Modeling, Analysis, and Design of Synchronverters for Microgrid Applications

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***Abstract*- In this paper, the synchronverter (SV) model is revised and thoroughly examined. Detailed simulation blocks are clarified and presented using Matlab/Simulink. The aim is to enhance inertia contribution to approach equivalent real synchronous generator (SG) and by another meaning grid-friendly inverter that mimic the operation of conventional SG. Improvements in the modes of operation grid-connected and stand-alone modes are obtained. SV is able to transfer seamlessly between the two modes and then as provide solution for smart grids and microgrids (MGs). An automatic synchronization unit is used to minimize disturbances at instant of connection to grid. Unlike most previous works in this area of research, the present one simulates also the pulse width modulation (PWM) inverter to monitor the dc bus condition during different conditions of operation. The results of simulation are presented to check the above ideas.**

***Index Terms*- load sharing, microgrid (MG), parallel inverters, renewable energy (RE), smart grid, static synchronous generator (SSG), synchronverter (SV), virtual synchronous generator (VSG), voltage drooping.**

I. Introduction

The sharing of produced power by renewable energy sources (RESs) as wind power and solar power… etc., is gradually increasing. Comparing with conventional power stations RESs are distributed in nature, so they are usually called distributed generators (DG).The electrical authority in Egypt planned to cover 20% of bulk energy generation by RESs by 2030 as an attempt to solve the electricity crisis. Worldwide, the electrical power system is currently undergoing a change from centralized generation to DG. This DG needs dc–ac conversion, to interface with the grid.

Algorithms have been developed to ensure that the current injected into the grid is clean sinusoidal [1].

When RESs will provide the majority of the grid power, the need will arise to operate them in the same way as conventional power generators using some techniques [2] – [3]. This will require energy-storage units so that the random fluctuations of the prime power source can be filtered out [4] – [9].

IEEE has defined a term; called static synchronous generator (SSG) [10], SVs is a particular type of SSGs.

The problem here is how to control the inverters in DGs so that these inverters can be integrated into the existing system and behave in the same way as conventional SG does. This assures a smooth transition from the existing conventional power grid to a grid dominated by inverters [11] – [13].

A SV will have all the properties of a SG, which is a complex nonlinear system. The parameters, as friction coefficient, inertia, field and mutual inductances can be selected without criteria of real material limitations present in SGs. The energy lost in the virtual mechanical friction is not lost in reality but directed back to the dc bus, no magnetic saturation and no eddy currents are present in this case.

This research follows as in Section II, the dynamic model of SGs is established and simulate performance of a SV is described, Section III, operation, e.g., frequency and voltage-drooping mechanisms for load sharing are described, Section IV, simulation results are given with conclusions in Section V.

II. Modeling of SG and SV

Fig. 1 shows the power part of a SV and Fig. 2 shows the block diagram of the programed part of SV. It has been derived based on the mathematical model of the three-phase round rotor SG [14]–[20].Here, the model established in [2] is used. It considers the following assumptions:

- Rotor type: round so that all stator inductances are constant.
- The effect of damper windings in the rotor is neglected.
- There are two poles.

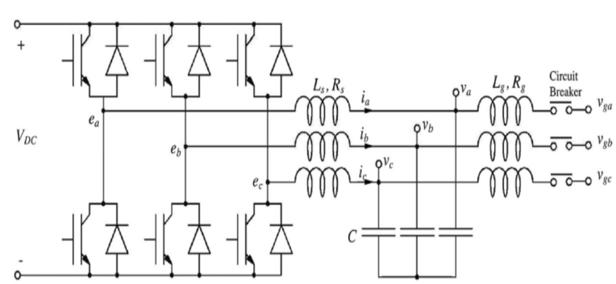


Fig.1. Power parts of a SV

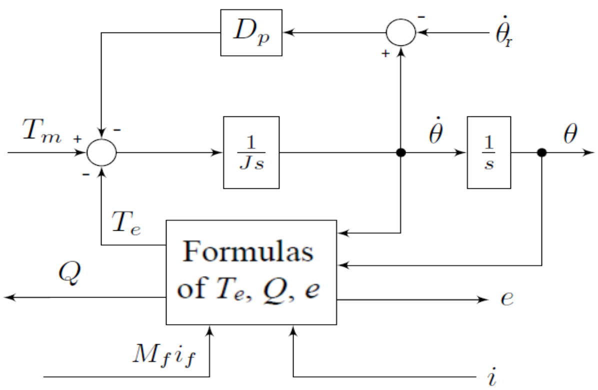


Fig.2. Programed part of SV

- There is no magnetic-saturation.

That paper uses relatively very small inertia so the results seem to have negligible hunting and shows exceptionally fast synchronization. In present work trying to have similar response at practical values of inertia necessitates using high values of drooping frequency coefficient as will be shown in V. The equations are summarized as

$$\theta^{\cdot\cdot} = {}^{1}/_{J}\left(T_m - T_e - D_p\,\theta^{\cdot}\right) \quad (1)$$

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

$$e = \theta^{\cdot} M_f\ i_f\ \widetilde{\sin}\,\theta \quad (3)$$

$$P = \theta^{\cdot} M_f\ i_f\ \langle i, \widetilde{\sin}\,\theta\rangle\,,$$

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

Where mechanical torque T_m is a control input while T_e is the electromagnetic torque, the state variables i is the inductor currents, v is the capacitor voltages, θ is the virtual angle, $\theta^{\cdot}$ is the virtual angular speed, M_f is the maximum mutual inductance between the stator windings and the field winding, J is the moment of inertia of all the parts rotating with the rotor, $\langle\cdot,\cdot\rangle$ denotes the conventional inner product. The term $M_f\,\langle i, \widetilde{\cos}\,\theta\rangle$ is a constant if the three phase currents are sinusoidal and balanced and called armature reaction, D_p is a damping factor, and

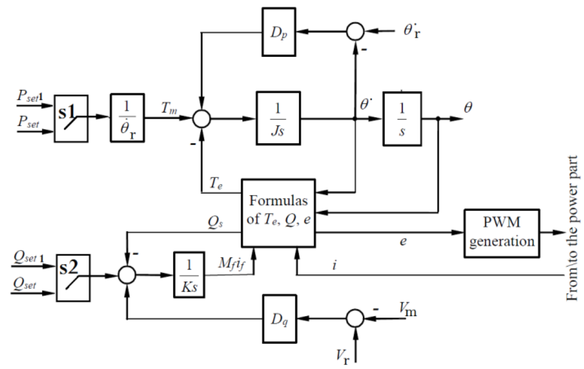


Fig.3. Proposed regulation of the power in a SV

$$\widetilde{\cos}\,\theta = \begin{bmatrix} \cos\theta \\ \cos(\theta-\frac{2\pi}{3}) \\ \cos(\theta-\frac{4\pi}{3}) \end{bmatrix}\ ,\ \widetilde{\sin}\,\theta = \begin{bmatrix} \sin\theta \\ \sin(\theta-\frac{2\pi}{3}) \\ \sin(\theta-\frac{4\pi}{3}) \end{bmatrix}$$

The filtering capacitors C should be chosen such that the resonant frequency $1/\sqrt{\mathrm{L_s C}}$ is approximately $\sqrt{\omega_n\omega_s}$, where ω_n is the nominal angular frequency of the grid voltage and ω_s is the angular switching frequency used to turn on/off the switches.

III. SV OPERATION

A. Real Power Regulation and Frequency Drooping

1) Case of Standalone (island) mode: In this mode is maintained SG rotor speed by the prim-mover and mechanical power of power covers the electrical power developed in addition to all power losses of the power conversion process. As the load increases the speed (and consequently frequency) decreases making speed governor permitting higher fuel input and this brings new power balance at smaller rotor speed (smaller frequency). To bring frequency back to its original value the no-load frequency setting of speed governor need to be raised up. The ratio $Dp = -\Delta T/\,\Delta\theta^{\cdot}$.is called the frequency droop. *The island mode is implemented in SV as shown in Fig.3 with switch S1 in lower position this is equivalent to* $P_{set} = 0, Q_{set} = 0$.

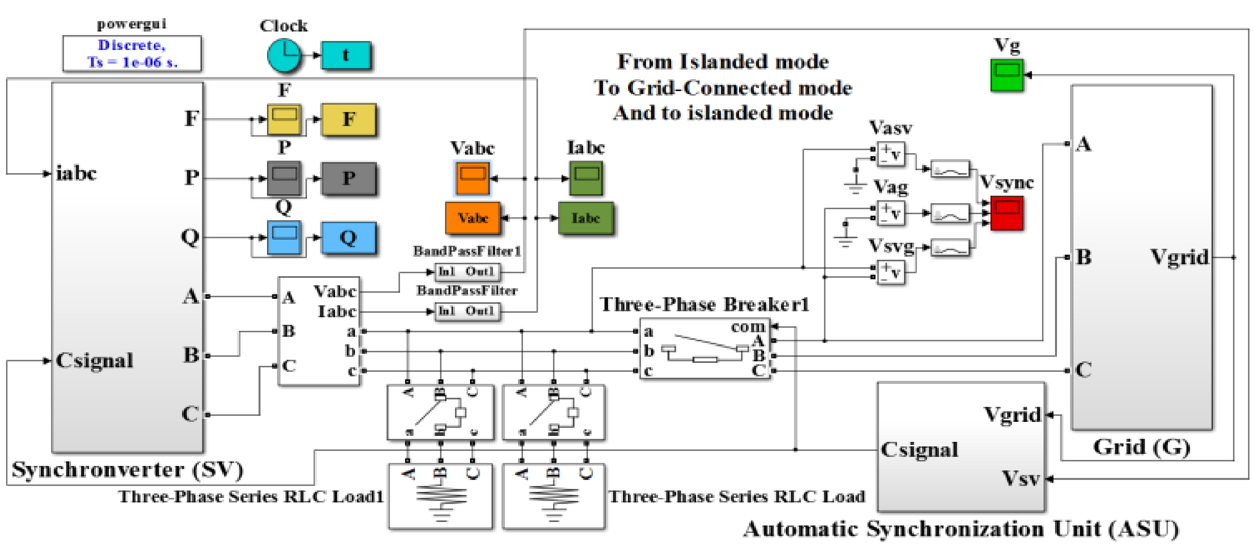


Fig.4 Complete Simulink model of one SV operated in the two modes (Island / Grid)

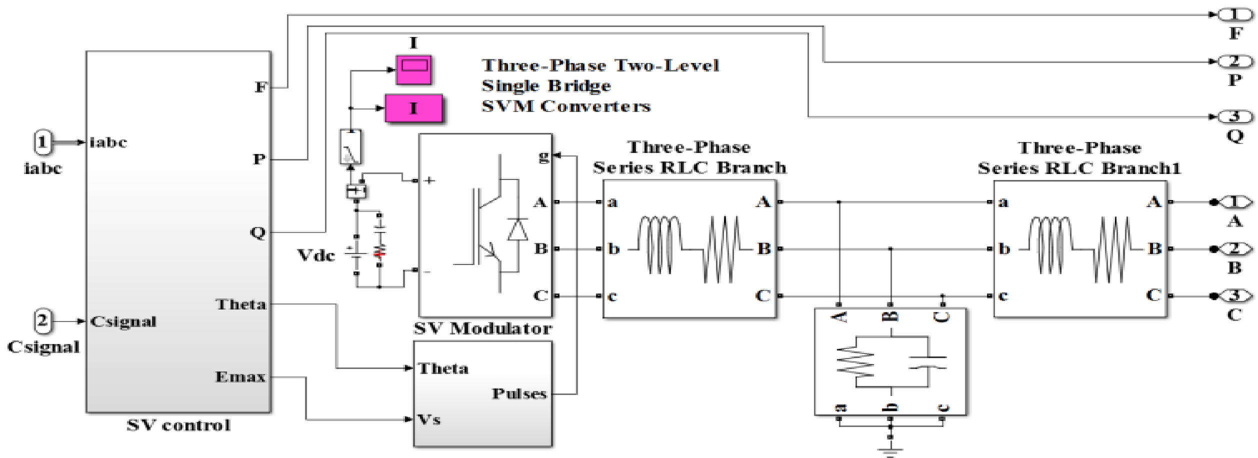


Fig.5 Complete Simulink model of SV

2) Case of Grid connected mode

For SGs, connected with grid the rotor speed maintained by grid frequency while the active load share is adjusted by the mechanical power input (P_{set}) from the prime-mover.

An important mechanism for SGs operating in parallel to share load evenly is to vary the real power delivered to the grid according to the SGs individual ratings. This is made by matching the droop characteristics of generators operating in parallel. This is called frequency droop control and is implemented in a SV as shown in Fig. 3 with switch S1 in the upper position. In this case the input (P_{set}) has the dominant effect, and the closed loop control adjust actual power share to be equals to P_{set}.

The regulation of the real power showed in the upper part of Fig. 3 has an inner frequency-droop loop. The time constant of the frequency-droop loop is $\tau_f = J/D_p$. Hence, if we have decided upon τ_f , then J should be chosen as $J = D_p\tau_f$.

In [2] the author used very small J is much smaller than for a real SG to have fast response in the frequency droop loop.

In our work aiming to make SV having good contribution to power system stored kinetic energy we use value of J very large than that used in [4]. Specifically we used J equals to that of SG with the same power rating. The increased value of time delay τ_f introduced is partially compensated by applying relatively larger value of D_p just to obtain satisfactory transient response. One must make a compromise between enough inertia contribution and fast dynamic response. However, as will be seen in simulation results the transient response is still faster than a conventional SG.

B. Regulation of Reactive Power and Voltage Drooping

1) Case of Standalone (island) mode: In this mode the terminal voltage is adjusted by excitation field current of SG while the reactive power Q flowing out of the SG equals that of the load. When the load increases the terminal voltage decreases and requires more field current to bring it back to original value.

In this mode there must be a control loop to adjust the terminal voltage to be fixed against load variations. This control loop is known practically as Automatic Voltage Regulator (AVR) and it is very important in SG operation due to the large voltage regulation of this type of generators.

As shown in the lower part of Fig.3 SV this is realized with switch S2 in the lower position. The difference between the reference voltage V_r and the amplitude V_m of the feedback voltage v_g from Fig. 1 is the voltage amplitude tracking error. This error is multiplied by a gain and used to generate $M_f\, i_f$ similar to main flux in real SG. The reference input Q_{set} in this mode is set to zero.

2) Case of Grid-connected mode: In this mode the

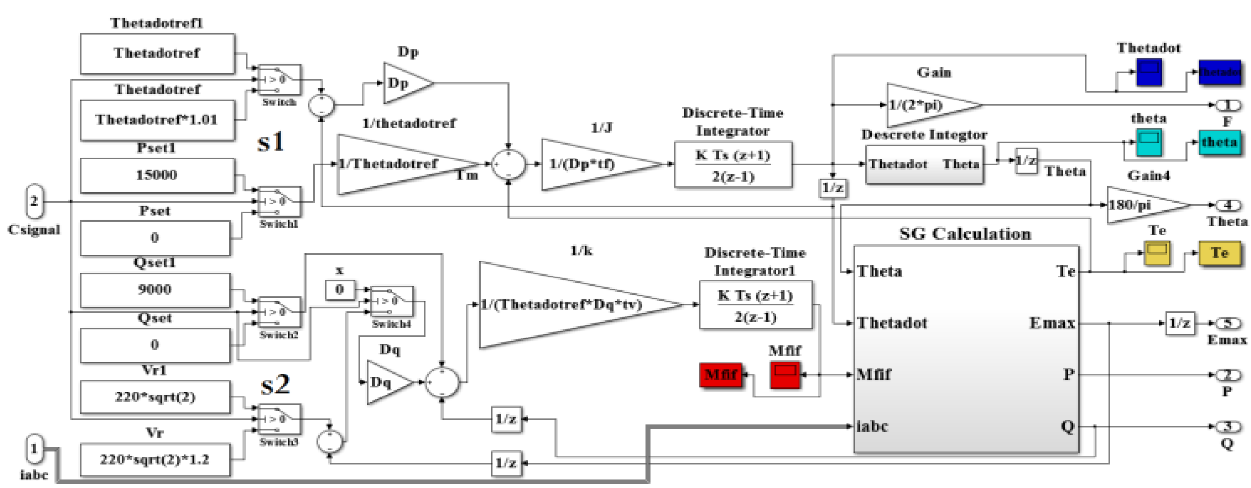


Fig.6 Complete Simulink model of SV control

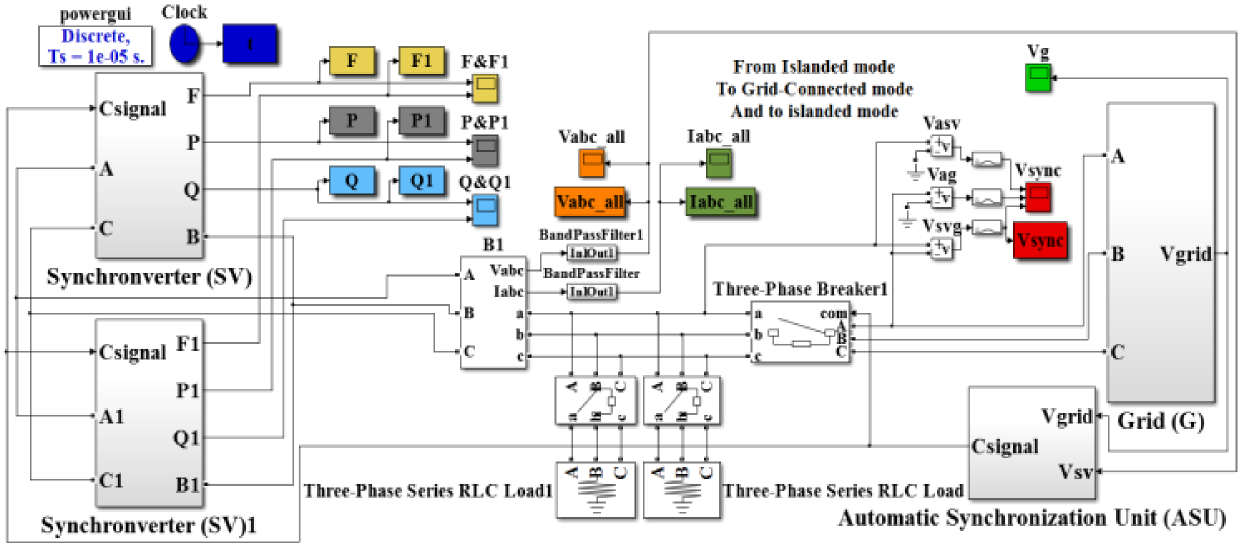


Fig.7 Complete Simulink model of two SVs simulating MG in the two modes (Island / Grid)

terminal voltage is fixed by grid. The regulation of reactive power share Q flowing of the SG is adjusted by the field excitation current or excitation emf (E_{max}).

The AVR in this case regulates only the reactive power share of SG; it has no effect on terminal voltage since it is fixed by the grid.

As shown in the lower part of SV in Fig.3 the control loop for the reactive power is realized. With two switches S2 in the upper positions, the difference between the reference value of the reactive power sharing Q_{set} and the actual Q multiplied by the voltage drooping coefficient D_q and is fed into an integrator with a gain $1/K$ to generate $M_f\, i_f$.

The time constant τ_v of the voltage loop can be estimated as; $\tau_v \approx K\, /\, \theta^{\cdot} D_q \approx K\, /\, \dot{\theta_r}\, D_q$.

The variation of $\theta^{\cdot}$ is very small. Hence, K follows if τ_v and Dq has been chosen. V_m, can be computed as $V_m \approx \theta^{\cdot}\, M_f\, i_f$.

IV. SIMULATION AND ANALYSIS OF RESULTS

We use the MATLAB-SIMULINK toolboxes to simulate the complete dynamic model of the SV, with each subsystem model is constructed individually, and then the whole dynamic model is formed by linking the different subsystems together. Important results of some subsystems are presented also in this section. The benefits of simulating the established models are:

- Tuning D_p and τ_f for the selected value of inertia equated to that of the corresponding SG.
- Examining voltage drooping loop in the two modes of operation.
- Studying the conditions of the DC bus under in different conditions.
- Testing the automatic synchronization unit.
- Proving the seamlessly transition between island and grid modes.
- Testing the sharing of active, reactive power in MG depending on SVs.

For the sake of illustration, Fig.4 shows the complete SIMULINK model of one SV operated in the two modes (Island / Grid).

The parameters of the SV and controller used in the simulations are given in Table I.

In the following we explain each separate building block and its functions and how it is connected to overall system. Description of building blocks

1) *The SV unit:* As shown in Fig.5 containing the SV control unit, PWM inverter unit and low pass filter unit.

2) *Automatic synchronization unit:* This unit tests the realization of ideal conditions of synchronization. At the correct instant this unit gives control logic signals to circuit breaker and changeover switches S1 and S2 to select the appropriate configuration of active and reactive power

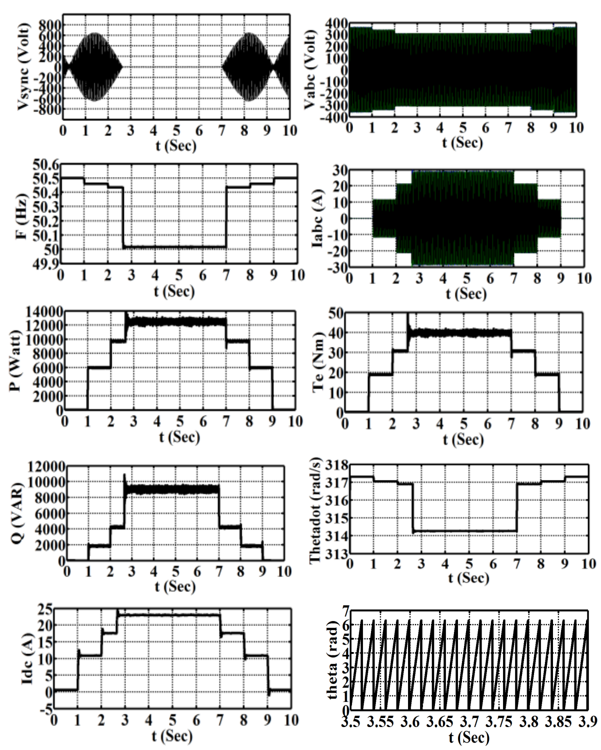


Fig.8. Simulation results of one SV operated in the two modes (Island / Grid)

TABLE I
PARAMETERS OF THE SYNCHRONVERTER AND CONTROLLER

Parameters	Values	Parameters	Values
L_s	5.3 mH	L_g	5.3 mH
R_s	0.166 Ω	R_g	0.166 Ω
C	22 µF	nominal frequency	50 Hz
R(parallel to *C*)	1000 Ω	nominal voltage (line-line)	220 Vrms
Rated power	16 KVA	DC –link voltage	600 V
Switching Frequency	10 KHz		
J	$0.15\ Kg.m^2$	*K*	157
Dp	75	*Dq*	100
τ_f	0.002 s	τ_v	0.002 s

controllers.

3) *The Grid unit:* As shown in Fig.4 is simulated by an ideal 3-phase supply standing for infinite bus of fixed voltage and fixed frequency and unlimited capacity.

4) *The Loads:* As shown in Fig.4 using three phase series loads by two steps.

B. The Simulation Results and Discussions

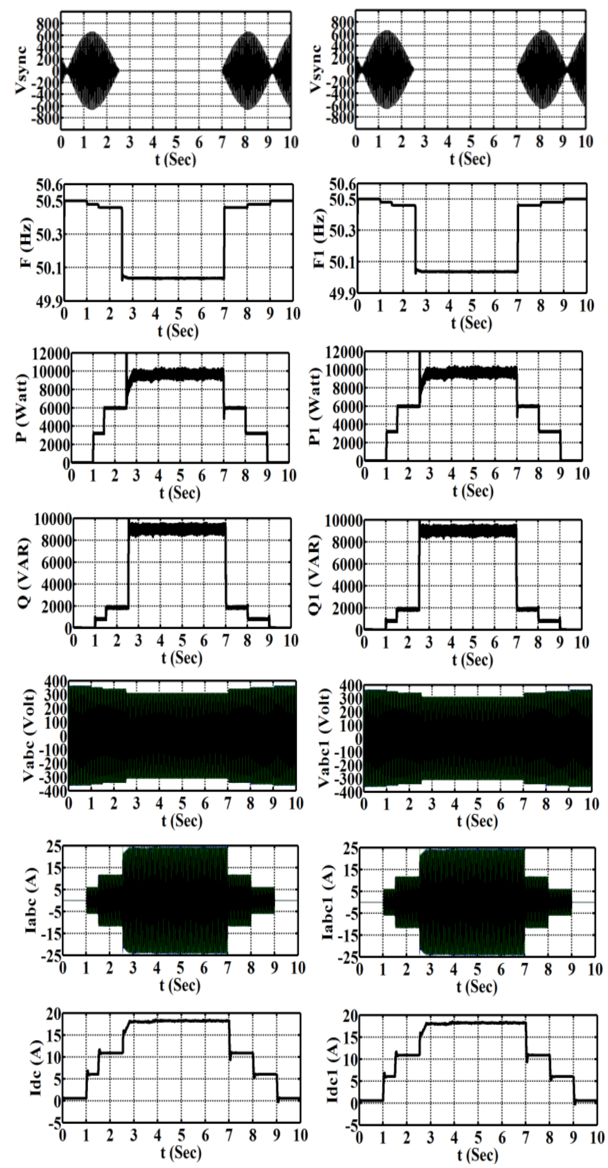
The SV can feed pre-set real power and reactive power to the grid and can automatically change the real power and reactive power fed to the grid according to the SV input power P_{set} and Q_{set}.

1) *One SV operated in the two modes (Island / Grid):* As shown in Fig.7 one SV is operated in island mode from *t*=0 to *t*=2.65 s, the no-load frequency is set to 50.5 Hz, and a 10kW+4kVAR load is switched on in two steps; at *t*=1 s and at *t*=1.5 s. the frequency drops to decreases in proportion to active power loading and the voltage drops in proportion to reactive loading. At *t*=2.65 s the synchronization unit detects the correct synchronization instant and takes actions to connect SV to grid. In grid mode the active power controller dictates active power share $P_{set} = 15\,kW$ and $Q_{set} = 9\,kVAR$ the SV frequency and voltage drops to their grid values. At *t*=7 s an intentional islanding is made; circuit breaker is tripped, the *P* and *Q* controllers are reconfigured to island operation. The previously connected loads are switched off and finally SV frequency and voltage returns to its no-load value. It worse noticing that the synchronization instant was very accurate. There was no noticeable disturbance caused by this event. The SV responded quickly both to the step change in active and reactive power demand. Concerning the dc link where the voltage is fixed by the battery while the dc current tracks the active power load of SV to satisfy power balance, $Vdc \times Idc = active\ power\ of\ SV$.

2) *Two SV operating in parallel to simulate a MG in the two modes (Island / Grid):* The MG is operated in sequence of events similar to the previous case. Fig. 8 showed the simulation results. Generally the results are similar to the previous case with only difference in lies in division of load equally between the two SVs.

V. CONCLUSION

In this research, the models of SV are simulated using Matlab 8.5/Simulink. Detailed simulation blocks are clarified and presented. The model used covers all the dynamics and steady state conditions without the restrictive assumptions normally imposed in such cases. The operation of SV, including active and reactive load sharing, have been described in detail. The model used here can be applied to investigate different problems of related to power systems dominated by parallel-operated inverters. In DG the SV is able to transfer seamlessly between the two modes and provide a solution for MGs. An automatic synchronization unit is used to minimize disturbances at instant of connection to grid. Response in different modes of operation is thoroughly examined.



(a) (b)

Fig.9 Simulation results of two SV operating in parallel to simulating MG in the two modes (Island / Grid)

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