$  and  $\dot{\theta}$  is controlled as

$$\dot{\theta} = \dot{\theta}_r + \Delta \dot{\theta} \quad (10)$$

where  $\Delta \dot{\theta}$  is the output of PI controller. Thus the power angle  $\delta$  settles down at a constant value that results in  $P = P_{set}$ . This mode of operation is called as the set mode. The set mode for the real power and reactive power is represented as  $P$  mode and  $Q$  mode respectively in this paper.

When the Switch  $S_p$  is turned OFF, then the PI controller is taken out of the loop and the synchronverter is operated in the frequency droop mode (represented as  $P_D$  mode in this paper). The frequency droop coefficient is given by,

$$D_p = - \frac{\Delta T}{\Delta \theta} \quad (11)$$

where  $\Delta \theta$  is the frequency deviation of the synchronverter from the nominal frequency.

### 3.2.3 REACTIVE POWER CONTROL (SET AND DROOP MODE)

The Switch  $S_Q$  in voltage droop loop will control the reactive power flow. When Switch  $S_Q$  is in OFF condition, the field excitation  $M_{fj}$  is varied depending on the tracking error between  $Q_{set}$  and  $Q$  by means of an integrator with gain  $1/K$ . Therefore, the generated reactive power  $Q$  tracks exactly the set-point  $Q_{set}$  irrespective of the voltage difference between  $V_n$  and  $V_g$ . This operation mode is called as the set mode for the reactive power control (represented as  $Q$  mode in this paper).

When Switch  $S_Q$  is in ON condition, then the voltage droop function is enabled and depending on the voltage error  $\Delta V = V_n - V_g$ , the field excitation  $M_{fj}$  is varied. Hence, the reactive power  $Q$  does not track exactly  $Q_{set}$ , but with steady-state error  $\Delta Q = Q_{set} - Q$ . The voltage droop coefficient is given by,

$$D_q = - \frac{\Delta Q}{\Delta V} \quad (12)$$

This operation mode is called as the voltage droop mode (represented as  $Q_D$  mode in this paper).

## IV. SIMULATION RESULTS

The proposed control strategy was verified in MATLAB 7.9/Simulink/SimPowerSystems. The parameters are given in Table 1. The inverter is connected to the grid via a step-up transformer. Here  $D_p = 0.2026$  is chosen which implies that a drop of 0.5% in the frequency (from the nominal frequency) causes the torque to increase by 100% (of the nominal power) and the voltage droop coefficient is chosen as  $D_q = 117.88$  so that drop of 5% in the voltage causes an increase of 100% of reactive power.

Table 1: Parameters used for simulation

Parameters	Values	Parameters	Values
$V_n$	$12\sqrt{2}$	$R$	$0.15\Omega$
$f_n$	50Hz	$L_g$	0.4mH
Rated power	100VA	$R_g$	$0.135\Omega$
$L_s$	0.45mH	$K_i$	18
$R_s$	$0.135\Omega$	$K_p$	0.5
$L$	0.9mH		

### 4.1 SELF SYNCHRONIZATION CONTROL

At simulation time  $t=0$ , switch  $S_C$  in Position 1,  $S_p$  turned ON,  $S_Q$  turned OFF, and circuit breaker in OFF condition, the synchronverter is in the self-synchronization mode with  $P_{set} = Q_{set} = 0$ . Here, circuit breaker is turned on at time  $t=2s$ .

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The set point for real power  $P_{set} = 100W$  was applied at  $t = 5$  s and the set-point for the reactive power  $Q_{set} = 100Var$  was applied at  $t = 10$ s. The  $P_D$  mode was enabled at  $t=15$  s by turning Switch  $S_P$  OFF and grid frequency was stepped up to  $f_g=50.2$  Hz (i.e. increased by 0.4%) at  $t = 20$  s. The  $Q_D$  mode was enabled at time  $t=25$ s. The grid frequency returned to nominal value at  $t=30$ s and the grid voltage was set to be 2% higher than the nominal grid voltage at  $t=30$ s. The simulation was stopped at time  $t=35$ s. The entire system responses from  $t=0$  to  $t=35$ s are shown in Figure 5.

At first synchronverter was operated in the self-synchronization mode to synchronize itself with the grid. When virtual current  $i_s$  is driven to zero, the synchronverter is synchronized with the grid. After circuit breaker is closed, virtual current was replaced by grid current. The transient current at the moment of circuit breaker closure is less than 10mA, and hence there was no problem to connect it to the grid. Synchronverter tracked the grid frequency very well without any problem. There are transient peaks in the frequency and power curve at each event. This is expected, similar to the

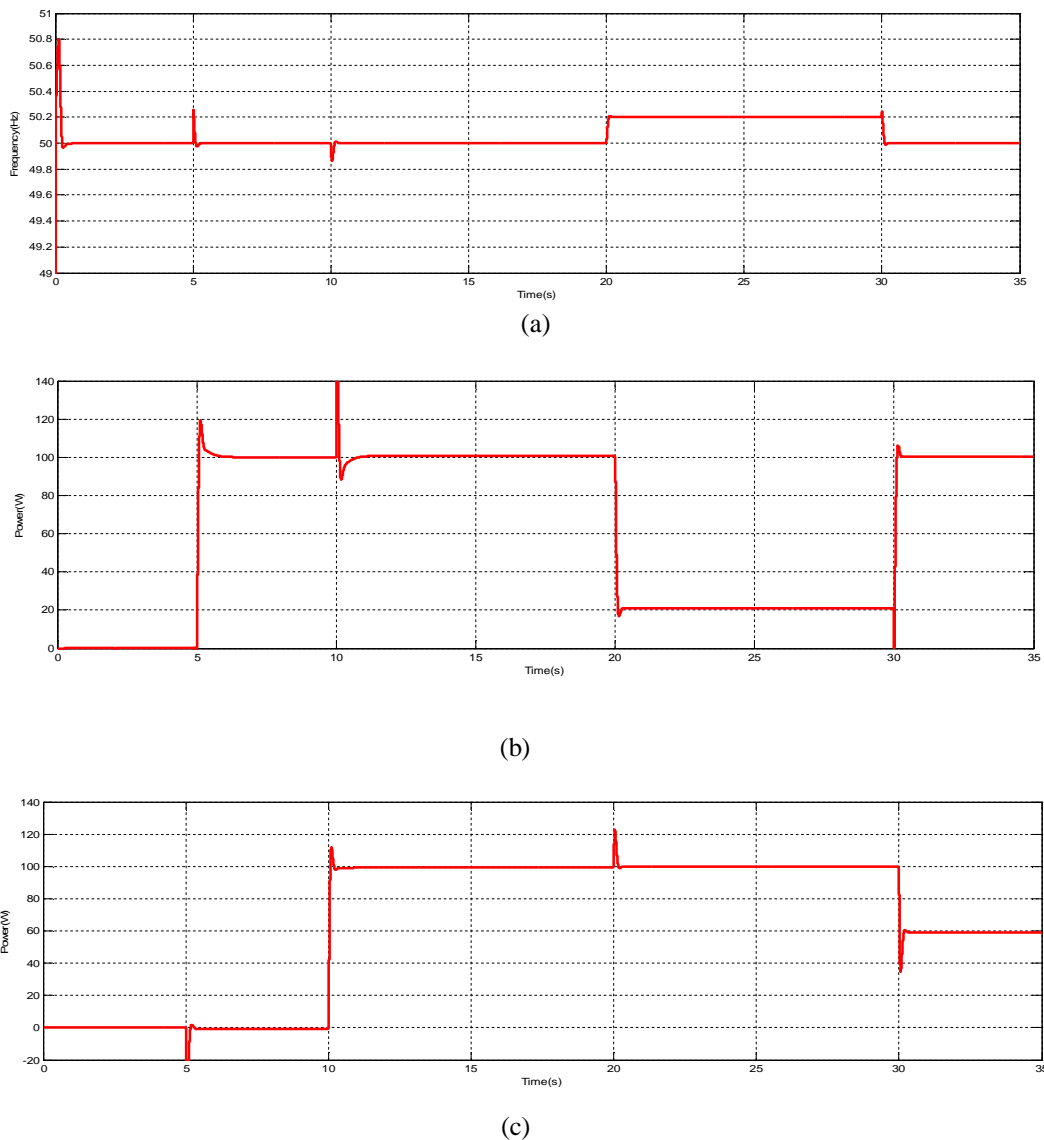


Figure 5: Simulation results when grid frequency is increased to 50.2Hz from  $t=20$  to  $t=30$ s and grid voltage is increased by 2% from  $t=30$  to  $t=35$ s (a) Synchronverter frequency (b) Real power (c) Reactive power

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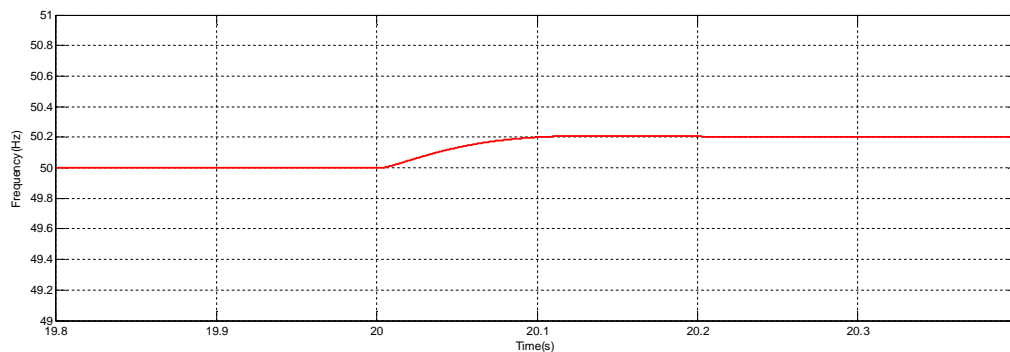
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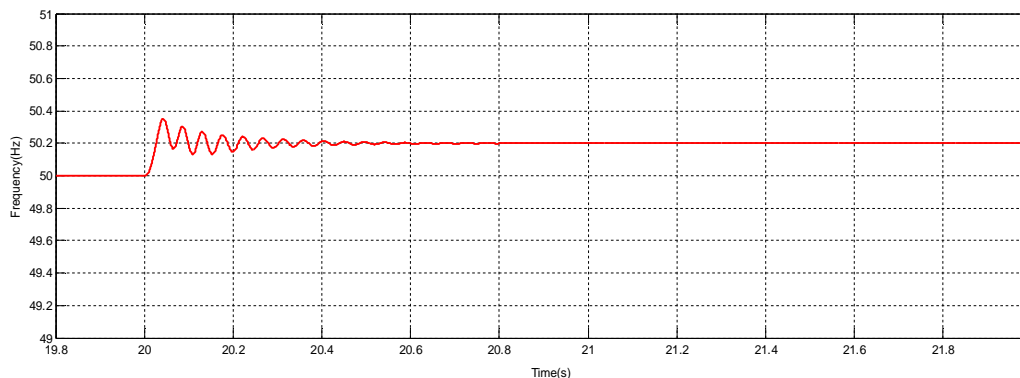
change in the speed of a synchronous machine as the operating condition changes. The real power and reactive power generated tracked exactly the set power during the set mode of operation. The frequency also tracked very well in the droop modes, but the real power changed with the grid frequency, as expected. When the  $P_D$  mode was enabled and the frequency was increased to  $f_g = 50.2$  Hz (ie, 0.4% higher than nominal value), then the real power dropped by 80W; i.e.  $\frac{0.4\%}{0.5\%} = 80\%$  of the nominal value. When grid frequency returned to nominal value, the power quickly jumped back to set value. Similarly, when  $Q_D$  mode was enabled and grid voltage is increased by 2%, the reactive power dropped by 40 Var, i.e.  $\frac{2\%}{5\%} = 40\%$  of the nominal power.

## 4.2 COMPARITIVE STUDY OF SYNCHRONVERTER WITH AND WITHOUT PLL IN TERMS OF SETTLING TIME

As grid frequency is continuously changing, the settling time of frequency curve is of great importance. The frequency responses when the grid frequency is increased by 0.2 Hz at  $t=20$ s is simulated for synchronverter with and without PLL.



(a)



(b)

Figure 6: Simulation results when grid frequency is increased to 50.2Hz from  $t=20$  to  $t=30$ s  
(a) Synchronverter frequency without using PLL (b) Synchronverter frequency with a PLL

Simulated results in Figure 6 shows that in the self-synchronization control, the frequency settles down accurately within 0.1s whereas the synchronverter frequency with PLL settles down at 0.8s. Thus the speed of synchronization is improved considerably in the proposed scheme.



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## VI.CONCLUSION

A self-synchronized inverter (called synchronverter) has been developed to integrate the renewable energy system to grid system. The self-synchronization control of grid connected inverter removes the need of a dedicated phase locked loop. This completely eliminates the problems that are associated with a conventional PLL. Thus, it simplified the controller, reduced the difficulty and complexity in tuning the parameters of PLL, reduced the development cost of PLL. It is able to synchronize with the grid before connection and track the grid frequency automatically after connection. Also, it is able to operate in different modes of power control without using the PLL. The controller is, in principle, a power controller with integrated capability of frequency and voltage regulation together with self-synchronization control. This leads to a compact control structure. Further, the speed of synchronization improved considerably in the self-synchronization control.

## REFERENCES

- [1] J. M. Carrasco, L. G. Franquelo, J. T. Bialasiewicz, E. Galvan, R. C. Portillo-Guisado, M. A. M. Prats, J. I. Leon, and N. Moreno-Alfonso, "Power-electronic systems for the grid integration of renewable energy sources: A survey," *IEEE Trans. Ind. Electron.*, vol. 53, no. 4, pp. 1002–1016, Aug. 2006.
- [2] H.-P. Beck and R. Hesse, "Virtual synchronous machine," in *Proc. 9th Int. Conf. EPQU*, 2007, pp. 1–6.
- [3] J. Driesen and K. Visscher, "Virtual synchronous generators," in *Proc. IEEE Power Energy Soc. Gen. Meeting–Conversion and Delivery of Electrical Energy in the 21st Century*, Jul. 2008, pp. 1–3.
- [4] Q.-C. Zhong and G. Weiss, "Synchronverters: Inverters that mimic synchronous generators," *IEEE Trans. Ind. Electron.*, vol. 58, no. 4, pp. 1259–1267, Apr. 2011.
- [5] F. Blaabjerg, R. Teodorescu, M. Liserre, and A. Timbuş, "Overview of control and grid synchronization for distributed power generation systems," *IEEE Trans. Ind. Electron.*, vol. 53, no. 5, pp. 1398–1409, Oct. 2006.
- [6] J. Svensson, "Synchronisation methods for grid-connected voltage source converters," *IEE Proc. Generat., Transmiss. Distrib.*, vol. 148, no. 3, pp. 229–235, May 2001.
- [7] M. Ciobotaru, R. Teodorescu, and F. Blaabjerg, "A new single-phase PLL structure based on second order generalized integrator," in *Proc. 37th IEEE Power Electron. Spec. Conf.*, 2006, pp. 1–6.
- [8] M. Karimi-Ghartemani and M. Iravani, "A new phase-locked loop (PLL) system," in *Proc. 44th IEEE Midwest Symp. Circuits Syst.*, 2001, pp. 421–424.
- [9] Q. Zhang, X.-D. Sun, Y.-R. Zhong, M. Matsui, and B.-Y. Ren, "Analysis and design of a digital phase-locked loop for single-phase grid-connected power conversion systems," *IEEE Trans. Ind. Electron.*, vol. 58, no. 8, pp. 3581–3592, Aug. 2011.
- [10] P. Rodriguez, J. Pou, J. Bergas, J. Candela, R. Burgos, and D. Boroyevich, "Decoupled double synchronous reference frame PLL for power converters control," *IEEE Trans. Power Electron.*, vol. 22, no. 2, pp. 584–592, Mar. 2007.
- [11] L. Harnefors, M. Bongiorno, and S. Lundberg, "Input-admittance calculation and shaping for controlled voltage-source converters," *IEEE Trans. Ind. Electron.*, vol. 54, no. 6, pp. 3323–3334, Dec. 2007.
- [12] D. Jovcic, L. Lamont, and L. Xu, "VSC transmission model for analytical studies," in *Proc. IEEE Power Eng. Soc. Gen. Meet.*, Jul. 2003, vol. 3, pp. 1737–1742.
- [13] C. da Silva, R. Pereira, L. da Silva, G. Lambert-Torres, B. Bose, and S. Ahn, "A digital PLL scheme for three-phase system using modified synchronous reference frame," *IEEE Trans. Ind. Electron.*, vol. 57, no. 11, pp. 3814–3821, Nov. 2010.
- [14] M. Karimi-Ghartemani, A. Khajehoddin, P. Jain, and A. Bakhshai, "Problems of startup and phase jumps in PLL systems," *IEEE Trans. Power Electron.*, vol. 27, no. 4, pp. 1890–1838, Sep. 2011.
- [15] R. Santos Filho, P. Seixas, P. Cortizo, L. Torres, and A. Souza, "Comparison of three single-phase PLL algorithms for UPS applications," *IEEE Trans. Ind. Electron.*, vol. 55, no. 8, pp. 2923–2932, Aug. 2008.
- [16] L. Zhang, L. Harnefors, and H.-P. Nee, "Power-synchronization control of grid-connected voltage-source converters," *IEEE Trans. Power Syst.*, vol. 25, no. 2, pp. 809–820, May 2010.
- [17] P. Kundur, *Power System Stability and Control*. New York: McGraw-Hill, 1994.
- [18] D. P. Kothari and I. J. Nagrath, *Electric Machines*, 3rd. New Delhi, India: McGraw-Hill, 2004.