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A Self-synchronized Synchronverter Technology for Integrating PV Inverters to Grid without Using a Phase Locked Loop

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***Abstract*— Photovoltaic systems are solar energy supply systems, which convert directly sunlight into electricity. A grid-connected inverter is typically used to interface the photovoltaic (PV) system into the utility grid. When significant portion of the grid power is inverter based, it will be advantageous to operate the inverter in the similar way as conventional power generators, or at least to imitate certain characteristics of the conventional generators. Synchronverter are grid connected inverter that mimics a synchronous generator. All conventional grid-connected inverters uses a phase locked loop (PLL) to provide the phase, frequency and amplitude of the grid voltage as references to the controller. But this PLL has got negative effects on the control performance. In this thesis the performance of the system is improved by removing the complex phase locked loop. It can automatically synchronize with the grid before connection and track the grid frequency after connection. This removes the slow element in the system that affects the speed of synchronization. Hence it considerably improves the control performance, reduces the complexity, cost and computational difficulty of the controller. Thus the controller is in principle, a power controller with integrated capability of frequency and voltage regulation together with self-synchronization control. Simulation results shows that the settling time as well as the peak overshoot of frequency tracking is improved considerably in the self-synchronization control.**

***Index Terms*— Droop control, grid connection, PLL, renewable energy, synchronization, synchronverters.**

I. INTRODUCTION

Major portion of the global energy demand is supplied by the burning of fossil fuels. But due to the increased air pollution, global warming concerns, diminishing fossil fuels and increasing cost have made it necessary to have renewable energy sources as a future solution. Among the renewable energy sources, photovoltaic system has greatest utilization nowadays. But due to low efficiency and controllability of the PV system, its connection to 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 photovoltaic system into the utility grid. When renewable power generation forms a significant portion of the grid power, then it will be advantageous to operate the inverter in the similar way as conventional power generators, or at least, to imitate certain characteristics of the conventional generators.

Synchronverter are grid connected inverter that mimics a synchronous generator [1]. It includes the mathematical model of a synchronous machine. A typical sychronverter will have all the good and bad properties of a synchronous generator (SG). The dynamics seen from the grid side will be same as those of an SG. The 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. This leads to a compact control structure.

For proper synchronization of inverters to the utility grid, grid connected inverters uses a phase locked loop (PLL) [2], [3]. The phase locked loop will provide the frequency, amplitude and phase of the grid voltage as the references to the power controller [4],[5]. But PLL have negative impact on the control performance [6], [7]. This PLL are inherently nonlinear and hence it is extremely difficult and time consuming to tune various parameters of PLL. Speed of synchronization, noise rejection capability, accuracy and transient response should be considered in the design of PLL. Even though great effort is done in the design of PLL [8]the synchronization unit is often not fast enough to obtain adequate accuracy and it also takes time for the power and voltage controller to track the references provided by PLL.

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. It can automatically synchronize with the grid before connection and track the grid frequency after connection. The controller is, in principle, a power controller with integrated capability of frequency and voltage regulation together with self-synchronization capability. This leads to a compact control structure for the controller. The self-synchronization capability of synchronverter will remove the major nonlinear element in the controller that affects the speed of synchronization. This simplifies the controller, reduced the development cost of PLL, reduced the difficult and complexity in tuning the PLL.

II. PV MODELING

Fig. 1 shows the equivalent circuit diagram of a PV cell. The equivalent circuit of a solar cell is represented by a current source in parallel with a diode. The model is a simplified version of the two diode model given by Gow and Manning

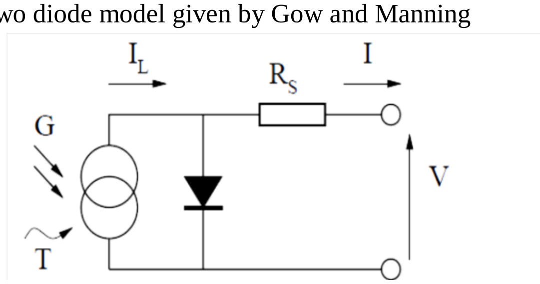


Fig. 1.Equivalent PV Model

The IV characteristics of the cell are represented in [9].

III. GRID CONNECTED PV SYSTEMS

A synchronverter is an inverter that mimics a synchronous generator. It consists of mainly a power part and electronic part. The power part as shown in Fig 2 includes three inverter legs that are operated by pulse width modulation (PWM) and filters to reduce the voltage ripples during switching operations. The electronic controller as shown in Fig 3 includes the mathematical model of a three phase round rotor synchronous machine. The modeling equations for synchronous machine are available in different sources [10]. The modeling equation of a round rotor synchronous machine is described by

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

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

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

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

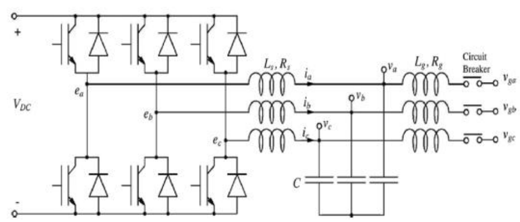


Fig 2: Electronic part of self-synchronized synchronverter

where T_m, T_e, e, θ, and Q are 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, if is field excitation current and M_f is the maximum mutual inductance between the stator and field windings. $\dot{\theta}$ is the virtual angular speed of the machine and i is the stator current flowing out of the machine.

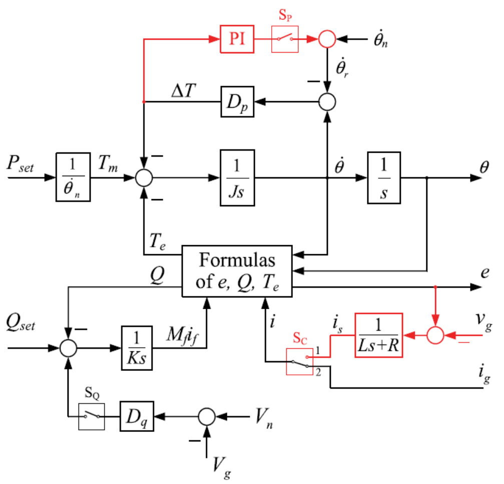


Fig 3: Electronic part of self-synchronized synchronverter

The synchronverter technology has mainly two channels: one for real power control and other for reactive power control. The real power is controlled by using a frequency droop control loop. This loop will regulate the virtual speed $\dot{\theta}$ of the synchronous machine. The reactive power is controlled by using a voltage droop control loop. This loop will regulate the field excitation $M_f i_f$, which is a function of the amplitude of voltage generated. Hence frequency control, voltage control, real power control, and reactive power control can be integrated in a single compact controller.

IV. SELF- SYNCHRONIZATION CONTROL

The self-synchronization function can be integrated into the synchronverter by making some changes to the core of the controller (as shown in in red lines). There are two major changes made:

i) A Virtual current i_s is generated from voltage error between generated voltage (e) and grid voltage (v_g) and current that is fed to the controller can be either the virtual current is or the grid current i_g

ii) A PI controller is added to regulate ΔT of the frequency droop block to zero and to generate the reference frequency $\dot{\theta}_r$ for the controller.

A. Initial Synchronization Operation

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

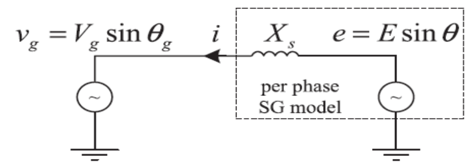


Fig4: Per phase model of SG connected to infinite bus

real power and reactive power generated by a SG/synchronverter are given by

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

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

where E is the amplitude of the induced voltage of SG, Vg is the amplitude of the infinite bus voltage, θ_g is the phase of grid voltage, θ is the phase of synchronverter and X_s is the synchronous reactance of synchronverter. If P and Q are controlled to be zero, theN generated voltage e is same as that of grid voltage v_g. Under this condition the SG can be connected to or disconnected from the grid without causing large system transients.

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 initial-synchronization mode and the inverter is able to synchronize with the grid. Until the circuit breaker is closed, the grid current ig is 0. Hence a virtual per-phase inductor Ls+R is introduced in order to mimic the process of connecting a physical machine to the grid. The virtual current i_s is given by

$$i_s = \frac{1}{Ls+R}(e - v_g) \qquad (7)$$

Using this virtual current, T_e and Q can be calculated according to (2) and (4). 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 the synchronverter to the grid. After circuit breaker is closed, the Switch S_C should be turned to position 2 so that the normal grid current ig is fed into the inverter controller. Hence no PLL is required during the initial synchronization operation.

B. Operation after Connecting To Grid

B.1. Frequency Control

The time constant $r_f = \frac{J}{D_p}$ of the frequencyloop is much smaller than the time constant $r_v = \frac{K}{\dot{\theta}_n D_q}$ of the voltage loop. Thus while considering the dynamics of frequency loop, field excitation $M_f i_f$ can be assumed as constant. Moreover, from equation (5), the real power generated is proportional to $\sin\delta$. Hence the electromagnetic torque T_e is proportional to $\sin\delta$. Suppose if grid frequency $\dot{\theta}_g$ decreases, then the power angle δ and the electromagnetic torque T_e increases. As a result, input to the integrator block $\frac{1}{Js}$ decreases and the synchronverter frequency $\dot{\theta}$ decreases. This process will continue until $\dot{\theta}=\dot{\theta}_g$. Similar process occurs if the grid frequency is increased. Hence, the synchronverter frequency $\dot{\theta}$ automatically converges to the grid frequency $\dot{\theta}_g$ without using a complex phase locked loop.

B.2. Real Power Control

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

$$\dot{\theta}=\dot{\theta}_r= \dot{\theta}_r+\Delta\dot{\theta} \quad (8)$$

where $\Delta\dot{\theta}$ is the output of PI controller. This mode of operation is called as the set mode for real power control. When Switch SP is turned OFF, then the PI controller is taken out of the loop and the synchronverter is operated in the frequency droop mode. The frequency droop coefficient is given by,

$$D_p = -\frac{\Delta T}{\Delta\dot{\theta}} \quad (9)$$

where $\Delta\dot{\theta}$ is the frequency deviation of the synchronverter from the nominal value of frequency.

B.3.Reactive Power Control

Switch S_Q in voltage droop loop will control the reactive power flow. When the Switch S_Q is in OFF condition, 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. When Switch S_Q is in ON condition, then depending on the voltage error $\Delta V = V_n - V_g$, the field excitation $M_f i_f$ is varied. As a result, the reactive power Q does not track exactly Q_{set}, but with a steady-state error $\Delta Q = Q_{set} - Q$. The voltage droop coefficient is given by,

$$Dq = -\frac{\Delta Q}{\Delta V} \quad (10)$$

This operation mode is called as the voltage droop mode.

V. 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 400V grid system by means of a step-up transformer. Here D_p= 0.2026 is chosen which indicates 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% reactive power. The PV cell temperature is maintained constant at 25^0C and the solar intensity is initial set at 1KW/m^2. At t=10s, irradiance is decreased to 0.75KW/m^2. BP Solar BP SX 150S PV module is chosen for MATLAB simulation model.

A. Initial Synchronization

Initially switch S_C is in Position 1, S_P turned ON, S_Q turned OFF, and the circuit breaker is in OFF condition i.e., in self-synchronization mode with P_{set} =Q_{set}=0. The virtual current generated from voltage error reduced to zero as shown in Fig 5. Then, the circuit breaker can be turned on at any time to connect the synchronverter to the grid. Here circuit breaker is turned on time t=2s. 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. Thus initial synchronization operation is done without using a dedicated phase locked loop.

B .Operation after Connecting to Grid

Set point for real power P_{set} = 20W was applied at t = 5s and the set-point for the reactive power Q_{set}= 20Var was also applied at t = 5s. The grid frequency was stepped down to f_g=49.8 Hz (i.e. decreased by 0.4%) at t= 20 s and also P_D mode was enabled at t=20 s by turning switch S_P OFF. The grid frequency returned to nominal value at t=30s and the grid voltage was set to be 2% lower than the nominal grid voltage at t=30s. Also Q_D mode was enabled at time t=30s by turning switch S_Q off. The simulation was stopped at time t=35s. The entire system responses from t=0 to t=35s are shown in Fig 6.

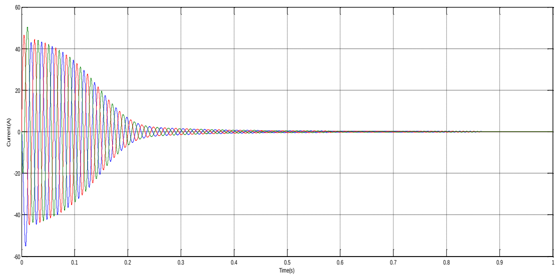
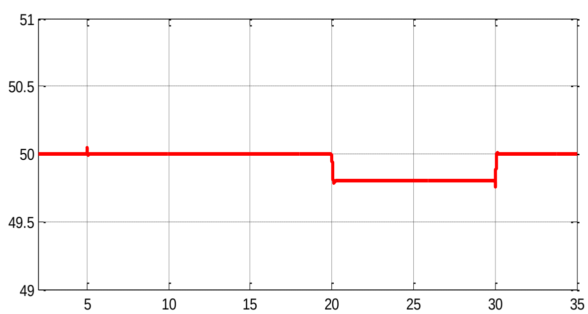


Fig 5: Virtual current

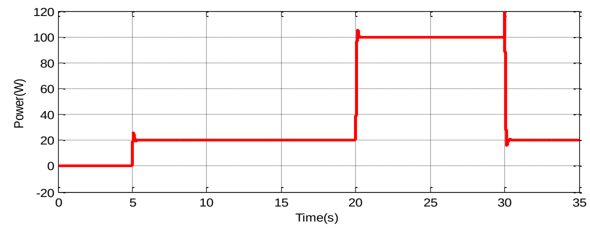
After the connection, irrespective of the set-points P_{set} and Q_{set} applied, the synchronverter frequency tracked exactly the grid frequency without any problem. The frequency also tracked very well in the droop modes, but the real power changed with the grid frequency, as expected. When the frequency was decreased to f_g= 49.8 Hz (0.4% higher than nominal value) and the P_D mode was enabled at t=20s the real power increased by 80 W, ie, 0.4%/0 .5%= 80% of the nominal value. When grid frequency returned to nominal value, the real power quickly jumped back to the set-value. Similarly, when and grid voltage is decreased by 2% and Q_D mode is enabled at t=30s, the reactive power increased by 40 Var, i.e., 2%/5%= 40% of the nominal power. When grid frequency is higher than nominal value also, the synchronverter frequency tracks exactly the grid frequency.

C. Comparative Study of Synchronverter with PLL and Self Synchronization Control

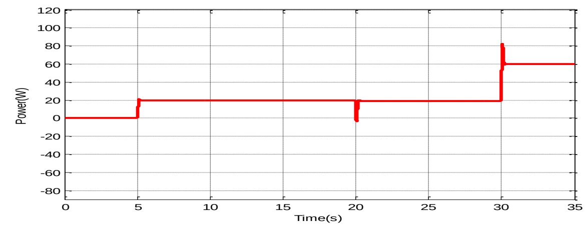
As grid frequency is continuously changing, the settling time and peak overshoot of frequency curve is of great importance.



(a)



(b)



(c)

Fig 6: Simulation results when grid frequency is decreased to 49.8Hz from t=20 to t=30s and grid voltage is decreased by 2% from t=30 to t=35s (a) Synchronverter frequency (b) Real power (c) Reactive power

Synchronverter frequency responses when the grid frequency is increased by 0.2 Hz at t=20 s is simulated both for synchronverter with and without PLL as shown in Fig. 7. Simulated results in Figure 7 shows that in the self-synchronization control, the frequency settles down accurately within 0.24s whereas the synchronverter frequency with PLL settles down at 0.8s. Also peak overshoot is considerably lower in the self-synchronization control. Thus the settling time and peak overshoot of frequency tracking is improved considerably in the proposed scheme.

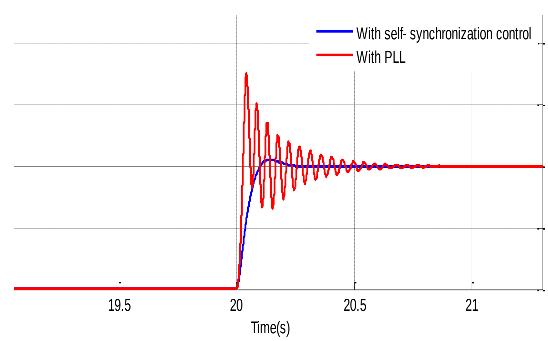


Fig 7: Simulation results when grid frequency is increased to 50.2Hz from t=20 to t=30s with self - synchronization control and with PLL

VI. CONCLUSION

A self-synchronized synchronverter has been developed to integrate the photovoltaic system into the utility grid. The self-synchronization control of inverter removes the need of a dedicated phase locked loop. This simplified the controller, reduced the development cost and effort, reduced the difficult and complexity in tuning the 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, voltage regulation and self-synchronization control. This leads to compact control structure. Simulated results shows that the settling time as well as the peak overshoot of frequency tracking is improved considerably in self-synchronization control.

REFERENCES

[1] 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.

[2] F. Blaabjerg, R. Teodorescu, M. Liserre, and A. Timbus, “Overview of control and grid synchronization for distributed power generation systems,”*IEEE Trans. Ind. Electron*., vol. 53, no. 5, pp. 1398–1409, Oct. 2006.

[3] .J. Svensson, “Synchronisation methods for grid-connected voltage source converters,” *IEE Proc. Generat., Transmiss. Distrib*., vol. 148, no. 3,pp. 229–235, May 2001.

[4] 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.

[5] 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.

[6] 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.

[7] 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.

[8] R. Santos Filho, P. Seixas, P. Cortizo, L. Torres, and A. Souza, “Comparison of three single-phase PLL algorithms for UPS applications,” *IEEETrans. Ind. Electron*., vol. 55, no. 8, pp. 2923–2932, Aug. 2008.

[9] J. A. Gow, C. D. Manning, “Development of a photovoltaic array model for use in power electronics simulationstudies,” *IEE Proceedings on Electric Power Applications*., vol. 146, no. 2, pp. 193-200, March 1999.

[10] P. Kundur, *Power System Stability and Control*. New York: McGraw-Hill, 1994.